UNIT 4

Sound and Waves

Chapter 11

Harmonic Motion

Introduction to Chapter 11

The motion we have studied so far has been from one place to another. In this chapter we will investigate harmonic motion, which is motion that repeats in cycles. From the orbit of the Earth to the rhythmic beating of your heart, harmonic motion is fundamental to our understanding of nature.

Investigations for Chapter 11

11.1	**Harmonic Motion**	*How do we describe the back and forth motion of a pendulum?*

The pendulum is an ideal start for investigating harmonic motion. The objective for this Investigation is to design a clock that can keep accurate time using a pendulum.

11.2	**Graphs of Harmonic Motion**	*How do we make graphs of harmonic motion?*

Graphs tell us much about straight-line motion. This Investigation will apply graphing techniques to oscillators. Learn how to read a heartbeat from an EKG and how to read the seismogram of a powerful earthquake!

11.3	**Simple Mechanical Oscillators**	*What kinds of systems oscillate?*

Many things in nature oscillate. Guitar strings, trees in the wind, and stretched rubber bands are all examples of oscillators. In this Investigation we will construct several simple oscillators and learn how to adjust their frequency and period.

Learning Goals

In this chapter, you will:

- ✔ Learn about harmonic motion and how it is fundamental to understanding natural processes.
- ✔ Use harmonic motion to keep accurate time using a pendulum.
- ✔ Learn how to interpret and make graphs of harmonic motion.
- ✔ Construct simple oscillators.
- ✔ Learn how to adjust the frequency and period of simple oscillators.
- ✔ Learn to identify simple oscillators.

Vocabulary

amplitude	harmonic motion	period	system
cycle	hertz	periodic motion	
frequency	oscillator	phase	

11.1 Harmonic Motion

As you watch moving things, you see two different kinds of motion. One kind of motion goes from one place to another. This is called *linear motion*. The concepts of distance, time, speed, and acceleration come from thinking about this kind of motion.

The second kind of motion is motion that repeats itself over and over. We call motion that repeats over and over **harmonic motion** and that is what you will learn about in this section. The word comes from *harmony* which means "multiples of." Swinging back and forth on a swing is a good example of harmonic motion (Figure 11.1). Many moving things have both kinds of motion. A bicycle moves forward but the wheels and pedals go around and around in harmonic motion (Figure 11.2).

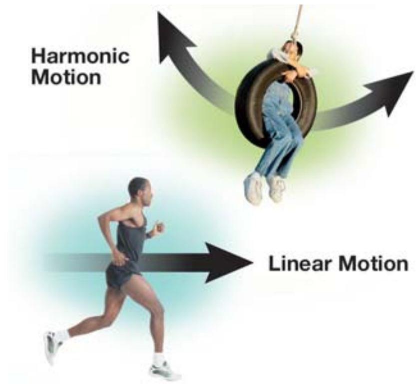
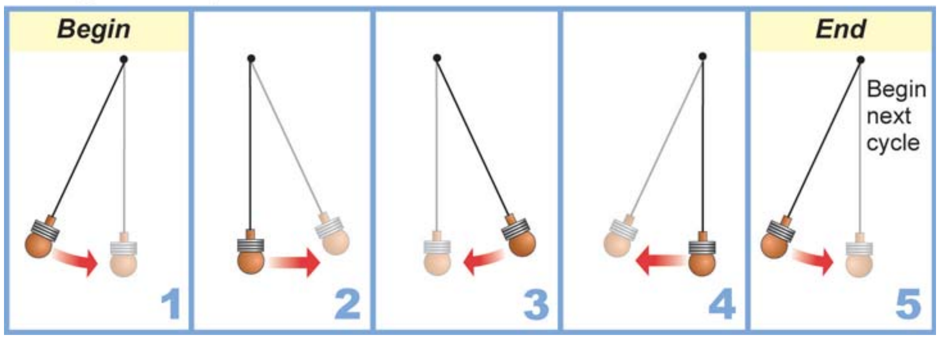


Figure 11.1: *Linear motion goes from one place to another without repeating. Harmonic motion repeats over and over the same way.*

Cycles, systems, and oscillators

What is a cycle? The **cycle** is the building block of harmonic motion. A cycle is a unit of motion that repeats over and over. All harmonic motion is a repeated sequence of cycles. The cycle of the pendulum is shown below.

The cycle of a pendulum



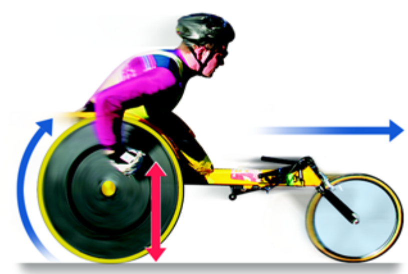


Figure 11.2: *Real-life situations can include both linear motion and harmonic motion.*

Finding the cycle When investigating harmonic motion we start by identifying the basic cycle. A cycle has a beginning and ending. Between beginning and end, the cycle has to include all the motion that repeats. The cycle of the pendulum is defined by where we choose the beginning. If we start the cycle when the pendulum is all the way to the left, the cycle ends when the pendulum has returned all the way to the left again. If we choose the cycle correctly, the motion of the pendulum is one cycle after the next with no gaps between cycles.

Harmonic motion in nature

Choosing a system

In science we often refer to a system. A system is a group we choose that includes all the things we are interested in. Choosing the system helps us concentrate on what is important and exclude what is not important. For the pendulum, the system is the hanger, string, and weight. We don't need to include the floor or the table, since these are not directly important to the motion.

We might choose the system differently depending on what we want to investigate. If we wanted to see how gravity affected the pendulum, we would have to include Earth's gravity as part of the system.

An oscillator is a system with harmonic motion

A system that shows harmonic motion is called an **oscillator**. The pendulum is an example of an oscillator. So is your heart and its surrounding muscles (Figure12.4). Oscillators can be very small. The electrons in the atom make harmonic motion, so an atom is an oscillator. Oscillators can also be very large. The solar system is an oscillator with each of the planets in harmonic motion around the sun. We are going to study oscillators using simple models, but what we learn will also apply to more complex systems, like a microwave communications satellite.

Earth is part of several systems in harmonic motion

Earth is a part of several oscillating systems. The Earth/sun system has a cycle of one year, which means Earth completes one orbit around the sun in a year. The Earth/moon system has a cycle of approximately one month. Earth itself has several different cycles (Figure 11.4). It rotates around its axis once a day making the 24-hour cycle of day and night. There is also a wobble of Earth's axis that cycles every 22,000 years, moving the north and south poles around by hundreds of miles. There are cycles in weather, such as the El Nino and La Nina oscillations in ocean currents that produce fierce storms every decade or so. Much of the planet's ecology depends on cycles.

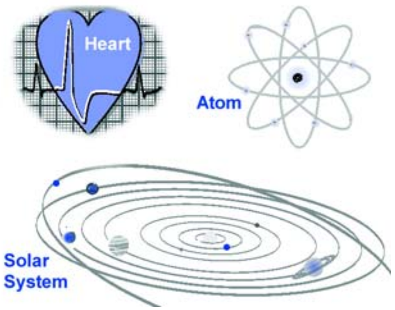


Figure 11.3: *The pendulum is an oscillator. Other examples of oscillators are an atom, your beating heart, and the solar system.*

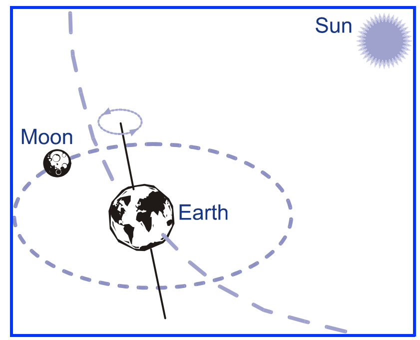


Figure 11.4: *The Earth/sun/moon system has many different cycles. The year, month, and day are the result of orbital cycles.*

Harmonic motion in art and music

Music comes from oscillations

Both light and sound come from oscillations. Music and musical instruments are oscillators that we design to create sounds with specific cycles that we enjoy hearing. Sound is an oscillation of the air. A moving speaker pushes and pulls on the air creating a small oscillation in pressure (Figure 11.5). The oscillation travels to where it hits your eardrum. Your vibrating eardrum moves tiny bones in the ear setting up more oscillations that are transmitted by nerves to the brain. There is harmonic motion at every step of the way, from the musical instrument to the perception of sound by your brain.

Color comes from oscillations

We see colors in light waves, which are oscillations of electricity and magnetism. Faster oscillations make blue light while slower oscillations make red light. When painting a picture, each color of paint contains different molecules that absorb and reflect different colors of light. The colors you see come from the interaction between the oscillations of light and the oscillations of the electrons in the pigment molecules.

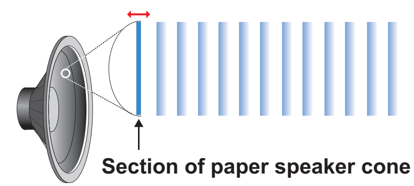


Figure 11.5: *A moving speaker oscillates back and forth, making sound that you can hear.*

Figure 11.6: *The cordless phone you use has an electronic oscillator at millions of cycles per second.*

Harmonic motion in technology

Oscillators are used in communications

Almost all modern communication technology relies on fast electronic oscillators. Cell phones use oscillators that make more than 100 million cycles each second (Figure 11.6). FM radio uses oscillators between 95 million and 107 million cycles per second. When you tune a radio you are selecting the frequency of the oscillator you want to listen to. Each station sets up an oscillator at a different frequency. Sometimes, you can get two stations at once when you are traveling between two radio towers with nearly the same frequency.

Oscillators are used to measure time

The cycles of many oscillators always repeat in the same amount of time. This makes harmonic motion a good way to keep time. If you have a pendulum that has a cycle one second long, you can count time in seconds by counting cycles of the pendulum. Grandfather clocks and mechanical watches actually count cycles of oscillators to tell time (Figure 11.7). Even today, the world's most accurate clocks keep time by counting cycles of light from a cesium atom oscillator. Modern atomic clocks are so accurate they lose only one second in 1,400,000 years!

Figure 11.7: *Clocks and watches use oscillators to keep time. This works because many oscillators have precisely stable cycles.*

Investigating harmonic motion

Period is the time for one cycle

What makes harmonic motion useful for clocks is that each cycle takes the same amount of time. The time for one cycle is called the **period**. Some clocks have a pendulum with a period of exactly two seconds. The gears in the clock cause the minute hand to move 1/60 of a turn for every 30 swings of the pendulum. The period is one of the important characteristics of all harmonic motion (Figure 11.8).

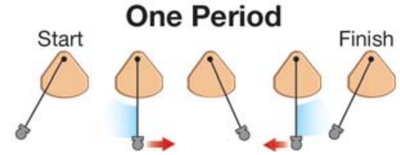


Figure 11.8: *The period is the time it takes to complete one cycle.*

Frequency is the number of cycles per second

Frequency is closely related to period. The **frequency** of an oscillator is the number of cycles it makes per second. Every day, we experience a wide range of frequencies. FM radio uses frequencies between 95 million and 107 million cycles per second (the FM standing for frequency modulation) (Figure 11.9). Your heartbeat probably has a frequency between one-half and two cycles per second. The musical note "A" has a frequency of 440 cycles per second. The human voice contains frequencies mainly between 100 and 2,000 cycles per second.

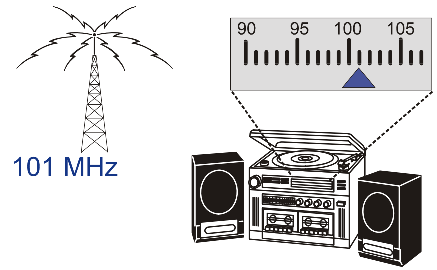


Figure 11.9: *When you tune a radio to receive a station, you are matching frequencies between receiver and transmitter.*

Frequency is measured in hertz

The unit of one cycle per second is called a **hertz**. A frequency of 440 cycles per second is usually written as 440 hertz, or abbreviated 440 Hz. The Hz is a unit that is the same in English and metric. When you tune into a station at 101 on the FM dial, you are actually setting the oscillator in your radio to a frequency of 101 megahertz, or 101,000,000 Hz. You hear music when the oscillator in your radio is exactly matched to the frequency of the oscillator in the transmission tower connected to the radio station.

Period and frequency

Period (seconds)

$$T = \frac{1}{f}$$

Frequency (hertz)

Frequency (hertz)

$$f = \frac{1}{T}$$

Period (seconds)

Frequency and period are inversely related. The period is the time per cycle. The frequency is the number of cycles per time. If the period of a pendulum is 1.25 seconds, its frequency is 0.8 cycles per second (0.8 Hz). If you know one, you can calculate the other.

Example:

Calculate the frequency of a pendulum that has a period of 1/4 second.

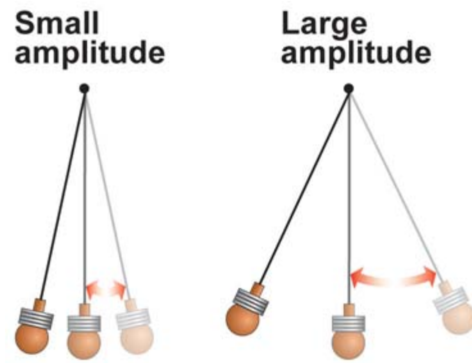
Solution:

(1) You are asked for frequency.
(2) You are given the period.
(3) The relationship you need is F=1/T.
(4) Plug in numbers.
F = 1 / (0.25 sec)
= 4 Hz

Amplitude

Amplitude describes the size of a cycle

Another important characteristic of a cycle is its size. The period tells how long the cycle lasts. The amplitude describes how big the cycle is. The diagram below shows a pendulum with small amplitude and large amplitude. With mechanical systems (such as a pendulum), the amplitude is often a distance or angle. With other kinds of oscillators, the amplitude might be voltage or pressure. The amplitude is measured in units appropriate to the kind of oscillation you are describing.



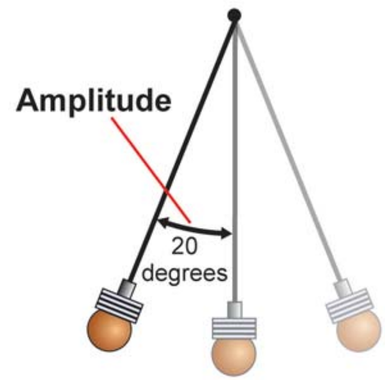
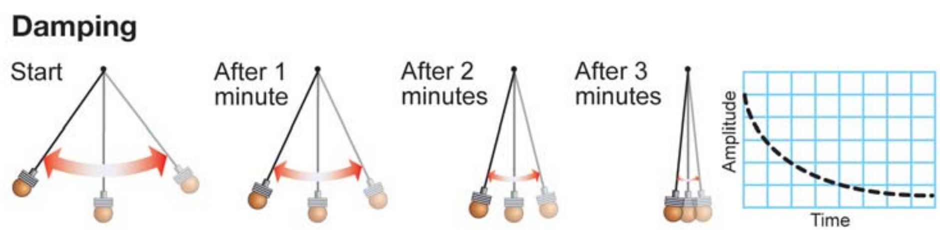


Figure 11.10: *A pendulum with an amplitude of 20 degrees swings 20 degrees away from the center.*

How do you measure amplitude?

The amplitude is the maximum distance the motion moves away from the average. For a pendulum, the average is at the center. The pendulum spends as much time to the right of center as it does to the left. For the pendulum in Figure 11.10, the amplitude is 20 degrees, because the pendulum moves 20 degrees away from center in either direction.



Damping

Friction slows a pendulum down, as it does all oscillators. That means the amplitude slowly gets reduced until the pendulum is hanging straight down, motionless. We use the word damping to describe the gradual loss of amplitude of an oscillator. If you wanted to make a clock with a pendulum, you would have to find a way to keep adding energy to counteract the damping of friction.

11.2 Graphs of Harmonic Motion

Harmonic motion graphs show cycles. This is what makes them different from linear motion graphs (Figure 11.11). The values of the period and amplitude can be read from the graphs. If you know the period and amplitude, you can quickly sketch a harmonic motion graph.

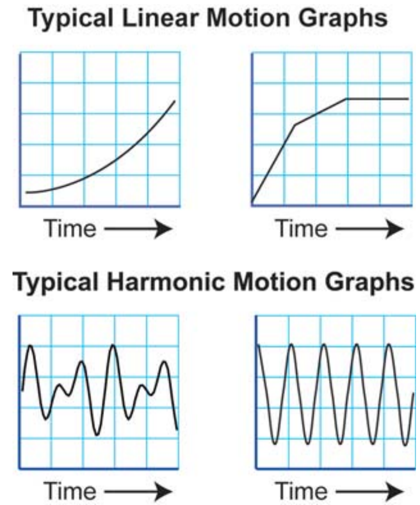


Figure 11.11: *Typical graphs for linear motion (top) and harmonic motion (bottom). Harmonic motion graphs show cycles.*

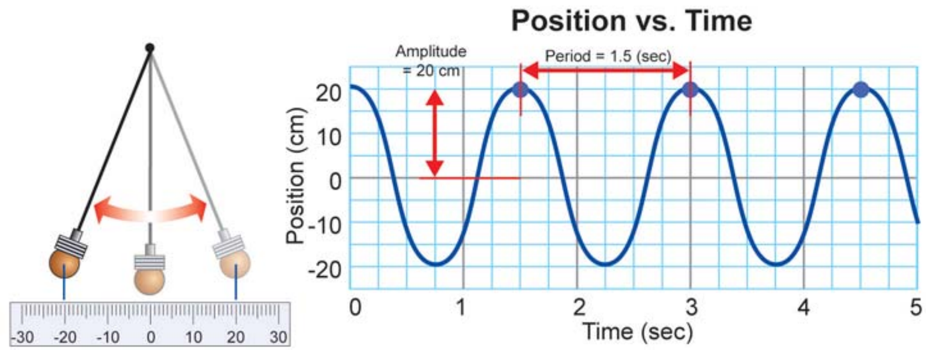
Reading harmonic motion graphs

Cycles and time

Most graphs of harmonic motion show how things change with time. The pendulum is a good example. The diagram below shows a graph of position vs. time for a pendulum. The graph shows repeating cycles just like the motion. Seeing a pattern of cycles on a graph is an indication that harmonic motion is present.

Using positive and negative numbers

Harmonic motion graphs often use positive and negative values to represent motion on either side of center. We usually choose zero to be at the equilibrium point of the motion. Zero is placed halfway up the *y*-axis so there is room for both positive and negative values. The graph alternates from plus to minus and back. The example graph below shows a pendulum swinging from +20 centimeters to -20 centimeters and back. The amplitude is the maximum distance away from center, or 20 centimeters.



Harmonic graphs repeat every period

Notice that the graph (above) returns to the same place every 1.5 seconds. No matter where you start, you come back to the same value 1.5 seconds later. Graphs of harmonic motion repeat every period, just as the motion repeats every cycle. Harmonic motion is sometimes called **periodic motion** for this reason.

Determining amplitude and period from a graph

Calculating amplitude from a graph

The amplitude is half the distance between the highest and lowest points on the graph. For the example in Figure 11.12, the amplitude is 20 centimeters, as illustrated by the calculation below. The difference between the highest and lowest value of the graph is the *peak-to-peak* value.

$$\text{Amplitude} = \tfrac{1}{2}(\text{high} - \text{low}) = \tfrac{1}{2}(20 - (-20))$$
$$= 20 \text{ cm}$$

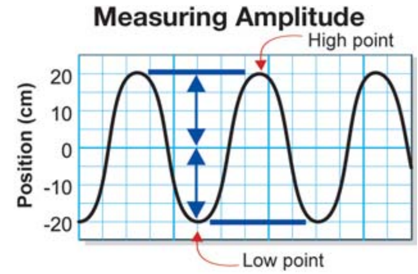
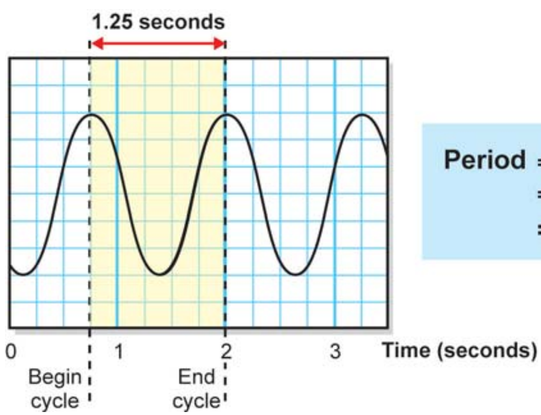


Figure 11.12: *The amplitude of a wave is one-half the peak-to-peak distance. In this graph of harmonic motion, the amplitude of the wave is 20 centimeters.*

Calculating period from a graph

To get the period from a graph, start by identifying one complete cycle. The cycle must begin and end in the same place on the graph. Figure 11.13 shows how to choose the cycle for a simple harmonic motion graph and for a more complex one. Once you have identified a cycle, you use the time axis of the graph to determine the period. The period is the time difference between the beginning of the cycle and the end. Subtract the beginning time from the ending time, as shown in the example below.



Period = (ending time - beginning time)
= (2.0 sec - 0.75 sec)
= 1.25 seconds

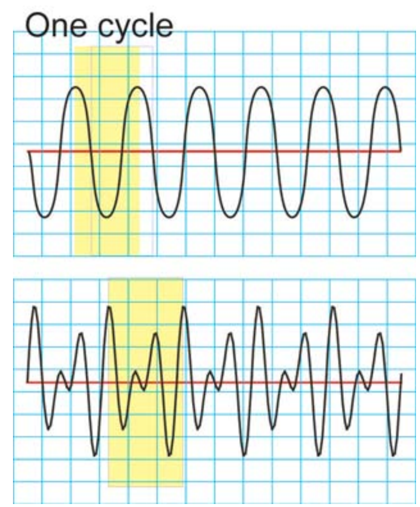


Figure 11.13: *The cycle is the part of the graph that repeats over and over. The gray shading shows one cycle for each of the graphs above. Before you can find the period, you need to identify the cycle.*

Circles and harmonic motion

Circular motion

Circular motion is very similar to harmonic motion. For example, a turning wheel returns to the same position every 360 degrees. Rotation is a cycle, just like harmonic motion. One key difference is that cycles of circular motion *always* have a length of 360 degrees. It does not matter how big the wheel is, each full turn is 360 degrees.

Figure 11.14 shows a shadow of a peg on a rotating wheel. As the wheel rotates, the shadow of the peg goes back and forth on the wall. If we make a graph of the position of the shadow, we get a harmonic motion graph. The period of the cycle is exactly the time it takes the wheel to turn 360 degrees.

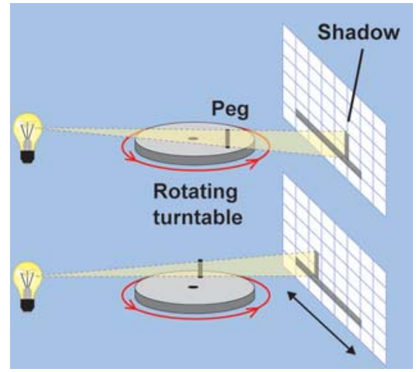


Figure 11.14: *The shadow of a peg moves back and forth on the wall as the turntable rotates. The shadow itself appears to be in harmonic motion.*

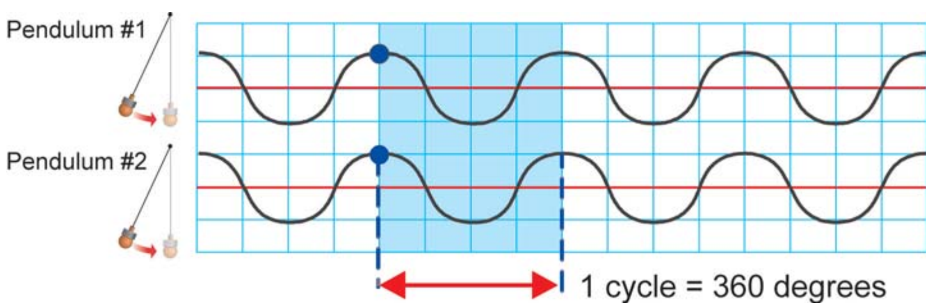
The phase of an oscillator

We often use degrees to tell us where we are within the cycle of an oscillator. For example, how would you identify the moment when the pendulum was one-tenth of the way through its cycle? If we let one cycle be 360 degrees, then one-tenth of that cycle is 36 degrees. Thirty-six degrees is a measure of the phase of the oscillator. The word “phase” means where the oscillator is in the cycle.

What do we mean by “in phase”?

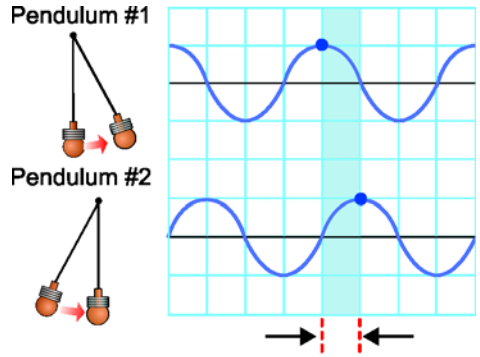
The concept of phase is important when comparing one oscillator with another. Suppose we have two identical pendulums, with exactly the same period. If we start them together, their graphs would look like the picture below. We describe the two pendulums as being *in phase* because cycles are aligned. Each oscillator is always at the same place at the same time.

Both pendulums in phase



Out of phase by 90 degrees

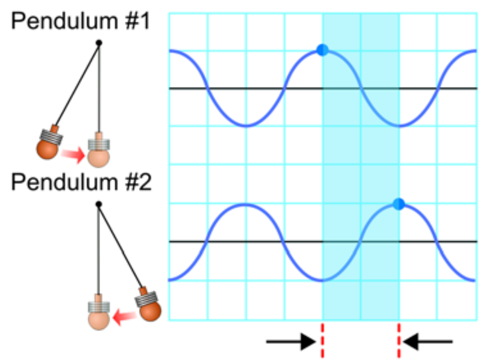
If we start the first pendulum swinging a little before the second one, the graphs look like the diagram to the right. Although, they have the same cycle, the first pendulum is always a little ahead of the second. The graph shows the lead of the first pendulum as a phase difference. Notice that the top graph reaches its maximum 90 degrees *before* the bottom graph. We say the two pendulums are *out of phase* by 90 degrees, or one-fourth of a cycle.



90 degrees phase difference

Out of phase by 180 degrees

When they are out of phase, the relative motion of the oscillators may differ by a little or by as much as half a cycle. Two oscillators 180 degrees out of phase are one-half cycle apart. The next diagram (right) shows that the two pendulums are always on opposite sides of the cycle from each other. The concepts of in phase and out of phase will be very important to our Investigations with waves and sound.



180 degree phase difference

Katherine Johnson

Katherine G. Johnson was born in 1918 in White Sulphur Springs, West Virginia. Her parents were determined to provide their children with high-quality education, traveling across the state so that Katherine and her siblings could attend a laboratory high school at West Virginia State College.

Johnson earned degrees in French and math from West Virginia State. She taught high school while pursuing graduate study in math and physics. In the early 1950's, she was hired as a mathematician by the government agency that later became NASA.

At NASA, Johnson worked out complicated math problems that determined the trajectories (paths) for manned and unmanned spacecraft. She was instrumental in planning the Apollo missions and helped develop their emergency navigation systems. She also worked on determining orbits for spacecraft like the Earth Resources Satellite.

Johnson received the Group Achievement Award presented to NASA's Lunar Spacecraft and Operations team, an Honorary Doctor of Laws degree from SUNY Farmingdale, and West Virginia State College Outstanding Alumnus of the Year award.

11.3 Simple Mechanical Oscillators

Harmonic motion is so common that it would be impossible to list all the different kinds of oscillators you might find. Fortunately, we can learn much about harmonic motion by looking at just a few examples. Once we understand some basic oscillators, we will have the experience needed to figure out more complex ones.

Examples of oscillators

The pendulum The simplest pendulum is a weight hanging from a string. The weight swings back and forth once it is pulled away and released. The force that always pulls the pendulum back to center comes from its weight (Figure 11.15). If you swing a pendulum to one side, the string causes it to lift slightly.

The period of a pendulum does not change much, even when its amplitude is changed. This is because two opposite effects occur. First, if you make the amplitude large, the pendulum has a greater distance to travel, which increases the period. But remember that by releasing it from a high position, it also starts with more energy. More energy means the pendulum goes faster and higher speed decreases the period. The effect of higher speed almost exactly cancels the effect of longer swing distance.

A mass on a spring If you have ever been in a car with worn-out shock absorbers, you have experienced another common oscillator. The system of a car and shock absorbers is an example of a mass on a spring. Springs resist being extended or compressed. Figure 11.16 shows how the force from a spring always acts to return to equilibrium. A mass attached to a spring adds inertia to the system. If the mass is given an initial push, the mass/spring system oscillates.

A vibrating string Vibrating strings are used in many musical instruments. A stretched rubber band is a good example. If you pull the rubber band to one side, it stretches a bit. The stretching creates a restoring force that tries to pull the rubber band back straight again. Inertia carries it past being straight and it vibrates. Vibrating strings tend to move much faster than springs and pendulums. The period of a vibrating string can easily be one-hundredth of a second (0.01) or shorter.

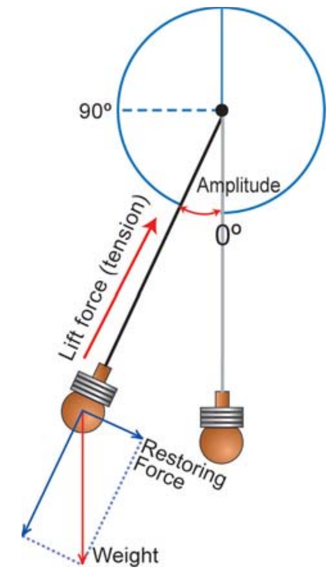


Figure 11.15: *The forces acting on the pendulum. The weight (gravity) points straight down.*

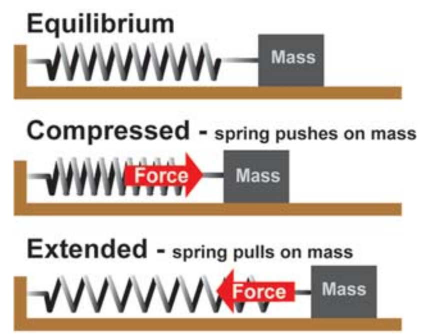


Figure 11.16: *A mass on a spring oscillator. When the spring is compressed or extended, it pushes the mass back toward equilibrium.*

Chapter 11 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

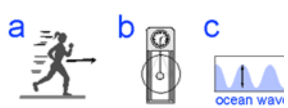
1. harmonic motion	a. A system in harmonic motion
2. cycle	b. A unit of one cycle per second
3. system	c. Back and forth or repeating motion
4. oscillator	d. A part of motion that repeats over and over
5. hertz	e. A group of things we think are important to consider when analyzing something
	f. Motion that goes from one point to another without repeating

Set Two

1. period	a. The number of cycles per second
2. frequency	b. The size of a cycle
3. amplitude	c. A way to identify where an oscillator is in its cycle
4. damping	d. The time it takes to complete one cycle
5. phase	e. Any process that causes cycles to get smaller and smaller in amplitude
	f. A unit of one cycle per second

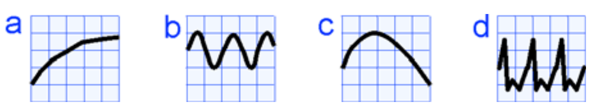
Concept review

1. Name three objects or systems around you that have cycles.
2. What is the relationship between frequency and period?
3. Which pictures show only periodic motion?

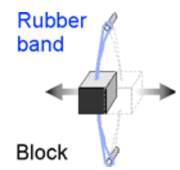


   a. A girl running a race.
   b. The swinging pendulum of a clock.
   c. An ocean wave rising and falling.
   d. A boy swinging.
   e. A car moving down the street.
4. If the length of the rope on a swing gets longer, the period of the swing will:
   a. Get longer.
   b. Get shorter.
   c. Stay the same.
   d. I need more information to answer.

5. In a pendulum experiment, the ____________ is the maximum angle that the pendulum swings away from center. (Pick one.)
    a. cycle
    b. amplitude
    c. period
    d. speed
6. Oscillations have something to do with the answers to which of the following questions? (You can pick more than one.)
    a. What color is it?
    b. How much mass does it have?
    c. How long is it?
    d. How loud is that noise?
    e. What radio station is this?
7. A clock is made using a pendulum to count the time. The weight at the bottom of the pendulum can be adjusted to make the length of the pendulum longer or shorter. The clock runs too fast, meaning it counts 50 minutes as one full hour. What should you do to correct the clock?
    a. Move the weight upward, making the pendulum shorter.
    b. Move the weight downward, making the pendulum longer.
    c. Add more weight to make the pendulum heavier.
8. Which of the graphs clearly shows harmonic motion? You may choose more than one.



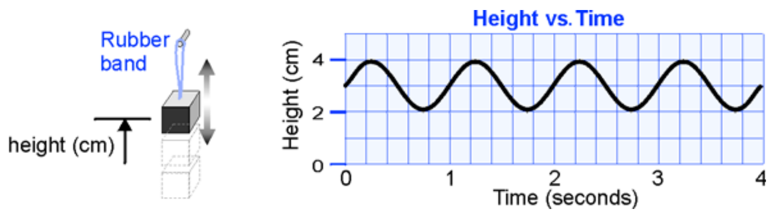
9. The measurement of 2.5 seconds could be:
    a. The frequency of an oscillator.
    b. The period of an oscillator.
    c. The mass of an oscillator.
    d. The system where we find an oscillator.
10. A measurement of 1 meter could be:
    a. The frequency of an oscillator.
    b. The amplitude of an oscillator.
    c. The mass of an oscillator.
    d. The system where we find an oscillator.
11. An oscillator is made with a rubber band and a block of wood, as shown in the diagram. What happens to the oscillator if we make the block of wood heavier?



    a. The frequency increases.
    b. The period increases.
    c. The frequency stays the same.
    d. The period stays the same.
12. If the amplitude of a pendulum is doubled, which of the following will be true?
    a. It will swing twice as far away from center.
    b. Its period will be twice as long.
    c. Its frequency will be twice as high.
    d. It must have twice the mass.

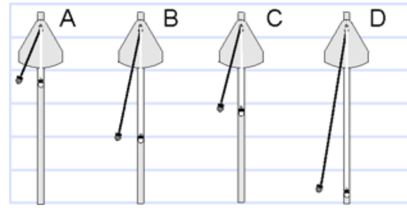
Problems

1. A person's heartbeat is measured to be 65 beats per minute. What is the period between heartbeats in seconds?
    a. 65 seconds
    b. 65 Hertz
    c. 0.92 seconds
    d. 1.08 seconds
2. A pendulum has a period of 1.5 seconds. How many cycles do you have to count to make one minute?
3. A string vibrates back and forth 30 times per second. What is the period of the motion of the string?
4. The graph shows the motion of an oscillator that is a weight hanging from a rubber band. The weight moves up and down. Answer the following questions using the graph.



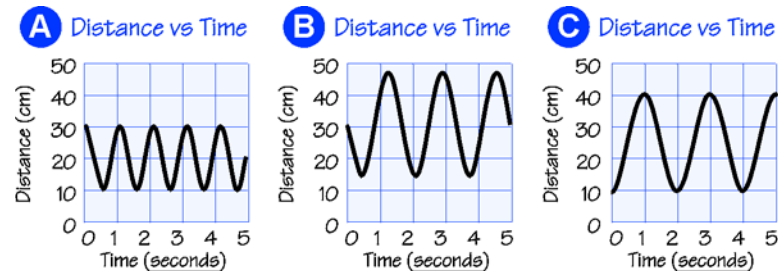
    a. What is the period?
    b. What is the amplitude?
    c. If you counted for 5 seconds, how many cycles would you count?

5. Four different groups of students make measurements of the period of a pendulum. Each group hands in a lab with no names on it. Can you tell which lab group was working with which pendulum? Match the letter of the pendulum to the number of the lab group.



Group	Period	Pendulum
1	1.0 sec	
2	1.2 sec	
3	1.4 sec	
4	1.7 sec	

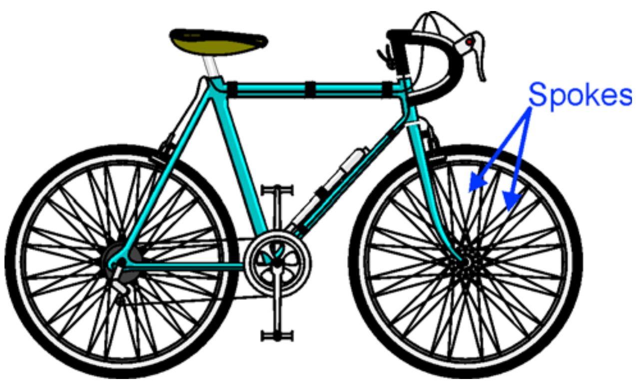
Questions 6, 7, and 8 refer to the three graphs below. Distance in these graphs means displacement of the oscillator.



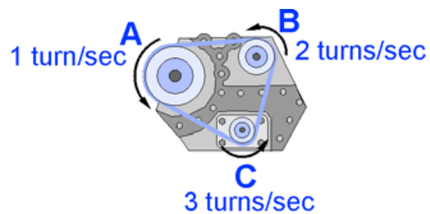
6. Which graph shows exactly 3 cycles?
7. Which graph has a period of 2 seconds?
8. Which graph has an amplitude of 10 centimeters?

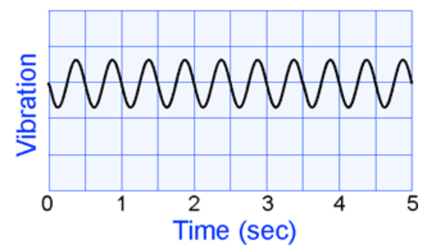
Applying your knowledge

1. What is the period of the rotation of the Earth that gives us day and night?
2. An animal research scientist films a small bird and counts 240 beats of the bird's wings in 2 minutes. What is the frequency of the motion of the bird's wings?
3. The Earth, moon, and sun make a system with many cycles. Give at least two examples of cycles that relate to the Earth, moon, or sun and also give the period of each example you find.



4. You invent a bicycle speedometer that counts how many spokes of the wheel pass by each second. You ride your bicycle to test the speedometer and measure 2,160 spokes pass in one minute.
   a. What is the frequency of spokes passing your sensor in hertz?
   b. The wheel has 36 spokes. How many turns per minute does the wheel make?
5. The human heart is both strong and reliable. As a demonstration of how reliable the heart is, calculate how many times your heart beats in one day. Start by measuring the frequency of your pulse in beats per minute and use the result for your calculation.





6. Frequency can be a clue to finding problems in engines before they cause serious damage. Suppose the engine has three spinning parts (A, B, C), each turning at a different speed. Since the speed of each part is different, the frequency of each is also different. If one part starts to wear out, it will vibrate more than it should. By looking at the frequency of vibration for the whole engine, you can spot which part is the problem by looking for vibrations at its characteristic frequency. The graph shows the vibration of the whole engine, including all three spinning parts. From the graph, can you tell which part is making too much vibration, and is therefore likely to fail?

UNIT 4

Sound and Waves

Chapter 12

Waves

Introduction to Chapter 12

Waves carry energy and information over great distances. A cell phone conversation is carried on waves that travel for thousands of miles. Waves on the ocean also travel thousands of miles before they splash at your feet on the beach. In this chapter, you will learn how to measure and control waves so that you can use them for music, communication, and many other useful things.

Investigations for Chapter 12

12.1	Waves	*How do we make and describe waves?*

A stretched string seems simple but it gets very interesting when you use it to make a wave! For this Investigation you will make wave pulses on springs and strings to see how they move and what they do at boundaries.

12.2	Waves in Motion	*How do waves move and interact with things?*

Waves in water are a familiar sight. In this Investigation we will use water waves to explore reflection, diffraction, and other things waves do.

12.3	Natural Frequency and Resonance	*What is resonance and why is it important?*

Everything has a natural frequency, and most things have more than one. When you force something to vibrate at its natural frequency you can make very large waves. In this Investigation we will use a fascinating electronic synthesizer to make waves on a vibrating string so that we can explore resonance and harmony. We will learn the foundation upon which all musical instruments are built.

Learning Goals

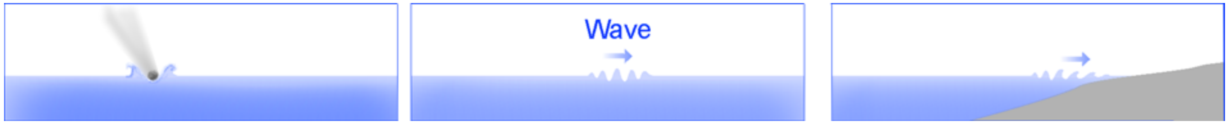
In this chapter, you will:

- ✔ Learn the role waves play in our daily lives, including our effort to communicate.
- ✔ Learn the parts and shapes of waves.
- ✔ Model transverse and longitudinal waves and their characteristics with a stretched string.
- ✔ Explore the properties of waves (like reflection and diffraction) with water.
- ✔ Investigate resonance and harmony using an electronic synthesizer.
- ✔ Learn how natural frequency and resonance are involved in making music.

Vocabulary

circular waves	diffraction	natural frequency	response
constructive interference	fundamental	plane waves	standing wave
continuous	harmonics	reflection	transverse wave
crest	hertz	refraction	trough
destructive interference	longitudinal wave	resonance	wave fronts

12.1 Waves



Suppose a big meteor falls into the ocean. The energy of the falling meteor creates a wave that carries the energy to distant shores. You watch a great musician on stage. The voice or instrument creates waves that carry the sound to your ears. You dial a cell phone to call a friend. A microwave comes from the antenna and carries a signal to your friend.

In this section you will learn about waves. What you learn will apply to the water waves, sound waves, and light waves you see around you all the time. What you learn will also apply to the radio waves and microwaves that are also around even though you can't feel them or see them. Even gravity has waves that astronomers believe are created when black holes crash into each other.

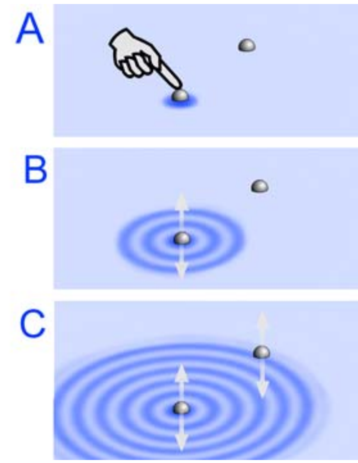


Figure 12.1: *If we poke a floating ball, it moves up and down in harmonic motion (A). The oscillating ball creates a wave (B) that travels on the surface of the water. The wave can cause oscillation of a second ball (C) placed far away from the first.*

Why learn about waves?

Waves carry oscillations from one place to another

A ball floating on the water is a good example of the difference between a wave and ordinary harmonic motion. If you poke the ball, it moves up and down. The oscillating ball creates a wave on the surface of the water that spreads outward, carrying the oscillation to other places (Figure 12.1). A second ball floating farther away also starts oscillating as soon as the wave reaches it. The wave started by an earthquake can travel around the world, reaching places far away from where it began.

Waves carry information and energy

We use waves to carry information and energy over great distances. The sound wave that travels through the air carries information about the vibration of the string from the instrument to your ear. Your ear hears the vibration as music. In a similar way, a radio wave carries sounds from a transmitter to your stereo. Another kind of radio wave carries television signals. A microwave carries cell phone conversations. Waves carry energy and information from one place to another. The information could be sound, color, pictures, commands, or many other useful things.

Waves are all around us.

Waves are part of everyday experience. We might not recognize all the waves we see, but they are there. Consider standing on the corner of a busy street. How are you affected by waves?

- The stoplight that you see with your eyes is a wave.
- The sounds that you hear are waves.
- The ripples in a puddle of water are waves.
- The electricity flowing in the wires attached to the street lights is a wave.
- Waves carry radio and TV and cell phone transmissions through the air around you.

There are waves *inside* the atoms that make up everything we see. By understanding how waves work we can learn about nature and also about technology (Figure 12.2).

How do you recognize a wave?

All waves have things in common. When you see the things in this list, you should suspect that there is some kind of wave involved.

Evidence for suspecting there are waves:

- Anytime you see a vibration that moves, there is a wave.
- Anything that makes or responds to sound uses waves.
- Anything that makes or responds to light uses waves.
- Anything that transmits information through the air (or space) without wires uses waves. This includes cell phones, radio, and television.
- Anything that allows you to "see through" objects uses waves. This includes ultrasound, CAT scans, MRI scans, and X rays (Figure 12.3).

Where can we find waves?

We will usually find waves whenever information, energy, or motion is transmitted over a distance without anything obviously moving. The remote control on a TV is an example. To change the channel you can use the remote or get up and push the buttons with your finger. Both actions carry information (the channel selected) to the TV. One uses physical motion and the other uses a wave that goes from the remote control to the television. Your knowledge of physics and waves tells you there must be some kind of wave because information traveled from one place to another, and nothing appeared to move. The wave is actually an infrared light wave, which is invisible to the eye.

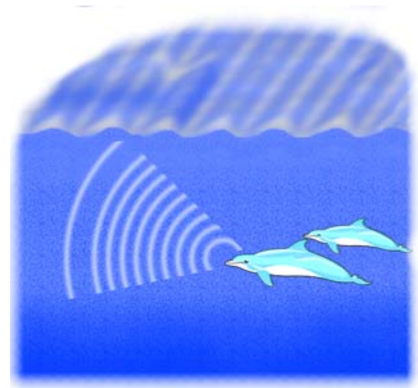


Figure 12.2: *The same system can support more than one kind of wave at the same time. Sound waves and light waves travel through water so dolphins can hear and see. At the same time, a boundary wave travels on the surface. Three of our five senses (sight, hearing, touch) respond to waves.*

Figure 12.3: *X rays use light waves to make images that show bones under the skin.*

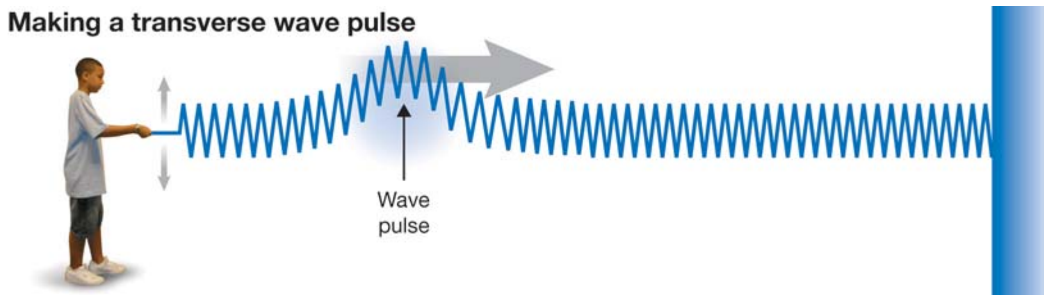
Transverse and longitudinal waves

Waves spread through connections

A wave moves along a string because the string is **continuous**. By continuous we mean it is connected to itself. Waves spread through connections. If we were to break the string in the middle, the wave would not spread across the break. Whenever you have an extended body that is all connected to itself, you get waves. The ocean is an example: Waves can travel all the way across because the water is continuous from one shore to another.

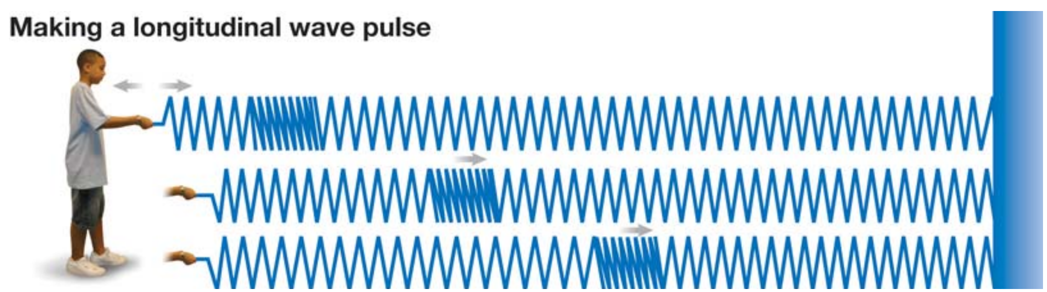
Transverse waves

A **transverse wave** has its oscillations perpendicular to the direction the wave moves. The wave moves from left to right. The oscillation is up and down. Water waves are also transverse waves because the up and down oscillation is perpendicular to the motion of the wave.



Longitudinal waves

A **longitudinal wave** has oscillations in the same direction as the wave moves. Stretch a fat Slinky with one end fastened to the wall. Give the free end a sharp push toward the wall and pull it back again. You see a compression wave of the Slinky that moves toward the wall. The compression wave on the Slinky is a longitudinal wave because the compression is in the direction the wave moves.



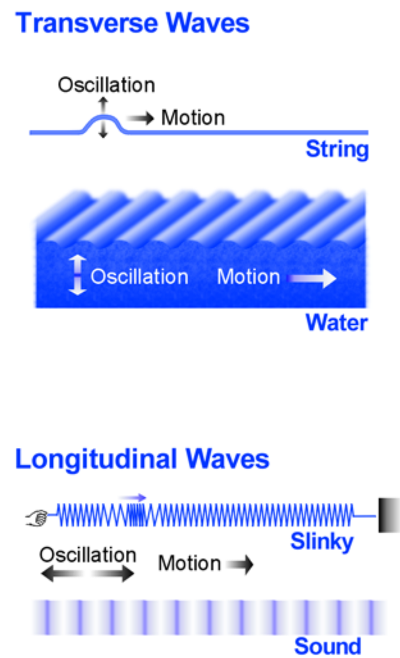


Figure 12.4: *Transverse waves oscillate perpendicular to the direction the wave moves. Strings and water are examples.*

Longitudinal waves oscillate in the same direction the wave moves. The Slinky and sound waves are examples.

Frequency, amplitude and wavelength

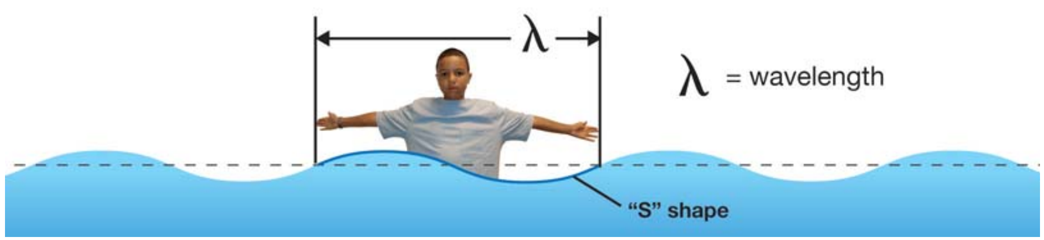
Basic properties Waves have cycles, frequency, and amplitude, just like oscillations. Because waves are spread out and move, they have new properties of wavelength and speed. Also, because waves are spread out, we have to be careful how we define and measure frequency and amplitude.

Frequency The frequency of a wave is a measure of how often it goes up and down (Figure 12.5). To measure the frequency, we look at one place as the wave passes through. The frequency of the oscillating motion of one point is the frequency of the wave. The wave also causes distant points to oscillate up and down *with the same frequency.* A wave carries its frequency to every area it reaches.

Frequency is measured in Hz Wave frequency is measured in **hertz** (Hz), just like any oscillation. A frequency of one hertz (1 Hz) describes a wave that makes everything it touches go through a complete cycle once every second. Your laboratory-size water waves typically have low frequencies, between 0.1 and 10 hertz.

Amplitude The amplitude of a wave is the largest amount that goes above or below average (Figure 12.6). You can also think of the amplitude as one-half of the distance between the highest and lowest places.

Wavelength Wavelength is the length of one complete cycle of a wave (Figure 12.7). For a water wave, this would be the distance from a point on one wave to the same point on the next wave. You could measure the wavelength from crest-to-crest or from trough-to-trough. For the vibrating string, the wavelength is the length of one complete "S" shape. We use the Greek letter "lambda" to represent wavelength. You write a lambda like an upside down "y."



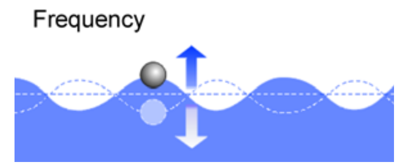


Figure 12.5: *The frequency of a wave is the frequency at which every point on the wave oscillates. The floating ball oscillates up and down at the frequency of the wave.*

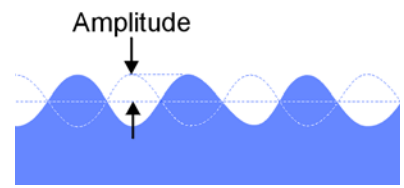


Figure 12.6: *The amplitude of a water wave is the maximum distance above the level surface. This is the same as half the distance between the lowest and highest places.*

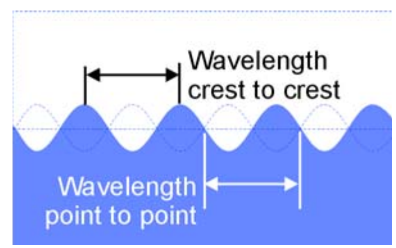
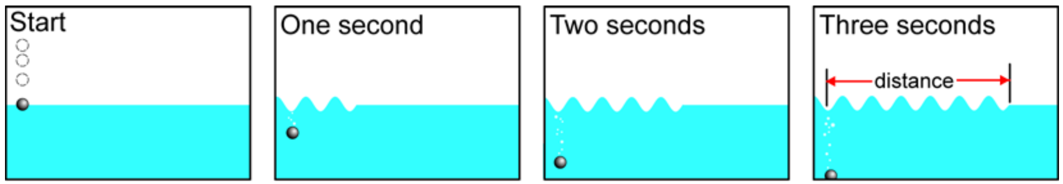


Figure 12.7: *The wavelength of a water wave can be measured from crest to crest. This is the same as the distance from one point on a wave to the same point on the next wave.*

Speed The speed of a wave describes how fast the wave can transmit an oscillation from one place to another. Waves can have a wide range of speeds. Most water waves are slow; a few miles per hour is typical. Light waves are extremely fast—186,000 miles per *second*. Sound waves travel at about 660 miles per hour, faster than water waves and much slower than light waves.



What is the speed of a wave? The speed of a wave is different from the speed of whatever the wave is causing to move. In a water wave, the surface of the water moves up and down. You could measure the up-down speed of the water surface, but that would NOT be the speed of the wave. The speed of the wave describes how quickly a movement of one part of the water surface is transmitted to another place. To measure the speed of the wave, you would have to start a ripple in one place and measure how long it takes the ripple to affect a place some distance away.

Speed is frequency times wavelength In one complete cycle, a wave moves forward one wavelength (Figure 12.8). The speed of a wave is the distance traveled (one wavelength) divided by the time it takes (one period). Since the frequency is the inverse of the period, it is usually easier to calculate the speed of the wave by multiplying wavelength and frequency. The result is true for sound waves, light waves, and even gravity waves. Frequency times wavelength is the speed of the wave.

$$\text{Speed} = \frac{\text{Distance Traveled}}{\text{Time Taken}} = \frac{\text{Wavelength}}{\text{Period}} = \text{Wavelength} \times \left(\frac{1}{\text{Period}}\right)$$

$$\text{Speed} = \text{Wavelength} \times \text{Frequency}$$

The speed of a wave

$$\underbrace{\mathbf{v}}_{\text{Speed (m/sec)}} = \overbrace{\mathbf{f}}^{\text{Frequency (hertz)}} \underbrace{\lambda}_{\text{Wavelength (meters)}}$$

A wave moves one wavelength in one cycle.

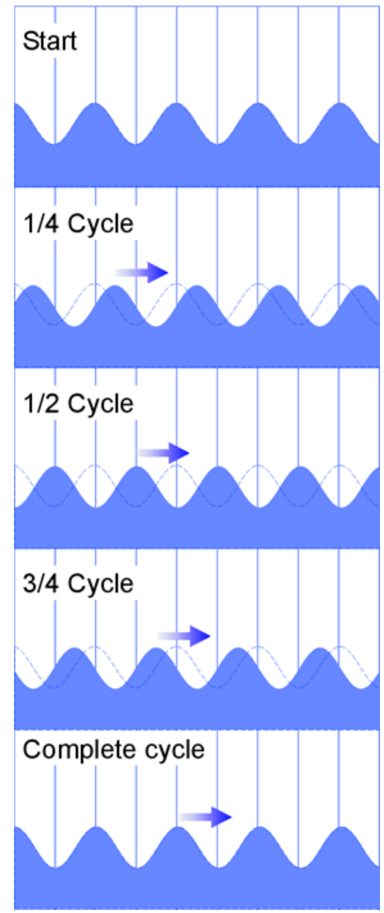


Figure 12.8: *A wave moves a distance equal to one wavelength in one cycle. Since a cycle takes one period, the speed of the wave is the wavelength divided by the period.*

12.2 Waves in Motion

In what shapes do we find waves?

What happens when a wave hits something?

You will learn the answers to these questions in this section. We start with waves in water, because these are easy to make and observe. The shape of wave fronts, and the explanation for reflection, diffraction, and other interesting things, can be seen in the lab. Almost every process we see with water waves also occurs with sound and light waves. Water waves are convenient because they are big and slow, so we can see the details of what happens. Light waves, on the other hand, are small and fast, and sound waves are invisible.

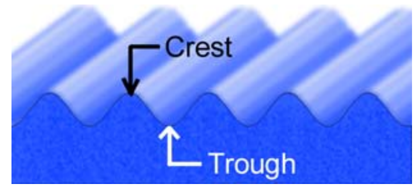


Figure 12.9: *The crest is the highest point on the wave. The trough is the low point.*

Wave shapes

Crests, troughs, and wave fronts

Since a wave extends over a large area, to talk about the motion of a wave we need to pick a reference point. You can think of a wave as a series of high points and low points. A **crest** is the shape of the high points of the wave, a **trough** is the low points. When we describe the shape and motion of wave, it is useful to think in terms of the crests. As the wave moves, the crests move. The crests of a wave are sometimes called **wave fronts**. You can think of the crest as the front of a wave if it helps you to remember the definition of a wave front (Figure 12.9).

Plane waves and circular waves

The shape of a wave is determined by the shape of the wave fronts. You can make waves in all shapes but **plane waves** and **circular waves** are easiest to create and study (Figure 12.10). The crests of a plane wave look like straight lines. The crests of a circular wave are circles. A plane wave is started by disturbing the water in a line. A circular wave is started by disturbing the water at a single point. A fingertip touched to the surface will start a circular wave.

Determining the direction the wave moves

The shape of the wave front determines the direction the wave moves. Circular waves have circular wave fronts that move outward from the center. Plane waves have straight wave fronts that move in a line perpendicular to the wave fronts. To change the direction the wave moves, you have to change the shape of the wave front. In later chapters, we will see that this is exactly how lenses work.

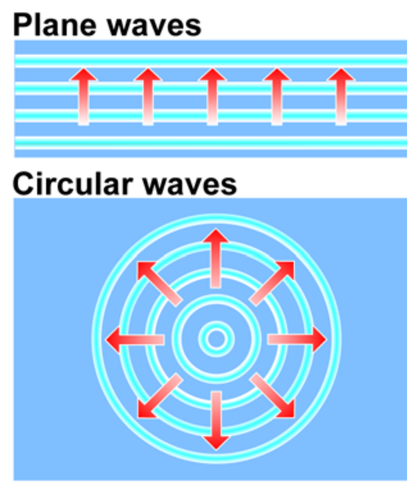


Figure 12.10: *Plane waves and circular waves. Plane waves move perpendicular to the wave fronts. Circular waves radiate outward from the center.*

What happens when a wave hits something?

The four wave interactions

Waves can do different things when they hit an obstacle (Figure 12.11).

Reflection	The wave can bounce off and go in a new direction.
Refraction	The wave can pass straight into and through the obstacle.
Diffraction	The wave can bend around or through holes in the obstacle.
Absorption	The wave can be absorbed and disappear.

Sometimes, the wave can do all those things at once, partly bouncing off, partly passing through, partly being absorbed, and partly going around. You may have noticed the radio in a car sometimes loses the station as you enter a tunnel. Part of the wave that carries the signal bends around the entrance to the tunnel and follows you in. Part is absorbed by the ground. The deeper in the tunnel you go, the weaker the wave gets until the radio cannot pick up the signal at all and you hear static. Simple things like mirrors and complex things like ultrasound or X rays all depend on how waves act when they encounter objects.

Boundaries

Waves are affected by boundaries where conditions change. The first three interactions (reflection, refraction, diffraction) usually occur when a wave crosses a boundary. Absorption can also occur at a boundary, but often happens within the body of a material.

Reflection

When a wave bounces off an obstacle we call it **reflection**. If you make water waves travel toward a wall they will be reflected. The wave that reflects is like the original wave but moving in a new direction. The wavelength and frequency are usually unchanged. The reflection of a wave happens at a boundary (or edge) where the wave has to pass from one condition to another. Mirrored sunglasses are a good example. The lenses reflect some light so they look like mirrors. The boundary is the surface of the lens where the light wave crosses from air to glass. Abrupt changes in material will almost always cause reflections.

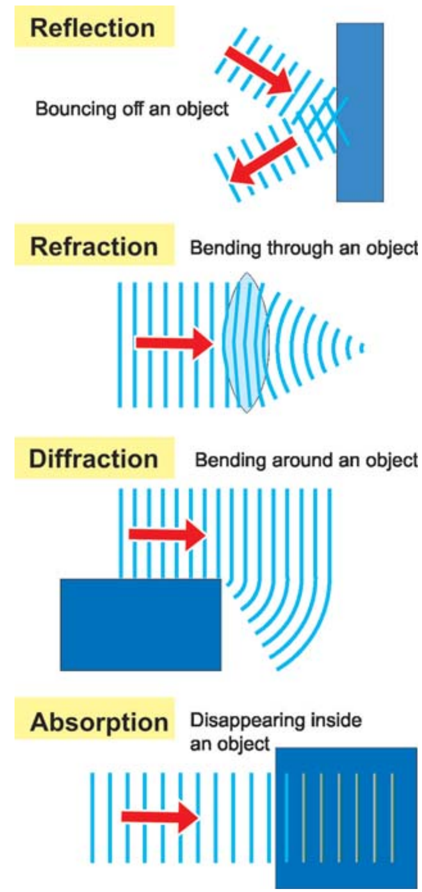
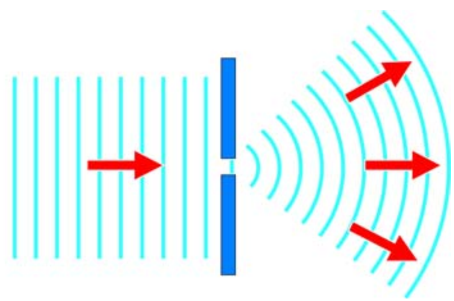


Figure 12.11: *The four processes for waves interacting with boundaries.*

Refraction Waves can cross boundaries and pass into or through objects. Placing a thin plate on the bottom of ripple tank creates a boundary where the depth of the water changes. If you look carefully, you see that waves are bent as they cross the boundary. The wave starts in one direction and changes direction as it crosses. We call it **refraction** when a wave bends as it crosses a boundary. We say the wave is *refracted* as it passes through the boundary. Refraction is useful because it allows us to shape and control waves. Eyeglasses are a very good example where refraction is used to change light waves. Glasses help people to see by bending the light waves into an easier shape for some people's eyes to focus.

Absorption Waves can be absorbed as they pass through objects. Absorption is what happens when the amplitude of a wave gets smaller and smaller as it passes through a material. Some objects and materials have properties that absorb certain kinds of waves. A sponge can absorb a water wave while letting the water pass. A heavy curtain absorbs sound waves. Theaters often use heavy curtains so the audience cannot hear backstage noise. Dark glass absorbs light waves, which is how some kinds of sunglasses work.

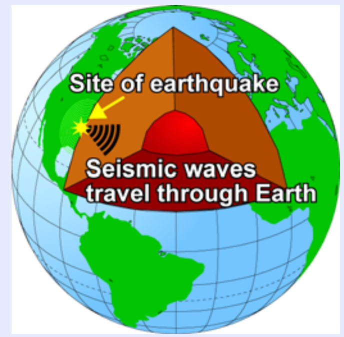
Diffraction through a small opening turns plane waves into circular waves.



Diffraction Waves can bend around obstacles and go through openings. The process of bending around corners or passing through openings is called **diffraction**. We say a wave is *diffracted* when it is changed by passing through a hole or around an edge. Diffraction usually changes the direction and shape of the wave. Diffraction turns a plane wave into a circular wave when the wave passes through a narrow opening. Diffraction explains why you can hear someone even though a door is only open a tiny crack. Diffraction causes the sound wave to spread out from the crack.

Seismic waves

Seismic waves are generated when Earth's crust slips in an earthquake. Two kinds of seismic waves travel through Earth: primary waves (P-waves) and secondary waves (S-waves).



P-waves are longitudinal. S-waves are transverse and cause powerful, sideways shaking of the ground. As the P-waves and S-waves encounter layers in the Earth, they refract and reflect. By studying the patterns of waves that are recorded after an earthquake, geologists have identified the parts of Earth's internal structure.

12.3 Natural Frequency and Resonance

Theoretically, waves can extend forever. Realistically, they are limited by the size of the system. Boundaries create conditions that favor special frequencies or wavelengths. Just as the length of the string set the period of the pendulum, the boundaries and properties of the system make certain waves much more powerful than others. The concepts of *resonance* and *natural frequency* apply to a huge range of natural and human-made systems. These two powerful ideas are the key to understanding the tides of the ocean, the way our ears separate sound, and even how a microwave oven works.

Natural frequency

The natural frequency is the frequency at which a system oscillates when it is disturbed.

Natural frequency

What is natural frequency?

If you pluck a guitar string in the middle it vibrates back and forth. If you pluck the same string 10 times in a row and measure the frequency of vibration you find that it is always the same. When plucked, the string vibrates at its natural frequency. The pendulum also had a natural frequency.

Why natural frequency is important

The natural frequency is important for many reasons:

1. All things in the universe have a natural frequency, and many things have more than one.
2. If you know an object's natural frequency, you know how it will vibrate.
3. If you know how an object vibrates, you know what kinds of waves it will create.
4. If you want to make specific kinds of waves, you need to create objects with natural frequencies that match the waves you want.

Microwave ovens, musical instruments, and cell phones all use the natural frequency of an oscillator to create and control waves. Musical instruments work by adjusting the natural frequency of vibrating strings or air to match musical notes. The A string on a guitar has a natural frequency of 440 hertz.

Figure 12.12: *A guitar uses the natural frequency of the strings to make the correct notes. Once it is tuned, the A string, when plucked, will always vibrate at 440 hertz.*

Changing the natural frequency

The natural frequency depends on many factors, such as the tightness, length, or weight of a string. We can change the natural frequency of a system by changing any of the factors that affect the size, inertia, or forces in the system. For example, tuning a guitar changes the natural frequency of a string by changing its tension.

Resonance

The response of an oscillator

To keep a system oscillating, we apply an oscillating force. For example, if you want to get a jump rope going, you shake the end up and down. What you are really doing is applying an oscillating force to the rope. The response of the rope is to oscillate up and down with the same frequency of your applied force.

If you try this, you notice that at certain frequencies your force is noticeably more effective at making the rope oscillate. For example, shaking the end up and down twice per second (1.6 Hz) results in an amplitude of a few centimeters. Slowing down to once per second (1 Hz) makes an amplitude of more than a meter! Slowing even more, to once every two seconds (0.5 Hz), causes the amplitude to drop back down again. Your experiment shows that the frequency of 1 hertz is *many times* more effective than any other frequency.

Resonance

The extra-strong response at 1 hertz is an example of **resonance**. You can think of resonance as having the natural frequency of the system exactly in tune with your force. Each cycle of your force exactly matches each cycle of the system. As a result, each push adds to the next one and the amplitude of the oscillation grows (Figure 12.13). Resonance happens when something is vibrated at its natural frequency (or a multiple of the natural frequency). Resonance is an important idea because it is used to transfer power into all kinds of waves from lasers to microwave ovens to musical instruments.

A swing is a good example of resonance

The example of a swing (that you might sit on at the park) is one of the best ways to describe resonance. With a swing, small pushes applied over time build up a large amplitude of motion. This happens because each push is synchronized to the natural motion of the swing. A forward push is always given when the swing is as far back as it can go. The swing is like a pendulum, which has a natural frequency. By applying small pushes at a frequency matched to the natural frequency, we are able to create a large motion. The interaction of the repeating pushes and the natural motion of the swing is what creates resonance. The effect of the resonance is that the swing's motion gets large even though the pushes are small. Resonance is not a single thing. Resonance is an interaction between a wave, a driving force, and the boundaries of the system.

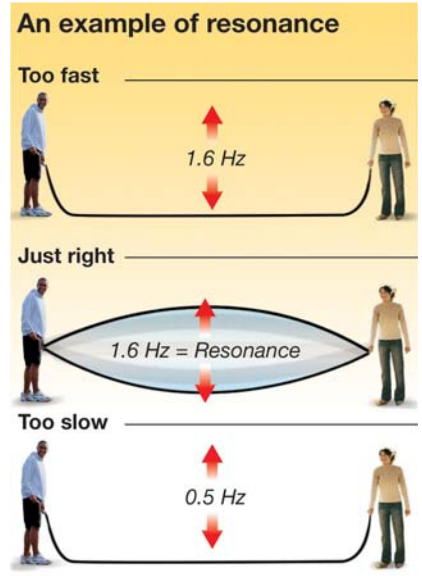


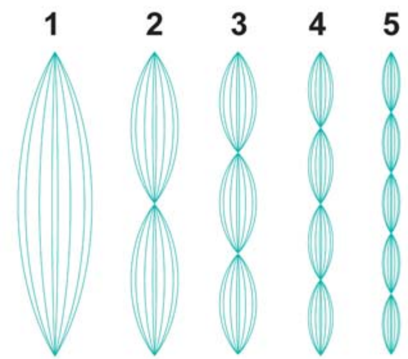
Figure 12.13: *A jump rope is a good experiment for resonance. If you shake it at the right frequency, it makes a big wave motion. If your frequency is not just right, the rope will not make the wave pattern at all.*

Standing waves on a string

What is a standing wave?

Although waves usually travel, it is possible to make a wave stay in one place. A wave that is trapped in one spot is called a **standing wave**. It is possible to make standing waves of almost any kind, including sound, water, and even light. A vibrating string is a great example for doing experiments with standing waves. Vibrating strings are what make music on a guitar or piano.

Harmonics are multiples of the natural frequency of a standing wave



The first five harmonics of the vibrating string

Standing waves occur at frequencies that are multiples of the **fundamental**, which is the natural frequency of the string. The fundamental and multiples of its frequency are called **harmonics**. The diagram to the left shows the first five harmonics. You can tell the harmonic number by counting the number of “bumps” on the wave. The first harmonic has one bump, the second has two bumps, the third has three, and so on. If the frequency of the first harmonic is 10 hertz, then the second will be at a frequency of 20 hertz, the third will be at 30 hertz, and so on.

Wavelength

A vibrating string moves so fast that your eye averages out the image and you see a wave-shaped blur (Figure 12.14). At any one moment the string is really in only one place within the blur. The wavelength is the length of one complete “S” shape on the string. Higher frequency waves have shorter wavelengths.

Why are standing waves useful?

Standing waves are useful because we can control their frequency and wavelength. Because the wave is trapped, it is easy to put power into it and make large amplitudes. In your microwave oven, there is a device called a magnetron. Inside the magnetron is a standing wave driven by electricity. A small hole in the boundary lets some of the wave’s energy out to cook food. The shape of the magnetron forces the standing wave to oscillate at exactly 2.4 billion cycles per second (2.4 gigahertz). Energy that leaks out at the same frequency is perfectly matched to heat water molecules in food.

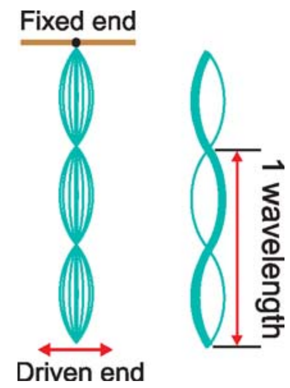


Figure 12.14: *A standing wave on a vibrating string. The wavelength is the length of one complete **S** shape of the wave.*

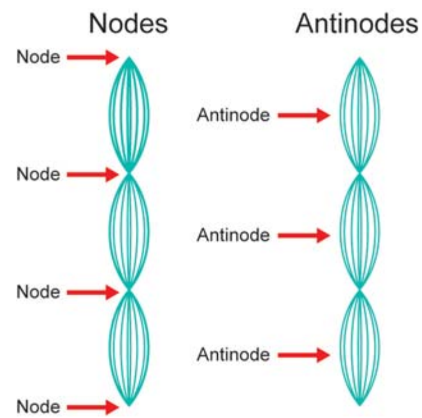


Figure 12.15: *Nodes and antinodes for the third harmonic of the vibrating string. Nodes are points where the string does not move. Antinodes are points of the greatest amplitude.*

Interference

What is interference? Interference happens when two or more waves come together. Because there are so many waves around us, they often interfere with each other. In fact, radio and television use the interference of two waves to carry music and video. The resonance of a vibrating string can be understood using the interference of waves. Sometimes on the ocean, two big waves add up to make a gigantic wave that may only last a few moments but is taller than ships, and can have a terrible impact.

Constructive interference Suppose you make two wave pulses on the stretched spring. One comes from the left and the other comes from the right. When they meet in the middle, they combine to make a single large pulse. This is called **constructive interference**. Constructive interference occurs when waves add up to make a larger amplitude (Figure 12.16).

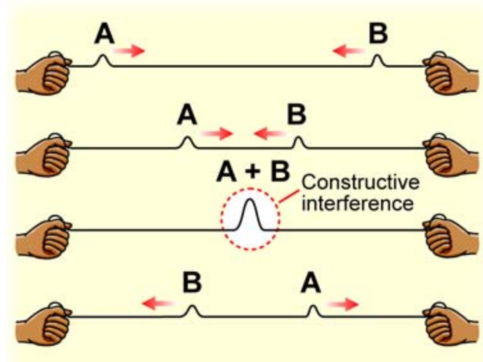


Figure 12.16: *Two wave pulses on the same side add up to make a single, bigger pulse when they meet. This is an example of constructive interference.*

Destructive interference There is another way to launch the two pulses. If we make pulses on opposite sides of the cord, something different happens. When the pulses meet in the middle they cancel each other out! One wants to pull the string up and the other wants to pull it down. The result is that the string is flat and both pulses vanish for a moment. This is called **destructive interference**. In destructive interference waves add up to make a smaller amplitude (Figure 12.17).

After they interfere, both wave pulses separate again and travel on their own. This is surprising if you think about it. For a moment, the middle of the cord is flat in the example of destructive interference. A moment later, two wave pulses come out of the flat part and race away from each other. Waves still store energy, even when they interfere.

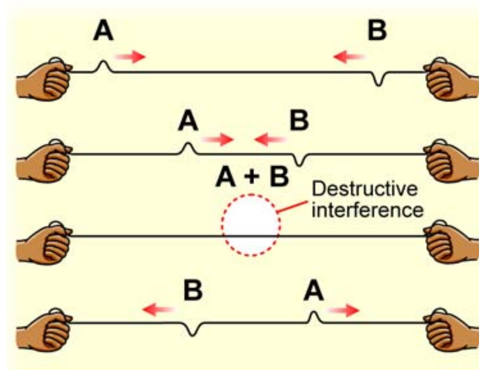


Figure 12.17: *Two equal wave pulses on opposite sides subtract when they meet. The upward movement of one pulse exactly cancels with the downward movement of the other. For a moment there is no pulse at all. This is an example of destructive interference.*

Waves at the atomic level Down at the scale of atoms, there are many extremely strong waves. Because there are so many and they are tiny and random, they interfere destructively on average. We don't see the wavelike nature of atoms because of large-scale destructive interference. In special cases, like with a magnetic resonance imaging (or MRI) machine, or a laser, we create constructive interference of atomic waves. The result is very powerful and useful technology.

Chapter 12 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. wave	a. A short length of wave that travels
2. vibration	b. A wave where the oscillation is perpendicular to the direction of motion
3. wave pulse	c. An oscillation that travels
4. transverse	d. A wave where the oscillation is in the same direction as the direction of motion
5. longitudinal	e. A word that means the same as oscillation
	f. The time it takes to complete one cycle

Set Two

1. wavelength	a. A place where a wave changes suddenly
2. natural frequency	b. The interaction of two or more waves with each other
3. resonance	c. A special frequency (or frequencies) at which objects vibrate if they are disturbed
4. interference	d. A special condition where the frequency you push matches the natural frequency of the system, resulting in large amplitude waves
5. boundary	e. The length of one complete wave
	f. A unit of one cycle per second

Set Three

1. reflection	a. The process where a wave gets smaller and smaller
2. refraction	b. The process of bouncing a wave off a boundary
3. diffraction	c. The process of bending a wave as it crosses a boundary
4. absorption	d. What happens when a wave bends around obstacles or through holes
	e. A word that means the same as oscillation

Set Four

1. node	a. A wave whose frequency is a multiple of another wave
2. antinode	b. A point on a wave where there is no motion
3. harmonic	c. A wave that is trapped between boundaries
4. standing wave	d. The place on a wave where the amplitude is largest
	e. The length of one complete wave

Concept review

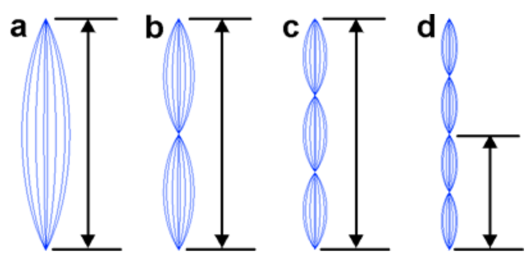
1. A wave which vibrates at 60 Hz has a higher _______ than a wave that vibrates at 30 Hz.

   a. wavelength
   b. frequency
   c. amplitude
   d. transverse

2. Which of the following things must involve a wave? You may choose more than one. Explain each of your choices.

   a. A bulldozer is moving the dirt for a highway.
   b. A person is talking to someone on a cell phone.
   c. An earthquake in the Pacific Ocean causes the floor of a house to shake in Texas.
   d. A car is going 70 miles per hour on a highway.
   e. Two people stop to listen to a jet plane passing overhead.
   f. A doctor makes an X ray to check for broken bones.
   g. An explorer shines a flashlight to see a passage in a cave deep underground.

3. Which of the following pictures shows a correct measure of the wavelength? You may choose more than one.



4. A wave is moving toward a hole in a wall. What will the wave look like as it passes through the wall?

5. Which of the following best describes what happens when a water wave hits a solid wall?

   a. reflection
   b. refraction
   c. diffraction
   d. absorption

6. An elastic string is attached to a wall on one end. A wave pulse traveling on the string reflects off the wall and comes back:

   a. On the same side of the string as it started.
   b. On the opposite side of the string from where it started.
   c. Split equally between both sides of the string.

7. A transverse wave is:

   a. A wave with a very high frequency, like light.
   b. A wave that oscillates perpendicular to the direction it moves.
   c. A wave that oscillates along the direction it moves.
   d. A wave with a frequency that is a multiple of another frequency.

8. A string with natural frequency of 15 Hz will likely show resonance when wiggled at which frequency.

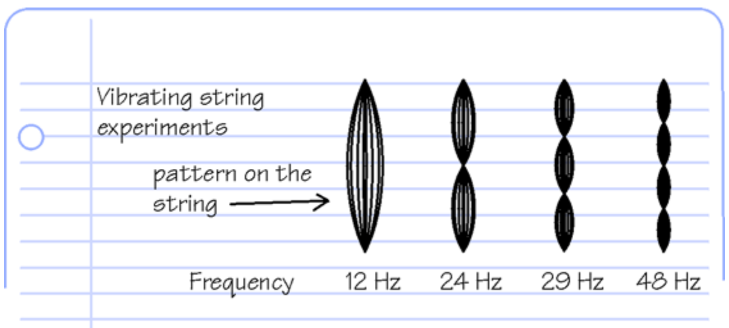
   a. 20 Hz
   b. 40 Hz
   c. 30 Hz
   d. 50 Hz

Problems

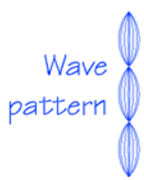
1. You find the pattern in the picture at a frequency of 40 Hz. Answer the following questions.
   a. What is the period?
   b. At what frequency will you find the third harmonic?
   c. At what frequency will you find the eighth harmonic?
   d. How many antinodes are in the wave in the picture?

40 Hz

2. A group of students shows you sketches in their lab book of four patterns they found on a vibrating string. You suspect that one of the pictures is either a fake, or a mistake. Which picture is the fake (or mistake) and how did you know?



3. The wave in the picture has how many nodes?



   a) Two
   b) Three
   c) Four
   d) None

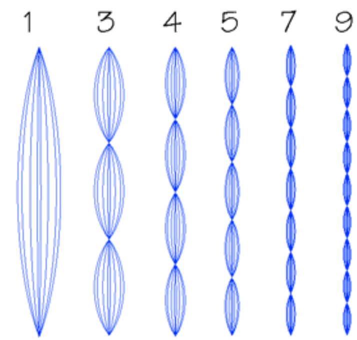
4. The wavelength of a wave on a string is 25 centimeters and the frequency is 20 Hz. Calculate the speed of the wave.

5. A wave has a frequency of 5 Hz and a wavelength of 2 meters. What is the speed of the wave?
   a. 10 m/sec
   b. 0.4 m.sec
   c. 2.5 m/sec
   d. 7 m/sec

6. You are doing a vibrating string experiment and observe the seventh harmonic at a frequency of 63 Hz. At what frequency will you find the third harmonic?
   a. 21 Hz
   b. 27 Hz
   c. 189 Hz m/sec
   d. 9 Hz

7. You are doing a vibrating string experiment and observe a resonance that looks like the picture below. You measure a frequency of 22 Hz. Fill in the rest of the data table with the frequency and wavelengths you would expect to find in an experiment. Note: Harmonics 6 and 8 are not included on the table.

Harmonic	Frequency	Wavelength
1		
2	22 Hz	1 meter
3		
4		
5		
7		
9		



Applying your knowledge

1. A guitar string is divided by frets. When you hold your finger on each fret, you make the length of the string shorter. This makes the wavelength shorter. If the wavelength gets shorter, the frequency must get higher to compensate.

   You know that multiplying frequency and wavelength for a vibrating string always gives you the same number. Suppose your guitar string is 68 centimeters long and vibrates with a natural frequency of 120 Hz. What length of string would you need to make it vibrate at 180 Hz, which is 1.5 times higher?

2. Marching is when many people walk exactly in step with each other. Tromp, tromp, tromp, every foot falls at exactly the same moment with a steady frequency. It has been known since early times that troops should never march across a bridge. When soldiers cross a bridge they all walk with a different pace. Discuss why marching across a bridge is a bad idea, knowing what you learned in this chapter.

3. Waves in the ocean are created by the wind acting on the surface of the water. It is suspected that many ships have been wrecked by the interference of two waves. Discuss how the meeting of two waves might sink a ship that could easily ride over a single wave.

4. Earthquakes make vibrations of the ground that can literally shake buildings to pieces. Buildings are not completely stiff, and tall buildings sway quite a bit. Swaying is a form of oscillation, and all buildings have at least one natural frequency. What do you think happens if the natural frequency of a building matches the frequency of an earthquake? How might you change the natural frequency of a building?

UNIT 4

Sound and Waves

Chapter 13

Sound and Music

Introduction to Chapter 13

Sound is one of the richest of our five senses. In this chapter you will explore a field of study that includes everything from making computers that can understand speech to building concert halls and speaker boxes. The end of the chapter provides an introduction to music, truly a universal language that humans have always enjoyed.

Investigations for Chapter 13

13.1	Sound	*What is sound and how do we hear it?*

The first investigation explores the perception of sound. Humans hear frequencies between 20 Hz and 20,000 Hz, a range that varies widely with people. You will measure the sensitivity of your own ears as well as those of your classmates.

13.2	Properties of Sound	*Does sound behave like other waves?*

Using an electronic synthesizer, you will create resonance, beats, and interference of sound waves. The evidence you collect will dramatically demonstrate that sound is a wave, and show you how to control sound waves for useful purposes.

13.3	Music	*What is music and how do we make music?*

The musical scale was known to humans 20,000 years before anyone invented writing. Musical sounds are derived from an elegant mathematical foundation of simple fractions and ratios. Once you know the ratios, you can design and build your own musical instruments.

Learning Goals

In this chapter, you will:

- Learn how we hear sound.
- Learn how your brain interprets sound to understand words and music.
- Learn what kinds of sounds we can hear, and what kinds we cannot hear.
- Learn what a sound wave is and how it travels.
- Learn how the loudness of sound is measured.
- Learn the basics of acoustics as applied to the design of buildings and musical instruments.
- Learn to read a sonogram and how a computer recognizes spoken words.
- Learn what *supersonic* means.
- Learn why a musical scale sounds good, or why it sounds bad.
- Learn how we tell voices and instruments apart from each other.

Vocabulary

acoustics	dissonance	pitch	sonogram
beat	harmonics	pressure	supersonic
cochlea	musical scale	reverberation	white noise
consonance	beats	ultrasound	decibel
pitch	harmony	sound	rhythm

13.1 Sound

Sound is one of the most important of our senses. We use sound to express the whole range of human emotion. In this section you will learn about sound and sound waves. Scientifically, sound is one of the simplest and most common kinds of waves. But what a huge influence it has on our everyday experience! Sound is a rich and beautiful palette from which musicians create works of joy, excitement, and drama. We know sound is a wave because:

1 Sound has a frequency that we hear as higher or lower pitch.
2 Sound has a wavelength that we can construct experiments to show.
3 The speed of sound is frequency times wavelength.
4 Resonance happens with sound.
5 Sound can be reflected, refracted, and absorbed.
6 Sound shows evidence of interference and diffraction.

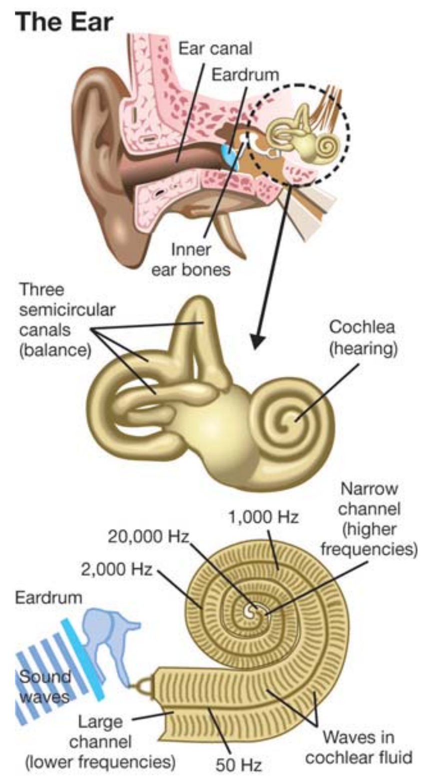


Figure 13.1: *The structure of the inner ear. When the eardrum vibrates, three small bones transmit the vibration to the cochlea. The vibrations make waves inside the cochlea, which vibrates nerves in the spiral. Each part of the spiral is sensitive to a different frequency.*

How do we hear a sound wave?

Hearing sound

We get our sense of hearing from the **cochlea**, a tiny fluid-filled organ in the inner ear (Figure 13.1). The inner ear actually has two important functions: providing our sense of hearing and our sense of balance. The three semicircular canals near the cochlea are also filled with fluid. Fluid moving in each of the three canals tells the brain whether the body is moving left-right, up-down, or forward-backward.

How the cochlea works

The perception of sound starts with the eardrum. The eardrum vibrates in response to sound waves in the ear canal. The three delicate bones of the inner ear transmit the vibration of the eardrum to the side of the cochlea. The fluid in the spiral of the cochlea vibrates and creates waves that travel up the spiral. The spiral channel of the cochlea starts out large and gets narrower near the end. The nerves near the beginning see a relatively large channel and respond to longer wavelength, low-frequency sound. The nerves at the small end of the channel respond to shorter wavelength, higher-frequency sound.

The range of human hearing

The range of human hearing is between 20 Hz and 20,000 Hz (20 kHz). The combination of the eardrum, bones, and the cochlea all contribute to the limited range of hearing. You could not hear a sound at 50,000 Hz, even at 100 decibels (loud). Animals such as cats and dogs can hear much higher frequencies because they have more sensitive structures in their inner ears.

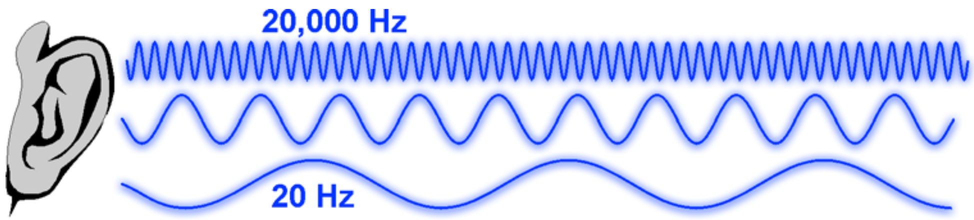


Figure 13.2: *Hearing protection is recommended when working in loud environments.*

Hearing ability changes with time

Hearing varies greatly with people and changes with age. Some people can hear very high frequency sounds and other people cannot. People gradually lose high frequency hearing with age. Most adults cannot hear frequencies above 15,000 Hz, while children can often hear to 20,000 Hz.

Hearing can be damaged by loud noise

Hearing is affected by exposure to loud or high-frequency noise. The nerve signals that carry sensation of sound to the brain are created by tiny hairs that shake when the fluid in the cochlea is vibrated. Listening to loud sounds for a long time can cause the hairs to weaken or break off. Before there were safety rules about noise, people who worked in mines or other noisy places often became partly deaf by the time they retired. It is smart to protect your ears by keeping the volume reasonable and wearing ear protection if you have to stay in a loud place (Figure 13.2). Many musicians wear earplugs to protect their hearing when playing in concerts!

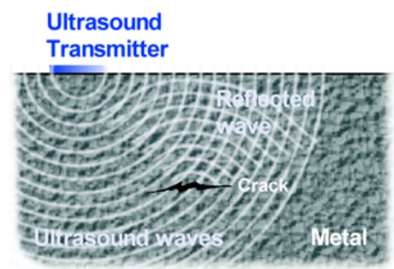


Figure 13.3: *Ultrasound can be used to find tiny cracks in metal. The crack reflects the sound wave. The reflection can tell the engineer the depth and size of the crack.*

Ultrasound

It is possible to make sound of much higher frequency than the human ear can hear. Ultrasound is sound that has very high frequency, often 100,000 Hz or more. We cannot hear ultrasound, but it can pass through the human body easily. Medical ultrasound instruments use the refraction and reflection of sound waves inside the body to create images. Doctors often take ultrasound pictures of a beating heart or a baby in the womb. Ultrasound is also used to find cracks in materials (Figure 13.3). If you pass ultrasound through a solid material, any small cracks create reflections that can be detected by instruments. Ultrasound examinations are routinely done on the structural frames of aircraft.

13.2 Properties of Sound

Like other waves, sound has the fundamental properties of frequency, wavelength, amplitude, and speed. Because sound is such a part of human experience, you probably already know its properties, but you know them by different names. For example, you will rarely hear someone complain about the high amplitude of sound. What you hear instead is that the sound is too *loud*.

What is sound?

Air pressure

Air, like any other gas, is made of free molecules whizzing around and bumping into each other (Figure 13.4). The molecules in a gas have lots of space around them. Because of the extra space it is easy to squeeze molecules together to fit more in a given volume. Squeezing more into the same volume makes the **pressure** of the gas go up (Figure 13.5). Pressure is a measure of the force felt by the walls of the container holding the gas. If there are more molecules bouncing off the walls, there is more pressure.

We can also lower the pressure. If we expand the volume, but don't let any molecules in or out, the pressure will go down. The pressure goes down because for every unit of area of our container there are fewer molecules bouncing off the walls.

We can also heat the gas up so the molecules move a little faster. Faster means they bang into the walls faster and bounce off with more force. Raising the temperature is a second way to increase pressure. For sound waves, however, we are mostly concerned with changes in density, or number of molecules per unit of volume.

Pressure is a restoring force

The pressure of a gas is a type of restoring force. If we increase the pressure in one place, the natural tendency is for the atoms to spread back out again, lowering the pressure. Conversely, if we reduce the pressure in one spot, other atoms nearby rush in to fill in the extra open space and raise the pressure. Atoms have mass, and therefore inertia. Pressure provides a restoring force. The combination of inertia and restoring force results in harmonic motion and waves. The harmonic motion is an oscillation in pressure and the wave is a sound wave.

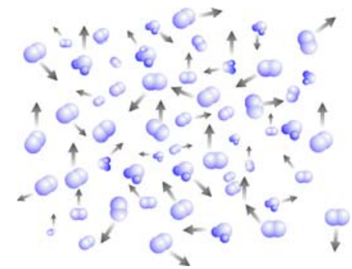


Figure 13.4: *Air is made of molecules in constant random motion, zooming around, bumping off each other and the walls of their container. There is a great deal of empty space between molecules.*

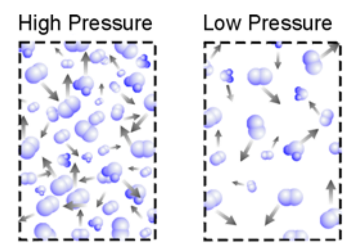
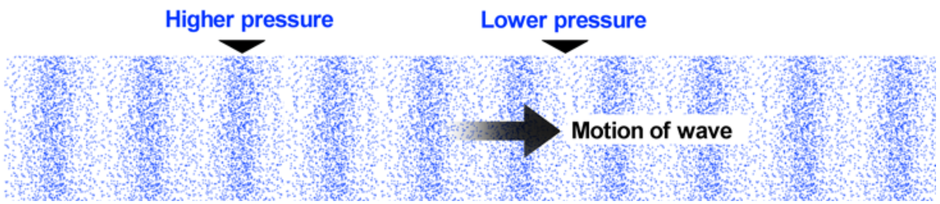


Figure 13.5: *More molecules per unit volume makes pressure go up. Fewer molecules makes pressure go down.*

Close-up look at a sound wave

Figure 13.6 shows a greatly magnified illustration of a speaker, a sound wave and the oscillation of pressure. If you touch the speaker surface you can feel the vibration. Imagine looking at the air very close to the speaker. The surface of the speaker is going back and forth. When the surface moves forward it pushes on the air touching the surface, compressing it and raising the pressure. The speaker then moves back and lowers the pressure. The back and forth motion of the speaker creates alternating layers of high and low pressure. The pressure waves travel away from the speaker as a sound wave.

A sound wave is a wave of alternating high pressure and low pressure regions of air. Anything that vibrates in air creates a sound wave. The wave travels away from the source and eventually reaches our ear, where it vibrates the eardrum and we hear the sound.



The pressure waves are small

It is hard to feel the pressure directly because the amplitude of the pressure wave is very small for most ordinary sounds. The vibrations of most sounds are also too fast for nerves in the skin to react. However, for very low frequency sounds you can feel the vibration with your skin. If you put your fingertips very close (but not touching) a speaker, you can feel the vibrating air for frequencies lower than about 100 Hz. Anyone who has listened to a loud bass guitar will confirm that sound is a vibration that you can feel at low frequencies!

Sound is a longitudinal wave

Sound waves are longitudinal because the air is compressed in the direction of travel. You can think of a sound wave like the compression wave on the Slinky. Anything that vibrates creates sound waves as long as there is air or some other material. Sound does *not* travel in space. Science fiction movies always add sound to scenes of space ships exploding. If the scenes were real, there would be total silence because there is no air in space to carry the sound waves.

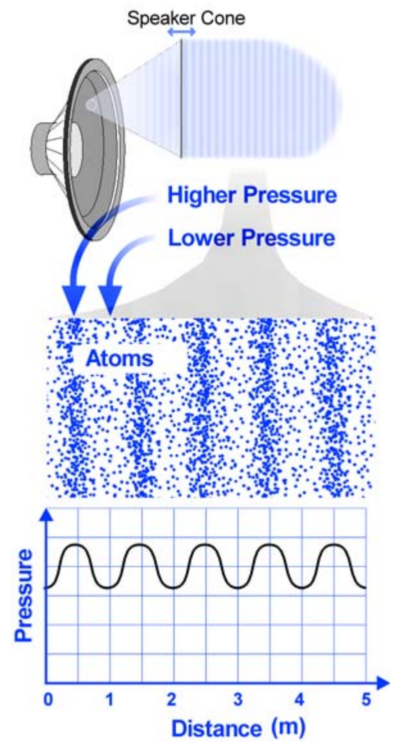
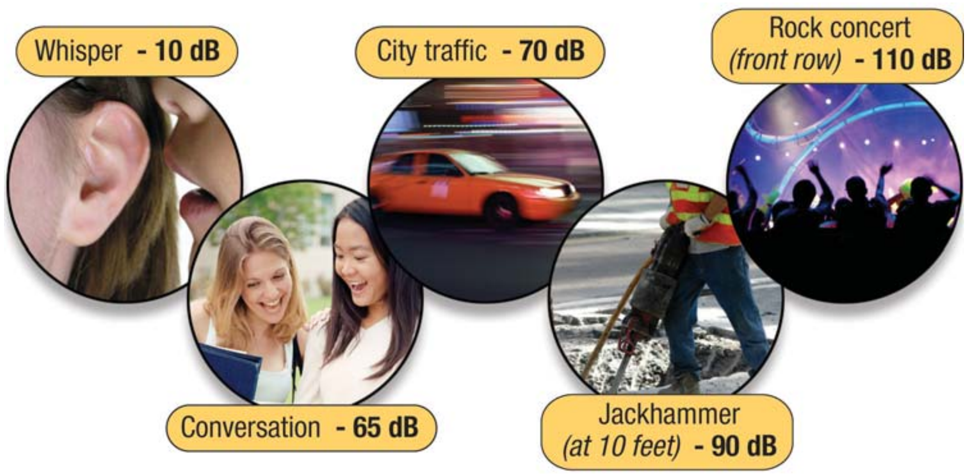


Figure 13.6: *What a sound wave might look like if you could see the atoms. The effect is greatly exaggerated to show the variation. In an actual sound wave, the difference in pressure between the highest and lowest is much smaller, less than one part in a million. From the graph you can tell the wavelength of this sound is about a meter.*

The loudness of sound

The decibel scale The loudness of sound is measured in decibels (dB). As you might expect, loudness is related to the amplitude of the sound wave. The amplitude of a sound wave is one half of the difference between the highest pressure and the lowest pressure in the wave. Because the pressure change in a sound wave is very small, almost no one uses pressure to measure loudness. Instead we use the decibel scale. Most sounds fall between 0 and 100 on the decibel scale, making it a very convenient number to understand and use. The graphic below shows where some sounds fall on the decibel scale.



What is a decibel?

The decibel scale is a *logarithmic* measure of sound pressure. This is different from linear measures you are familiar with. Every increase of 20 dB means the pressure wave has 10 times greater amplitude.

Logarithmic scale	Linear Scale
Decibels (dB)	Amplitude
0	1
20	10
40	100
60	1,000
80	10,000
100	100,000
120	1,000,000

We use the decibel scale because our ears can hear such a wide range of amplitudes. Our ears also hear changes in loudness proportional to dB and not to amplitude. Every 20 dB increase sounds about twice as loud.

The sensitivity of the ear

The actual oscillations in pressure from a sound wave are very small (Figure 13.7). Table 13.1 gives some examples of the amplitude for different decibel levels. As you can see, the human ear is very sensitive. We can easily hear a pressure wave that is only 2 parts different out of 100 million! If you were looking at a pile of a million coins, you could never notice one missing. Yet our ears can detect a change in pressure of less than one part in a 100 million! This exquisite sensitivity is why hearing can be damaged by listening to very loud noises for a long time.

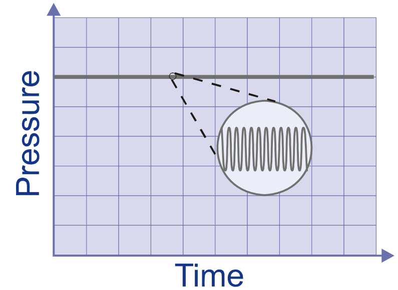


Figure 13.7: *The amplitude of a sound wave is very small. Even an 80 dB noise (quite loud) creates a pressure variation of only a few millionths of an atmosphere.*

Table 13.1: ***Loudness and amplitude of sound waves in air***

Loudness in Decibels	Amplitude of Pressure Wave (fraction of 1 atmosphere)
20 dB	2 / 1,000,000,000
40 dB	2 / 100,000,000
80 dB	2 / 1,000,000
120 dB	2 / 10,000

Acoustics

Reducing the loudness of sound is important in many applications. For example, a library might want to absorb all sound to maintain quiet. A recording studio might want to block sound from the outside from mixing with sound from the inside. **Acoustics** is the science and technology of sound. Knowledge of acoustics is important to many careers, from the people who design stereo speakers to the architects who designed your school.

Soundproofing

Because the ear is so sensitive, it is difficult to block sound. Sound can be transmitted through materials or through gaps in walls and around doors (Figure 13.8). Sound can also be reflected from hard surfaces. A good soundproofing design addresses all ways that sound can travel. To stop transmitted sound, we use dense, thick wall materials such as concrete or brick. Careful sealing around doors and openings stops sound from leaking through cracks. Thick curtains and carpets help absorb reflected sound on floors and walls. Acoustic tiles are used to reduce the loudness of sound reflected off the ceiling. Music is often recorded in studios with good soundproofing so only music inside the studio is recorded and not sounds from outside.

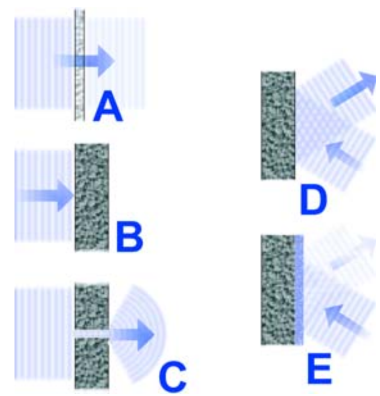


Figure 13.8: *Soundproofing requires careful attention to the way sound behaves.*
(A) It can pass through thin walls.
(B) It is stopped by dense walls.
(C) It goes through cracks.
(D) It reflects from hard surfaces.
(E) Carpet reduces reflection of sound.

The frequency of sound

Frequency and pitch

We hear the different frequencies of sound as having different **pitch**. A low-frequency sound has a low pitch, like the rumble of a big truck. A high-frequency sound has a high pitch, like a whistle or siren. The range of frequencies that humans can hear varies from about 20 Hz to 20,000 Hz.

The sensitivity of the ear

How we respond to the loudness of sound is affected by the frequency of the sound as well as by the amplitude (Figure 13.9). High-frequency sounds seem louder than low-frequency sounds, even if the decibel level is the same. This is because our ears are more sensitive to sounds between 100 and 2,000 Hz than to sounds outside this range. Most of the frequencies that make up speech are between 100 and 2,000 Hz.

Sound can have more than one frequency

Most sound that we hear contains many frequencies, not just one. A good analogy is to think of sound as having a recipe. The different frequencies are like different ingredients. To make the sound of a guitar you add a bunch of one frequency, a bit of a few different frequencies, and a pinch of a few others (Figure 13.10). The opposite process also works. You can take a complex sound and break it down into different amounts of pure frequencies.

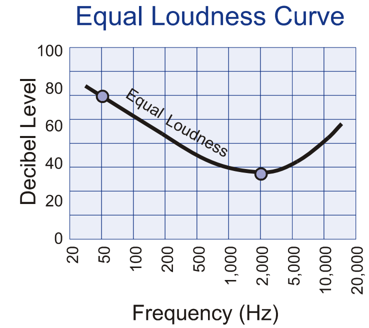
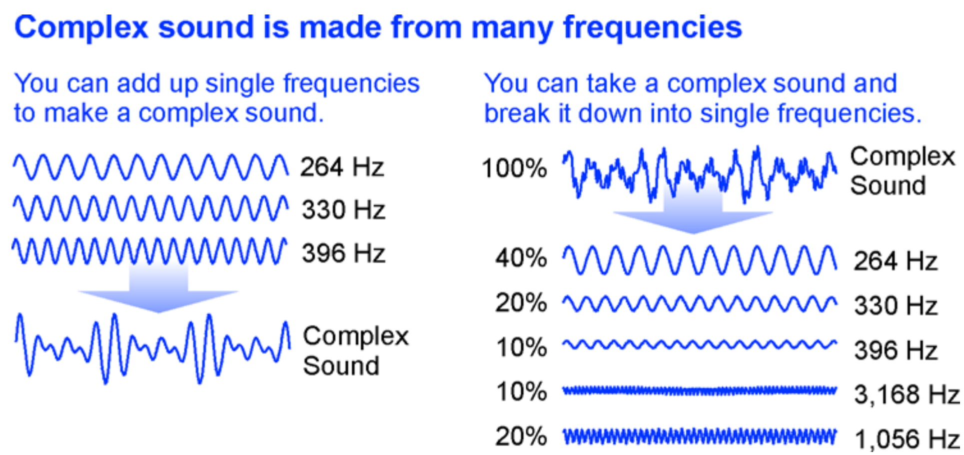


Figure 13.9: *How loud we perceive sound to be depends on the frequency as well as the amplitude. The ear is most sensitive to sounds around 2,000 Hz. The solid line on the graph represents sounds that are heard as equally loud. From the graph you can tell that an 80 dB sound at 50 Hz seems just as loud as a 38 dB sound at 2,000 Hz.*



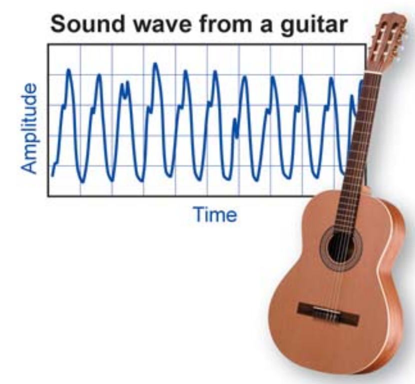


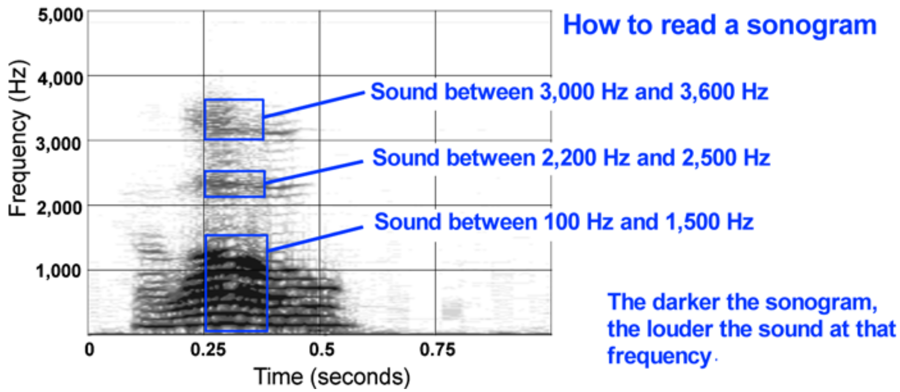
Figure 13.10: *The sound wave from a guitar playing the note E. Several frequencies are present because the graph is not a simple wave.*

Finding meaning in sound

Each nerve in the ear responds to a different range of frequency. One nerve might hear 330 Hz while another hears 800 Hz. Our brain has learned to assemble all the different frequencies and attach meanings to different patterns. The spoken word "hello" has a characteristic sound that contains a pattern of frequencies. We are taught to recognize the pattern and interpret the sound to be a word with meaning.

Think about reading one single word from a story. You recognize the word, but it does not tell you much about the story. When you read the whole story you put all the words together to get the meaning. The brain does a similar thing with different frequencies of sound. A single frequency by itself does not have much meaning. The meaning comes from patterns in many frequencies together.

Reading a sonogram



Sonograms

A sonogram is a special kind of graph that shows how loud "sound" is at different frequencies. The sonogram above is for a male voice saying "hello." The word lasts from 0.1 seconds to about 0.6 seconds. You can see lots of sound below 1,500 Hz and two bands of sound near 2,350 Hz and 3,300 Hz. Every person's sonogram is different, even when saying the same word.

White noise

Sometimes you do not want to hear meaning in sound, like when you want to go to sleep. Many people find white noise to be a relaxing sound. White noise is an equal mixture of all frequencies, like white light is a mixture of all colors. Because all frequencies are at the same level there is no pattern the brain can recognize. The lack of pattern is helpful for relaxing because it can drown out more distracting noises, like people talking or a television.

Talking to computers

Today there are programs that allow you to speak while the computer types what you say. Many people see a day when we talk to our computers rather than type at a keyboard.

Voice recognition programs have to be trained. The program gives you a story to read. The program knows every word in the story. You read the story into the microphone and the computer learns to recognize words from the frequency patterns of your voice.

Since everyone's voice is different, voice programs work only for the person who trained them! The computer types nonsense if you talk into a program trained to someone else's voice.

The wavelength of sound

Bass and treble speakers

Speakers that have great bass (low frequency) are large. Speakers that have good treble (high frequency) are usually much smaller. This is because of the wavelength and energy of the different frequencies of sound (Figure 13.11). The chart below gives some typical frequencies and wavelengths for sound in air.

Table 13.2: ***Frequency and wavelength for some typical sounds***

Frequency (Hz)	Wavelength	Typical Source
20	17 meters	rumble of thunder
100	3.4 meters	bass guitar
500	70 cm (27”)	average male voice
1,000	34 cm (13”)	female soprano singer
2,000	17 cm (6.7”)	fire truck siren
5,000	7 cm (2.7”)	highest note on a piano
10,000	3.4 cm (1.3”)	whine of a jet turbine
20,000	1.7 cm (2/3”)	highest pitched sound you can hear

Why the wavelength of sound is important

Although we usually think about different sounds in terms of frequency, the wavelength can also be important. If there are boundaries or objects similar in size to the wavelength we will get resonance. Resonance makes certain sounds much louder. If you want to make sound of a certain wavelength, you often need to have a vibrating object that is similar in size to the wavelength (Figure 13.12). This is the reason organ pipes are made in all different sizes. Each pipe is designed for a specific wavelength of sound.

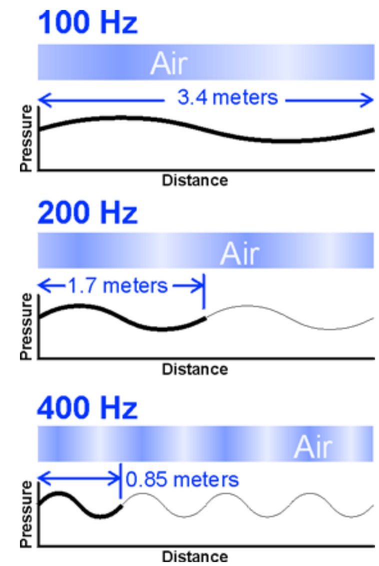


Figure 13.11: *The frequency and wavelength of sound are inversely related. When the frequency goes up, the wavelength goes down proportionally.*

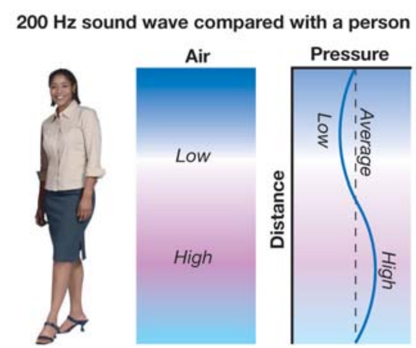


Figure 13.12: *A 200 Hz sound has a wavelength about equal to the height of a person.*

The speed of sound

Sound is fast, about 340 meters per second

Sound moves faster than most motion you are familiar with. Under average conditions the speed of sound is about 340 meters per second (660 mph). Ordinary passenger jets fly slower than sound, usually around 400 to 500 miles per hour. We use the term **supersonic** to describe motion that is faster than sound. Only one kind of passenger jet (the Concorde) is supersonic (Figure 13.13). If you were on the ground watching the Concorde flying toward you, there would be silence. The sound would be *behind* the plane, racing to catch up. You would hear the sound after the plane passed overhead. You would also hear a deafening sonic boom when the sound finally reached your ears.

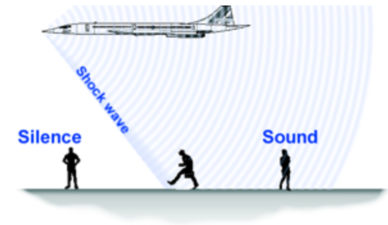


Figure 13.13: *The Concorde is a supersonic jet. If one flew overhead, you would not hear the sound until the plane was far beyond you. The boundary between sound and silence is called a shock wave. It is almost as if all the sound were compressed into a thin layer of air. The person in the middle hears a sonic boom as the shock wave passes over him. Because the sonic boom can shatter windows, planes are not allowed to fly over cities at supersonic speeds.*

The speed depends on pressure and temperature

The speed a sound wave travels in air depends on how fast the molecules in the air are moving. If the molecules are moving slowly (cold), sound does not travel as fast as when they are moving fast (hot). The kind of molecules also affects the speed of sound. Air is made up of mostly of oxygen (O_2) molecules and nitrogen (N_2) molecules. Lighter molecules, like hydrogen (H_2), move faster for a given temperature. Because of the speed difference, sound travels faster in hydrogen than in air.

Like other waves, the speed of sound also depends on the strength of the restoring force. High pressure creates larger restoring forces and increases the speed of sound. Lower pressure decreases the restoring force and decreases the speed of sound.

Sound in liquids and solids

Sound can also travel through liquid and solid materials, like water and steel (Figure 13.14). The speed of sound in other materials is often faster than in air. The restoring forces in solid steel (for example) are much stronger than in a gas. Stronger restoring forces tend to raise the speed of sound. People used to listen for an approaching train by putting an ear to the rails. The sound of the approaching train travels much faster through the steel rails than through the air.

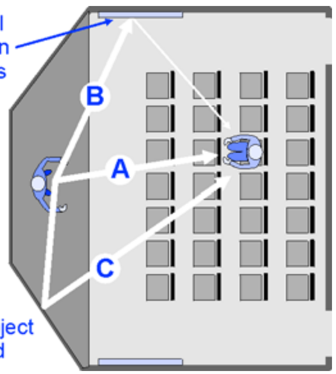
Material	Sound speed (m/sec)
Air	330
Helium	965
Water	1530
Wood (average)	2000
Gold	3240
Steel	5940

Figure 13.14: *The speed of sound in various materials (helium and air at 0°C and 1 atmospheric pressure).*

How sound waves are affected by surfaces

Reverberation

Sound waves reflect from hard surfaces. In a good concert hall the reflected sound adds to the direct sound. You hear a multiple echo celled reverberation. The right amount of reverberation makes the sound seem livelier and richer. Too much reverberation and the sound gets muddy from too many reflections. Concert hall designers work hard on the shape and surface of the walls and ceiling to provide the best reverberation. Some concert halls even have movable panels that can be raised or lowered from the ceiling to help with the sound.



Making a good concert hall

Direct sound (**A**) reaches the listener along with reflected sound (**B, C**) from the walls. The shape of the room and the surfaces of the walls must be designed so that there is some reflected sound, but not too much.

Interference can also affect sound quality

Reverberation also causes interference of sound waves. When two waves interfere, the total can be louder or softer than either wave alone. The diagram above shows a musician and an audience of one person. The sound reflected from the walls interferes as it reaches the listener. If the distances are just right, one reflected wave might be out of phase with the other. The result is that the sound is quieter at that spot. An acoustic engineer would call it a *dead spot* in the hall. Dead spots are areas where destructive interference causes some of the sound to cancel with its own reflections. It is also possible to make very loud spots where sound interferes constructively. Good concert halls are designed to have even sound, not too lively, but not too quiet, either.

Diffraction

Because sound is a wave, it can be diffracted. This means that sound can bend around objects and pass through openings of any size.

Avery Fisher Hall

New York's Philharmonic Hall opened in 1962, and it was an acoustic disaster. The building was beautiful but the sound quality in the hall was awful, with loud spots, dead spots, and muddy reflections. How did some of the best architects and acoustic experts go wrong?

The hall was redesigned in 1976 by Cyril Harris, an acoustical specialist from Columbia University. Professor Harris altered almost all of the interior, changing wall shapes, and adding or moving many absorbing and reflecting panels. The sound quality was greatly improved and the building was renamed Avery Fisher Hall.

13.3 Music

Music is a combination of sound and rhythm that we find pleasant. The kinds of sounds and rhythms can be very different for different styles of music. Some people like music with a heavy beat and strong rhythm. Other people like music where the notes rise and fall in beautiful melodies. Music can be slow or fast, loud or soft, happy or sad, comforting or scary. In this chapter we will learn what kinds of sounds music is made from.

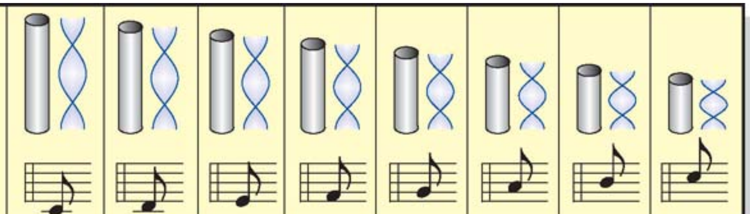
Pitch and rhythm

Pitch The pitch of a sound is how high or low we hear its frequency. Pitch and frequency usually mean the same thing. However, because pitch depends on the human ear and brain, sometimes pitch and frequency can be different. The way we hear a pitch can be affected by the sounds we heard before and after.

Rhythm Rhythm is a regular time pattern in a sound. Rhythm can be loud and soft, tap-tap-TAP-tap-tap-TAP-tap-tap-TAP. Rhythm can be made with sound and silence or with different pitches. People respond naturally to rhythm. Cultures of people are distinguished by their music and the special rhythms used in the music.

The musical scale Most of the music you listen to is made from a set of frequencies called a **musical scale**. The scale that starts on the note C is show in the diagram below.

C major scale



Note	C	D	E	F	G	A	B	C
Frequency (Hz)	264	297	330	352	396	440	495	528
Ratio to C-264	$^1/_1$ $\left(\frac{264}{264}\right)$	$^9/_8$ $\left(\frac{297}{264}\right)$	$^5/_4$ $\left(\frac{330}{264}\right)$	$^4/_3$ $\left(\frac{352}{264}\right)$	$^3/_2$ $\left(\frac{396}{264}\right)$	$^5/_3$ $\left(\frac{440}{264}\right)$	$^{15}/_8$ $\left(\frac{495}{264}\right)$	$^2/_1$ $\left(\frac{528}{264}\right)$

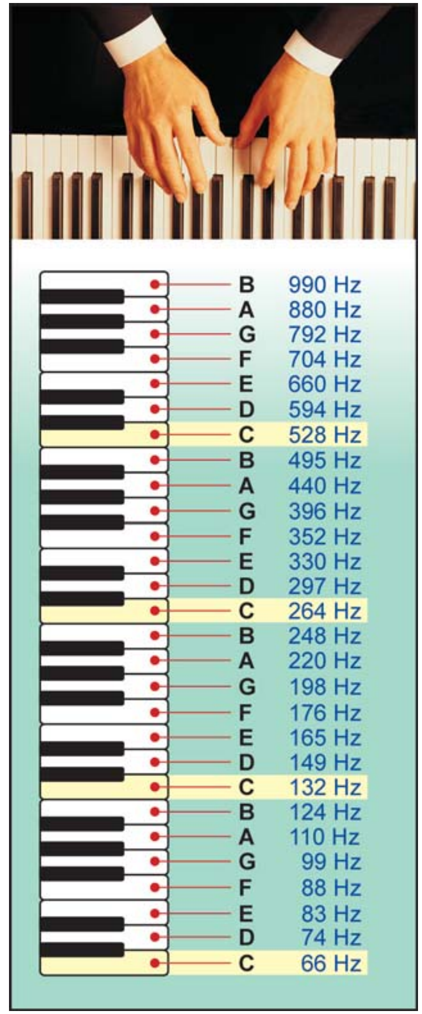


Figure 13.15: *A portion of a piano keyboard showing the frequencies of the notes*. Four octaves are shown. A grand piano has 88 keys and covers seven octaves. (*tuned to perfect C major scale)*

Consonance, dissonance, and beats

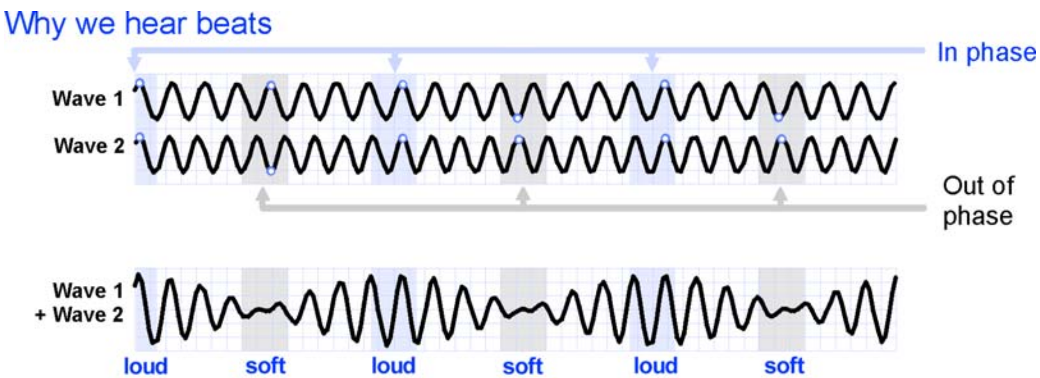
Harmony

Music can have a profound effect on people's mood. The tense, dramatic soundtrack of a horror movie is a vital part of the audience's experience. Harmony is the study of how sounds work together to create effects desired by the composer. Harmony is based on the frequency relationships of the musical scale.

Beats

An interesting thing happens when two frequencies of sound are close, but not exactly the same. The phase of the two waves changes in a way that makes the loudness of the sound seem to oscillate or **beat**. Sometimes the two waves are in phase, and the total is louder than either wave separately. Other times the waves are out of phase and they cancel each other out, leaving periods of silence. The rapid alternations between loudness and silence are referred to as beats. Most people find beats very unpleasant to listen to. Out-of-tune instruments make beats. The frequencies in the musical scale are chosen to reduce the occurrence of beats.

Beats come from adding two waves that are only slightly different in frequency



Consonance and dissonance

When we hear more than one frequency of sound and the combination sounds good, we call it **consonance**. When the combination sounds bad or unsettling, we call it **dissonance**. Consonance and dissonance are related to beats. When frequencies are far enough apart that there are no beats, we get consonance. When frequencies are too close together, we hear beats that are the cause of dissonance. Dissonance is often used to create tension or drama. Consonance can be used to create feelings of balance and comfort.

Echolocation and beats

Bats "see" at night using ultrasound waves instead of light. A bat's voice is like a "sonic flashlight" shining a beam of sound. A bat emits bursts of sound that rise in frequency, called "chirps." When the sound reflects from a bug, the bat's ears receive the echo. Since the frequency of the chirp is always changing, the echo comes back with a slightly different frequency. The difference between the echo and the chirp makes *beats* that the bat can hear. The beat frequency is proportional to how far the bug is from the bat. A bat triangulates the bug's position by comparing the echo from the left ear with that of the right ear.

Harmonics and the "color" of sound

The same note can sound different

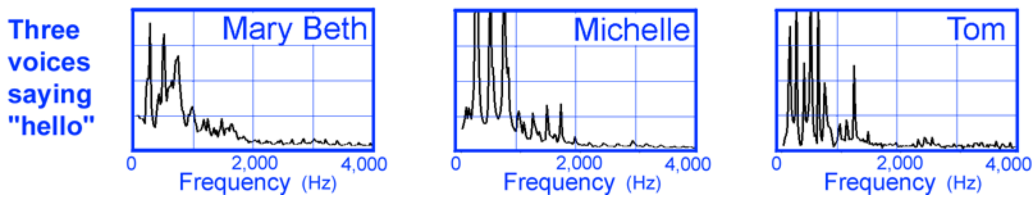
The same note sounds different when played on different instruments. As an example, suppose you listen to the note C-264 Hz played on a guitar and the same C-264 Hz played on a piano. A musician would recognize both notes as being C because they have the same frequency and pitch. But the guitar sounds like a guitar and the piano sounds like a piano. If the frequency of the note is the same, what gives each instrument its characteristic sound?

Instruments make mixtures of frequencies

The answer is that the sound we hear is not a single pure frequency. If the piano and the guitar both made a pure 264 Hz sound, we could not tell the difference. We can tell because real instruments make sounds with many frequencies. The most important one is still the fundamental note (for example, C-264 Hz). The variation comes from the **harmonics**. Remember, harmonics are frequencies that are multiples of the fundamental note. We have already learned that a string can vibrate at many harmonics. The same is true for all instruments. A single C from a grand piano might include 20 or more different harmonics.

Recipes for sound

A good analogy is that each instrument has its own *recipe* for sound. The "guitar" sound shown in Figure 13.16 has a mix of many harmonics. For this guitar, the fundamental is twice as big as the 2nd harmonic. There are strong 3rd, 4th and 5th harmonics. The piano recipe would have a different mix.



Human voices

The human voice also has harmonics. We recognize different people's voices by the patterns in frequency. The diagrams above show the frequencies of male and female voices saying the word "hello." The frequencies range from 100 Hz to about 4,000 Hz. The peaks in the diagrams indicate the harmonics in the voices. Each voice has a unique set of harmonics. This is why it is possible to identify someone by their voice even if you only hear that person say "hello."

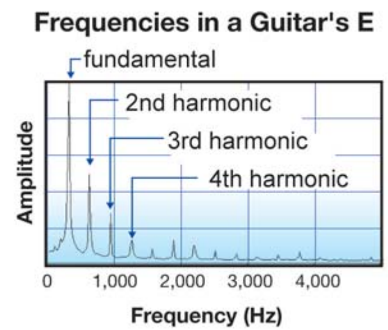


Figure 13.16: *This graph shows the frequencies in a guitar playing an E note. Notice how many harmonics there are!*

Chapter 13 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. sound	a. The force of molecules colliding with each other and the walls of a container
2. pressure	b. A scale to measure the loudness of sound
3. soundproofing	c. A pressure wave we hear with our ears
4. cochlea	d. Building and designing ways to control sound
5. decibel	e. The highest frequency of sound
	f. The part of the ear that senses sound

Set Two

1. ultrasound	a. The technology of making and using sound
2. acoustics	b. How we hear different frequencies of sound
3. pitch	c. A graph showing frequency, loudness, and time
4. sonogram	d. An equal mixture of all frequencies of sound
5. white noise	e. Sound of frequencies too high for the human ear to hear
	f. The speed of sound

Set Three

1. supersonic	a. The time pattern in sound
2. reverberation	b. A set of frequencies that we find pleasant to listen to
3. rhythm	c. The effect of multiple echoes in a room
4. musical scale	d. A speed faster than the speed of sound
5. octave	e. A nerve in the ear that is sensitive to sound
	f. The interval between a frequency and double the frequency

Set Four

1. note	a. The artistic mixing of sounds of many different frequencies
2. beats	b. When two or more sounds are pleasant to hear together
3. consonance	c. When two or more sounds are unpleasant to hear together
4. dissonance	d. The loudness of sound
5. harmony	e. A frequency of sound that is part of a musical scale
	f. An oscillation in loudness that occurs when two frequencies of sound are close but not equal

Concept review

1. A string that vibrates at 150 Hz creates a sound wave of:

    a. 150 cycles/sec   b. 150 decibels

    c. 150 m/sec   d. 150 meters

2. Which of the following is evidence that sound is a wave? You may choose more than one.

    a. Sound has a frequency we hear as differences in pitch.
    b. Some sounds are represented by special symbols.
    c. The speed of sound is the product of frequency times wavelength.
    d. We observe interference and diffraction of sound.

3. Which frequencies can most people hear? You may choose more than one.

    a. 300 Hz   b. 10,000 Hz

    c. 2,500 Hz   d. 100,000 Hz

    e. 5 Hz   f. 50,000 Hz

4. Ultrasound is used for:

    a. Making images of the body for medical purposes.
    b. Extremely loud music.
    c. Making digital recordings for music CDs.
    d. Creating scary soundtracks for horror movies.

5. Air pressure is affected by (you may choose more than one):

    a. The movement of atoms and molecules.
    b. The temperature of a gas.
    c. Sound waves.
    d. Light waves.

6. The decibel scale is a measure of the _______ of a sound wave?

    a. frequency
    b. wavelength
    c. amplitude
    d. speed

7. The human voice contains only one frequency of sound at a time. True or false?

8. We recognize people's voices by patterns in the frequency of sound. True or false?

9. The frequency of sound has no effect on how loud we hear the sound. True or false?

10. A sonogram is a graph that shows how patterns of frequency change over time, as when someone is speaking. True or false?

11. If you wanted to create a very quiet room, you would do what (you may choose more than one):

    a. Cover the walls and ceilings with a hard surface like paneling.
    b. Cover surfaces with materials like carpet and foam.
    c. Seal doors and windows to eliminate cracks.

12. Arrange the following in order of the speed of sound in the material: air, wood, steel, water, helium.

Fastest   Slowest

13. Beats are caused by:

    a. Two frequencies of sound that are close but not identical.
    b. Two frequencies of sound that are consonant.
    c. Two frequencies of sound that are exactly one octave apart.
    d. Two frequencies of sound that are exactly the same.

14. Choose *all* the following that are true of the human voice:

    a. The frequencies of female voices are usually lower than male voices.
    b. The frequencies of female voices are usually higher than male voices.
    c. Voices mostly contain frequencies between 100 Hz and 2,000 Hz.
    d. Voices mostly contain frequencies between 2,000 Hz and 10,000 Hz.

Problems

1. The speed of sound is approximately 340 m/sec. What is the wavelength of a sound wave with a frequency of 1,000 Hz?

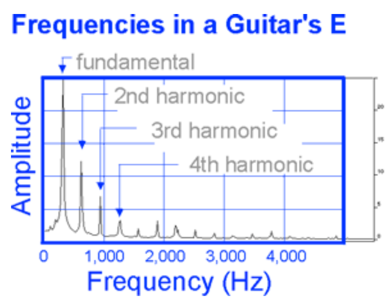
    a. 3.4 meters
    b. 34 centimeters
    c. 340 meters
    d. 2.9 meters

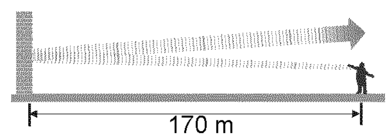
2. If a sound is 20 decibels louder than another sound, the amplitude of the louder sound is:

    a. 20 times the amplitude of the softer sound.
    b. 10 times the amplitude of the softer sound.
    c. 20 pounds per square inch more than the softer sound.
    d. 2 times the amplitude of the softer sound.

3. What is the loudest frequency shown in the graph?

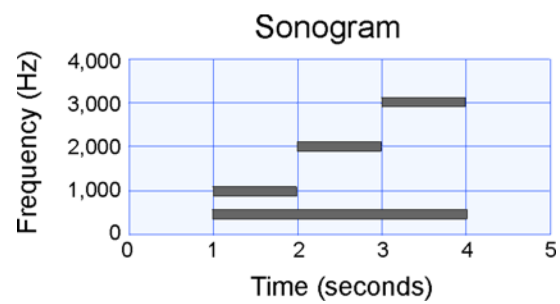
    a. The fundamental.
    b. The second harmonic.
    c. The third harmonic.
    d. The fourth harmonic.





4. Suppose you stand in front of a wall that is 170 meters away. If you yell, how long does it take for the echo to get back to you if the speed of sound is 340 m/sec?

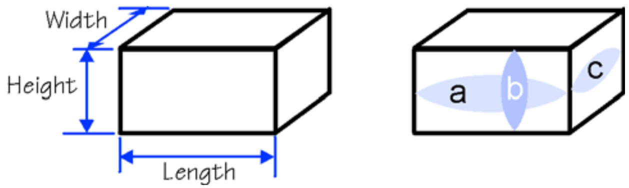
5. The sonogram shows:



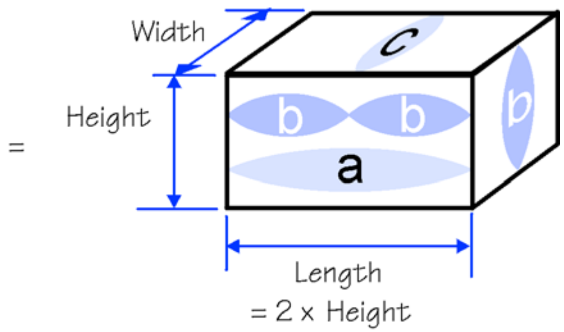
    a. A frequency of 1,000 Hz that lasts for 1 second.
    b. A frequency of 1,000 Hz that lasts for 2 seconds.
    c. A frequency of 1,500 Hz that lasts for 1 second.
    d. A frequency of 1,500 Hz that lasts for 2 seconds.

Applying your knowledge

1. Resonance applies to sound waves in boxes just like it does to strings. However, in a box there are three dimensions: length, width, and height. Each dimension can support a wave, so there can be three different wavelengths (a, b, c) that are resonant in a box.



Suppose you are designing stereo speakers and you don't want resonance. Resonance would make some wavelengths (frequencies) of sound always be louder than others. This is usually bad for music. You want speakers to reproduce sound as it was recorded, and not make some sounds louder than others.



You can't escape some resonance. But suppose one side of your box was exactly twice another side. Then the second harmonic of one resonance (a) would be the same as the first harmonic of another resonance (b) and your sound problem would be twice as bad. Can you think of a rule for the three dimensions of a speaker box that would make sure that none of the three resonances, or their lower harmonics, would ever overlap?

2. Railroad engineers could always tell when a train was coming long before they could hear it. They would put their ear to the track and listen to the steel rails. Compare the speed of sound in steel to the speed of sound in air and explain why listening to the rails was a smart thing to do.

3. When it was first invented, the telephone was a marvel. The electronics of Alexander Graham Bell's days were much less sophisticated than we have today. Today, stereo makers claim they can reproduce frequencies over the whole range of human hearing from 20 Hz to 20,000 Hz. The early telephones could not deliver such a range. Look back at the graphs of frequencies of voices in the chapter. What is the minimum range of frequencies that telephones had to cover to make people's voices understandable? Have you ever noticed that a voice on the telephone never sounds like a real person's voice? Why do you think that is?