Seton Home Study School Edition

openstax™

Physics

HIGH SCHOOL

Physics

SENIOR CONTRIBUTING AUTHORS

PAUL PETER URONE, CALIFORNIA STATE UNIVERSITY, SACRAMENTO

ROGER HINRICHS, STATE UNIVERSITY OF NEW YORK, COLLEGE AT OSWEGO

CONTRIBUTING AUTHORS

FATIH GOZUACIK, PENNSYLVANIA DEPARTMENT OF EDUCATION

DENISE PATTISON, EAST CHAMBERS ISD

CATHERINE TABOR, NORTHWEST EARLY HIGH SCHOOL

openstax™

Seton Home Study School Edition

Contents

Note: Chapters 10, 21, 22, and 23 have been omitted from the
Seton Home Study School edition of this textbook.

CHAPTER 1
What is Physics?

Figure 1.1 Galaxies, such as the Andromeda galaxy pictured here, are immense in size. The small blue spots in this photo are also galaxies. The same physical laws apply to objects as large as galaxies or objects as small as atoms. The laws of physics are, therefore, surprisingly few in number. (NASA, JPL-Caltech, P. Barmby, Harvard-Smithsonian Center for Astrophysics).

Chapter Outline

INTRODUCTION Take a look at the image above of the Andromeda Galaxy (Figure 1.1), which contains billions of stars. This galaxy is the nearest one to our own galaxy (the Milky Way) but is still a staggering 2.5 million light years from Earth. (A light year is a measurement of the distance light travels in a year.) Yet, the primary force that affects the movement of stars within Andromeda is the same force that we contend with here on Earth—namely, gravity.

You may soon realize that physics plays a much larger role in your life than you thought. This section introduces you to the realm of physics, and discusses applications of physics in other disciplines of study. It also describes the methods by which science is done, and how scientists communicate their results to each other.

1.1 Physics: Definitions and Applications

Section Learning Objectives

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

- Describe the definition, aims, and branches of physics
- Describe and distinguish classical physics from modern physics and describe the importance of relativity, quantum mechanics, and relativistic quantum mechanics in modern physics
- Describe how aspects of physics are used in other sciences (e.g., biology, chemistry, geology, etc.) as well as in everyday technology

Section Key Terms

atom	classical physics	modern physics
physics	quantum mechanics	theory of relativity

What Physics Is

Think about all of the technological devices that you use on a regular basis. Computers, wireless Internet, smart phones, tablets, global positioning system (GPS), MP3 players, and satellite radio might come to mind. Next, think about the most exciting modern technologies that you have heard about in the news, such as trains that levitate above their tracks, *invisibility cloaks* that bend light around them, and microscopic robots that fight diseased cells in our bodies. All of these groundbreaking advancements rely on the principles of **physics**.

Physics is a branch of science. The word *science* comes from a Latin word that means *having knowledge*, and refers to the knowledge of how the physical world operates, based on objective evidence determined through observation and experimentation. A key requirement of any scientific explanation of a natural phenomenon is that it must be testable; one must be able to devise and conduct an experimental investigation that either supports or refutes the explanation. It is important to note that some questions fall outside the realm of science precisely because they deal with phenomena that are not scientifically testable. This need for objective evidence helps define the investigative process scientists follow, which will be described later in this chapter.

Physics is the science aimed at describing the fundamental aspects of our universe. This includes what things are in it, what properties of those things are noticeable, and what processes those things or their properties undergo. In simpler terms, physics attempts to describe the basic mechanisms that make our universe behave the way it does. For example, consider a smart phone (Figure 1.2). Physics describes how electric current interacts with the various circuits inside the device. This knowledge helps engineers select the appropriate materials and circuit layout when building the smart phone. Next, consider a GPS. Physics describes the relationship between the speed of an object, the distance over which it travels, and the time it takes to travel that distance. When you use a GPS device in a vehicle, it utilizes these physics relationships to determine the travel time from one location to another.

Figure 1.2 Physics describes the way that electric charge flows through the circuits of this device. Engineers use their knowledge of physics to construct a smartphone with features that consumers will enjoy, such as a GPS function. GPS uses physics equations to determine the driving time between two locations on a map. (@gletham GIS, Social, Mobile Tech Images)

As our technology evolved over the centuries, physics expanded into many branches. Ancient peoples could only study things that they could see with the naked eye or otherwise experience without the aid of scientific equipment. This included the study of kinematics, which is the study of moving objects. For example, ancient people often studied the apparent motion of objects in the sky, such as the sun, moon, and stars. This is evident in the construction of prehistoric astronomical observatories, such as Stonehenge in England (shown in Figure 1.3).

Figure 1.3 Stonehenge is a monument located in England that was built between 3000 and 1000 B.C. It functions as an ancient astronomical observatory, with certain rocks in the monument aligning with the position of the sun during the summer and winter solstices. Other rocks align with the rising and setting of the moon during certain days of the year. (Citypeek, Wikimedia Commons)

Ancient people also studied statics and dynamics, which focus on how objects start moving, stop moving, and change speed and direction in response to forces that push or pull on the objects. This early interest in kinematics and dynamics allowed humans to invent simple machines, such as the lever, the pulley, the ramp, and the wheel. These simple machines were gradually

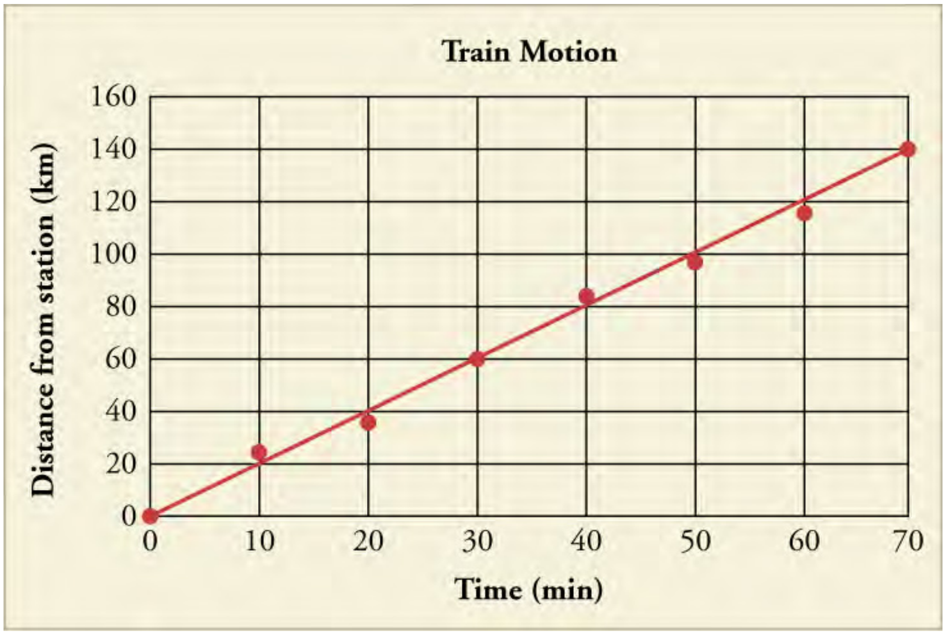

Figure 1.27 The completed graph with the trend line included.

Analyzing a Graph Using Its Equation

One way to get a quick snapshot of a dataset is to look at the equation of its trend line. If the graph produces a straight line, the equation of the trend line takes the form

$$y = mx + b.$$

The b in the equation is the y-intercept while the m in the equation is the **slope**. The y-intercept tells you at what y value the line intersects the y-axis. In the case of the graph above, the y-intercept occurs at 0, at the very beginning of the graph. The y-intercept, therefore, lets you know immediately where on the y-axis the plot line begins.

The m in the equation is the slope. This value describes how much the line on the graph moves up or down on the y-axis along the line's length. The slope is found using the following equation

$$m = \frac{Y_2 - Y_1}{X_2 - X_1}.$$

In order to solve this equation, you need to pick two points on the line (preferably far apart on the line so the slope you calculate describes the line accurately). The quantities Y_2 and Y_1 represent the y-values from the two points on the line (not data points) that you picked, while X_2 and X_1 represent the two x-values of the those points.

What can the slope value tell you about the graph? The slope of a perfectly horizontal line will equal zero, while the slope of a perfectly vertical line will be undefined because you cannot divide by zero. A positive slope indicates that the line moves up the y-axis as the x-value increases while a negative slope means that the line moves down the y-axis. The more negative or positive the slope is, the steeper the line moves up or down, respectively. The slope of our graph in Figure 1.26 is calculated below based on the two endpoints of the line

$$\begin{aligned} m &= \frac{Y_2 - Y_1}{X_2 - X_1} \\ m &= \frac{(80\text{ km}) - (20\text{ km})}{(40\text{ min}) - (10\text{ min})} \\ m &= \frac{60\text{ km}}{30\text{ min}} \\ m &= 2.0\text{ km/min}. \end{aligned}$$

Equation of line: $y = (2.0\ \text{ km/min})\,x + 0$

Because the x axis is time in minutes, we would actually be more likely to use the time t as the independent (x-axis) variable and write the equation as

$$y = (2.0 \text{ km/min})\, t + 0. \tag{1.4}$$

The formula $y = mx + b$ only applies to **linear relationships**, or ones that produce a straight line. Another common type of line in physics is the **quadratic relationship**, which occurs when one of the variables is squared. One quadratic relationship in physics is the relation between the speed of an object its centripetal acceleration, which is used to determine the force needed to keep an object moving in a circle. Another common relationship in physics is the **inverse relationship**, in which one variable decreases whenever the other variable increases. An example in physics is Coulomb's law. As the distance between two charged objects increases, the electrical force between the two charged objects decreases. **Inverse proportionality**, such the relation between x and y in the equation

$$y = k/x,$$

for some number k, is one particular kind of inverse relationship. A third commonly-seen relationship is the **exponential relationship**, in which a change in the independent variable produces a proportional change in the dependent variable. As the value of the dependent variable gets larger, its rate of growth also increases. For example, bacteria often reproduce at an exponential rate when grown under ideal conditions. As each generation passes, there are more and more bacteria to reproduce. As a result, the growth rate of the bacterial population increases every generation (Figure 1.28).

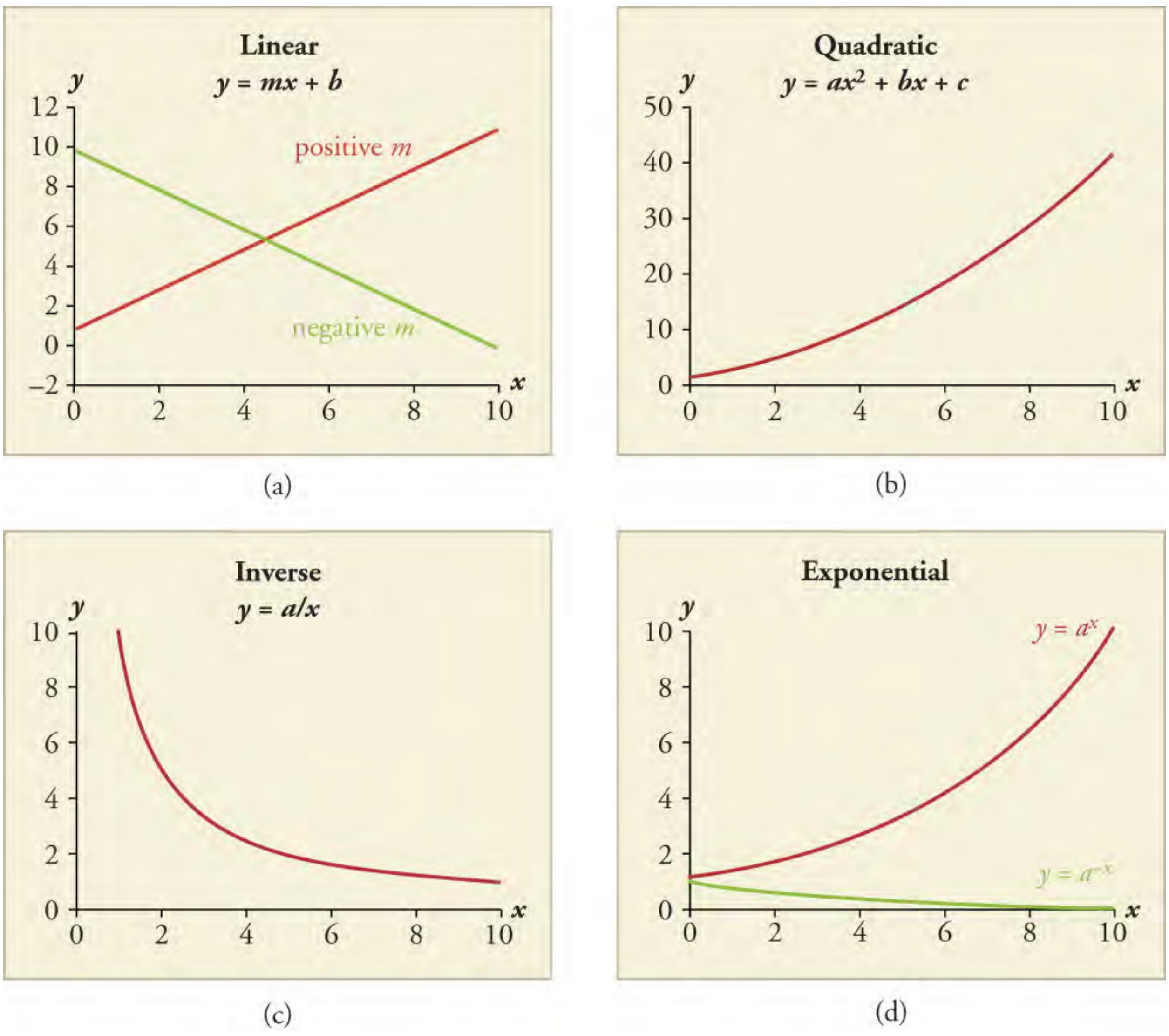

Figure 1.28 Examples of (a) linear, (b) quadratic, (c) inverse, and (d) exponential relationship graphs.

Using Logarithmic Scales in Graphing

Sometimes a variable can have a very large range of values. This presents a problem when you're trying to figure out the best scale to use for your graph's axes. One option is to use a **logarithmic (log) scale**. In a logarithmic scale, the value each mark labels

Check Your Understanding

12. Identify some advantages of metric units.

a. Conversion between units is easier in metric units.
b. Comparison of physical quantities is easy in metric units.
c. Metric units are more modern than English units.
d. Metric units are based on powers of 2.

13. The length of an American football field is $100\ \text{yd}$, excluding the end zones. How long is the field in meters? Round to the nearest $0.1\ \text{m}$.

a. $10.2\ \text{m}$
b. $91.4\ \text{m}$
c. $109.4\ \text{m}$
d. $328.1\ \text{m}$

14. The speed limit on some interstate highways is roughly $100\ \text{km/h}$. How many miles per hour is this if $1.0\ \text{mile}$ is about $1.609\ \text{km}$?

a. 0.1 mi/h
b. 27.8 mi/h
c. 62 mi/h
d. 160 mi/h

15. Briefly describe the target patterns for accuracy and precision and explain the differences between the two.

a. Precision states how much repeated measurements generate the same or closely similar results, while accuracy states how close a measurement is to the true value of the measurement.
b. Precision states how close a measurement is to the true value of the measurement, while accuracy states how much repeated measurements generate the same or closely similar result.
c. Precision and accuracy are the same thing. They state how much repeated measurements generate the same or closely similar results.
d. Precision and accuracy are the same thing. They state how close a measurement is to the true value of the measurement.

KEY TERMS

accuracy
how close a measurement is to the correct value for that measurement

ampere
the SI unit for electrical current

atom
smallest and most basic units of matter

base quantity
physical quantity chosen by convention and practical considerations such that all other physical quantities can be expressed as algebraic combinations of them

base unit
standard for expressing the measurement of a base quantity within a particular system of units; defined by a particular procedure used to measure the corresponding base quantity

classical physics
physics, as it developed from the Renaissance to the end of the nineteenth century

constant
a quantity that does not change

conversion factor
a ratio expressing how many of one unit are equal to another unit

dependent variable
the vertical, or y-axis, variable, which changes with (or is dependent on) the value of the independent variable

derived quantity
physical quantity defined using algebraic combinations of base quantities

derived units
units that are derived by combining the fundamental physical units

experiment
process involved with testing a hypothesis

exponential relationship
relation between variables in which a constant change in the independent variable is accompanied by change in the dependent variable that is proportional to the value it already had

fundamental physical units
the seven fundamental physical units in the SI system of units are length, mass, time, electric current, temperature, amount of a substance, and luminous intensity

hypothesis
testable statement that describes how something in the natural world works

independent variable
the horizontal, or x-axis, variable, which is not influence by the second variable on the graph, the dependent variable

inverse proportionality
a relation between two variables expressible by an equation of the form $y = k/x$ where k stays constant when x and y change; the special form of inverse relationship that satisfies this equation

inverse relationship
any relation between variables where one variable decreases as the other variable increases

kilogram
the SI unit for mass, abbreviated (kg)

linear relationships
relation between variables that produce a straight line when graphed

log-log plot
a plot that uses a logarithmic scale in both axes

logarithmic scale
a graphing scale in which each major tick on an axis is the previous tick multiplied by some value; minor ticks are often included at intermediate values which are logarithmically spaced

meter
the SI unit for length, abbreviated (m)

method of adding percents
calculating the percent uncertainty of a quantity in multiplication or division by adding the percent uncertainties in the quantities being added or divided

model
system that is analogous to the real system of interest in essential ways but more easily analyzed

modern physics
physics as developed from the twentieth century to the present, involving the theories of relativity and quantum mechanics

observation
step where a scientist observes a pattern or trend within the natural world

order of magnitude
the size of a quantity in terms of its power of 10 when expressed in scientific notation

physics
science aimed at describing the fundamental aspects of our universe—energy, matter, space, motion, and time

precision
how well repeated measurements generate the same or closely similar results

principle
description of nature that is true in many, but not all situations

quadratic relationship
relation between variables that can be expressed in the form $y = ax^2 + bx + c$, which produces a curved line when graphed

quantum mechanics
major theory of modern physics which describes the properties and nature of atoms and their subatomic particles

science
the study or knowledge of how the physical world operates, based on objective evidence determined through observation and experimentation

scientific law
pattern in nature that is true in all circumstances studied thus far

scientific methods
techniques and processes used in the constructing and testing of scientific hypotheses, laws, and theories, and in deciding issues on the basis of experiment and observation

scientific notation
way of writing numbers that are too large or small to be conveniently written in simple decimal form; the measurement is multiplied by a power of 10, which indicates the number of placeholder zeros in the measurement

second
the SI unit for time, abbreviated (s)

semi-log plot
A plot that uses a logarithmic scale on one axis of the graph and a linear scale on the other axis.

significant figures
when writing a number, the digits, or number of digits, that express the precision of a measuring tool used to measure the number

slope
the ratio of the change of a graph on the y axis to the change along the x-axis, the value of m in the equation of a $y = mx + b$:+b

theory
explanation of patterns in nature that is supported by much scientific evidence and verified multiple times by various groups of researchers

theory of relativity
theory constructed by Albert Einstein which describes how space, time and energy are different for different observers in relative motion

uncertainty
a quantitative measure of how much measured values deviate from a standard or expected value

universal
applies throughout the known universe

y-intercept
the point where a plot line intersects the y-axis

SECTION SUMMARY

1.1 Physics: Definitions and Applications

- Physics is the most fundamental of the sciences, concerning itself with energy, matter, space and time, and their interactions.
- Modern physics involves the theory of relativity, which describes how time, space and gravity are not constant in our universe can be different for different observers, and quantum mechanics, which describes the behavior of subatomic particles.
- Physics is the basis for all other sciences, such as chemistry, biology and geology, because physics describes the fundamental way in which the universe functions.

1.2 The Scientific Methods

- Science seeks to discover and describe the underlying order and simplicity in nature.
- The processes of science include observation, hypothesis, experiment, and conclusion.
- Theories are scientific explanations that are supported by a large body experimental results.
- Scientific laws are concise descriptions of the universe that are universally true.

1.3 The Language of Physics: Physical Quantities and Units

- Physical quantities are a characteristic or property of an object that can be measured or calculated from other measurements.
- The four fundamental units we will use in this textbook are the meter (for length), the kilogram (for mass), the second (for time), and the ampere (for electric current). These units are part of the metric system, which uses powers of 10 to relate quantities over the vast ranges encountered in nature.
- Unit conversions involve changing a value expressed in one type of unit to another type of unit. This is done by using conversion factors, which are ratios relating equal quantities of different units.
- Accuracy of a measured value refers to how close a measurement is to the correct value. The uncertainty in a measurement is an estimate of the amount by which the measurement result may differ from this value.
- Precision of measured values refers to how close the agreement is between repeated measurements.
- Significant figures express the precision of a measuring tool.
- When multiplying or dividing measured values, the final answer can contain only as many significant figures as the least precise value.
- When adding or subtracting measured values, the final answer cannot contain more decimal places than the least precise value.

KEY EQUATIONS

1.3 The Language of Physics: Physical Quantities and Units

slope intercept form	$y = mx + b$
quadratic formula	$y = ax^2 + bx + c$
positive exponential formula	$y = a^x$
negative exponential formula	$y = a^{-x}$

CHAPTER 14
Sound

Figure 14.1 This tree fell some time ago. When it fell, particles in the air were disturbed by the energy of the tree hitting the ground. This disturbance of matter, which our ears have evolved to detect, is called sound. (B.A. Bowen Photography)

Chapter Outline

INTRODUCTION If a tree falls in a forest (see Figure 14.1) and no one is there to hear it, does it make a sound? The answer to this old philosophical question depends on how you define sound. If sound only exists when someone is around to perceive it, then the falling tree produced no sound. However, in physics, we know that colliding objects can disturb the air, water or other matter surrounding them. As a result of the collision, the surrounding particles of matter began vibrating in a wave-like fashion. This is a sound wave. Consequently, if a tree collided with another object in space, no one would hear it, because no sound would be produced. This is because, in space, there is no air, water or other matter to be disturbed and produce sound waves. In this chapter, we'll learn more about the wave properties of sound, and explore hearing, as well as some special uses for sound.

14.1 Speed of Sound, Frequency, and Wavelength

Section Learning Objectives

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

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

Section Key Terms

rarefaction sound

Properties of Sound Waves

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

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

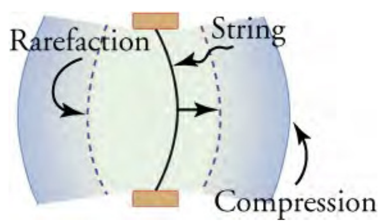

Figure 14.2 A vibrating string moving to the right compresses the air in front of it and expands the air behind it.

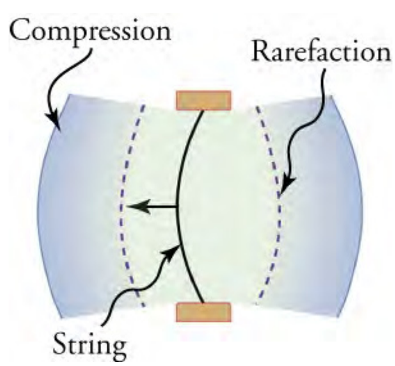

Figure 14.3 As the string moves to the left, it creates another compression and rarefaction as the particles on the right move away from the string.

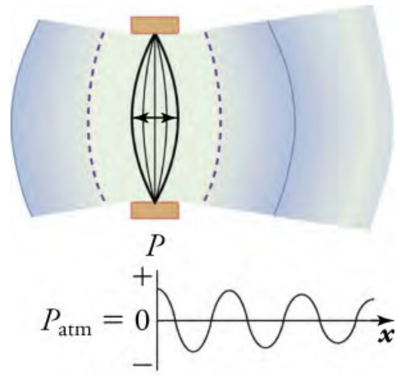

Figure 14.4 After many vibrations, there is a series of compressions and rarefactions that have been transmitted from the string as a sound wave. The graph shows gauge pressure (P_{gauge}) versus distance *x* from the source. Gauge pressure is the pressure relative to atmospheric pressure; it is positive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

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

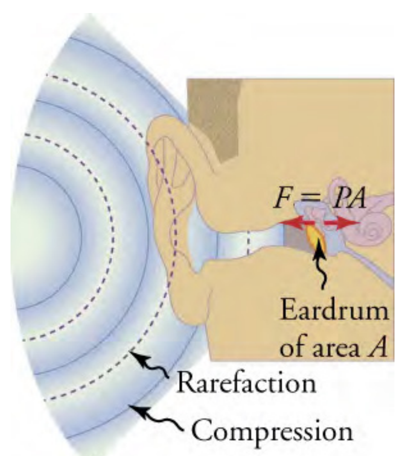

Figure 14.5 Sound wave compressions and rarefactions travel up the ear canal and force the eardrum to vibrate. There is a net force on the eardrum, since the sound wave pressures differ from the atmospheric pressure found behind the eardrum. A complicated mechanism converts the vibrations to nerve impulses,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

The Speed of Sound

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

Medium	v_w (m/s)
Gases at 0 °C	
Air	331
Carbon dioxide	259
Oxygen	316
Helium	965
Hydrogen	1290
Liquids at 20 °C	
Ethanol	1160
Mercury	1450
Water, fresh	1480
Sea water	1540
Human tissue	1540
Solids (longitudinal or bulk)	
Vulcanized rubber	54
Polyethylene	920
Marble	3810
Glass, Pyrex	5640
Lead	1960
Aluminum	5120
Steel	5960

Table 14.1 Speed of Sound in Various Media

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

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

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

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

$$v = f\lambda, \tag{14.1}$$

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

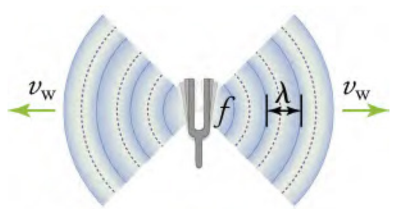

Figure 14.7 A sound wave emanates from a source vibrating at a frequency f, propagates at v, and has a wavelength λ .

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

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

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

Snap Lab

Voice as a Sound Wave

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

- sheet of paper
- tape
- table

Instructions

Procedure

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

GRASP CHECK

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

a. amplitude of the wave
b. frequency of the wave
c. speed of the wave

d. wavelength of the wave

WORKED EXAMPLE

What Are the Wavelengths of Audible Sounds?

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

STRATEGY

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

Solution

(1) Identify the knowns. The values for v and f are given.

(2) Solve the relationship between speed, frequency and wavelength for λ .

$$\lambda = \frac{v}{f}. \tag{14.2}$$

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

$$\lambda_{\text{max}} = \frac{348.7 \text{ m/s}}{20 \text{ Hz}} = 17 \text{ m} \approx 20 \text{ m (1 sig. figure)} \tag{14.3}$$

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

$$\lambda_{\text{min}} = \frac{348.7 \text{ m/s}}{20,000 \text{ Hz}} = 0.017 \text{ m} \approx 2 \text{ cm (1 sig. figure)} \tag{14.4}$$

Discussion

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

Practice Problems

1. What is the speed of a sound wave with frequency 2000 Hz and wavelength 0.4 m?
   a. 5×10^3 m/s
   b. 3.2×10^2 m/s
   c. 2×10^{-4} m/s
   d. 8×10^2 m/s

2. Dogs can hear frequencies of up to 45 kHz. What is the wavelength of a sound wave with this frequency traveling in air at 0°C?
   a. 2.0×10^7 m
   b. 1.5×10^7 m
   c. 1.4×10^2 m
   d. 7.4×10^{-3} m

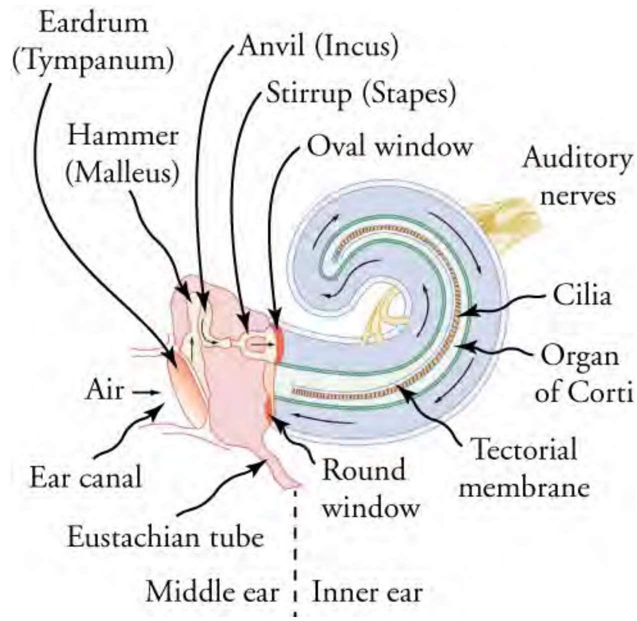

Figure 14.12 The inner ear, or cochlea, is a coiled tube about 3 mm in diameter and 3 cm in length when uncoiled. As the stapes vibrates against the oval window, it creates pressure waves that travel through fluid in the cochlea. These waves vibrate the tectorial membrane, which bends the cilia and stimulates nerves in the organ of Corti. These nerves then send information about the sound to the brain.

FUN IN PHYSICS

Musical Instruments

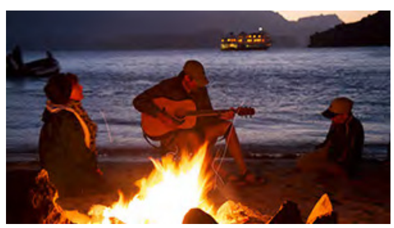

Figure 14.13 Playing music, also known as “rocking out”, involves creating vibrations using musical instruments. (John Norton)

Yet another way that people make sounds is through playing musical instruments (see the previous figure). Recall that the perception of frequency is called pitch. You may have noticed that the pitch range produced by an instrument tends to depend upon its size. Small instruments, such as a piccolo, typically make high-pitch sounds, while larger instruments, such as a tuba, typically make low-pitch sounds. High-pitch means small wavelength, and the size of a musical instrument is directly related to the wavelengths of sound it produces. So a small instrument creates short-wavelength sounds, just as a large instrument creates long-wavelength sounds.

Most of us have excellent relative pitch, which means that we can tell whether one sound has a different frequency from another. We can usually distinguish one sound from another if the frequencies of the two sounds differ by as little as 1 Hz. For example, 500.0 and 501.5 Hz are noticeably different.

Musical notes are particular sounds that can be produced by most instruments, and are the building blocks of a song. In Western music, musical notes have particular names, such as A-sharp, C, or E-flat. Some people can identify musical notes just by listening to them. This rare ability is called *perfect*, or *absolute, pitch*.

When a violin plays middle C, there is no mistaking it for a piano playing the same note. The reason is that each instrument produces a distinctive set of frequencies and intensities. We call our perception of these combinations of frequencies and intensities the *timbre* of the sound. It is more difficult to quantify timbre than loudness or pitch. Timbre is more subjective. Evocative adjectives such as dull, brilliant, warm, cold, pure, and rich are used to describe the timbre of a sound rather than quantities with units, which makes for a difficult topic to dissect with physics. So the consideration of timbre takes us into the realm of perceptual psychology, where higher-level processes in the brain are dominant. This is also true for other perceptions of sound, such as music and noise. But as a teenager, you are likely already aware that one person's music may be another person's noise.

GRASP CHECK

If you turn up the volume of your stereo, will the pitch change? Why or why not?

a. No, because pitch does not depend on intensity.
b. Yes, because pitch is directly related to intensity.

Check Your Understanding

9. What is sound intensity?

a. Intensity is the energy per unit area carried by a wave.
b. Intensity is the energy per unit volume carried by a wave.
c. Intensity is the power per unit area carried by a wave.
d. Intensity is the power per unit volume carried by a wave.

10. How is power defined with reference to a sound wave?

a. Power is the rate at which energy is transferred by a sound wave.
b. Power is the rate at which mass is transferred by a sound wave.
c. Power is the rate at which amplitude of a sound wave changes.
d. Power is the rate at which wavelength of a sound wave changes.

11. What word or phrase is used to describe the loudness of sound?

a. frequency or oscillation
b. intensity level or decibel
c. timbre
d. pitch

12. What is the mathematical expression for sound intensity level β?

a. $\beta\,(\text{dB}) = 10\log_{10}\left(\frac{I_0}{I}\right)$
b. $\beta\,(\text{dB}) = 20\log_{10}\left(\frac{I}{I_0}\right)$
c. $\beta(dB) = 20\log_{10}\left(\frac{I_0}{I}\right)$
d. $\beta\,(\text{dB}) = 10\log_{10}\left(\frac{I}{I_0}\right)$

13. What is the range frequencies that humans are capable of hearing?

a. $20\text{ Hz to} 200,000\text{ Hz}$
b. 2 Hz to $50,000\text{ Hz}$
c. 2 Hz to $2,000\text{ Hz}$
d. 20 Hz to $20,000\text{ Hz}$

14. How do humans change the pitch of their voice?

a. Relaxing or tightening their glottis
b. Relaxing or tightening their uvula
c. Relaxing or tightening their tongue
d. Relaxing or tightening their larynx

References

Nave, R. Vocal sound production—HyperPhysics. Retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/music/voice.html

KEY TERMS

amplitude
the amount that matter is disrupted during a sound wave, as measured by the difference in height between the crests and troughs of the sound wave.

beat
a phenomenon produced by the superposition of two waves with slightly different frequencies but the same amplitude

beat frequency
the frequency of the amplitude fluctuations of a wave

damping
the reduction in amplitude over time as the energy of an oscillation dissipates

decibel
a unit used to describe sound intensity levels

Doppler effect
an alteration in the observed frequency of a sound due to relative motion between the source and the observer

fundamental
the lowest-frequency resonance

harmonics
the term used to refer to the fundamental and its overtones

hearing
the perception of sound

loudness
the perception of sound intensity

natural frequency
the frequency at which a system would oscillate if there were no driving and no damping forces

overtones
all resonant frequencies higher than the fundamental

pitch
the perception of the frequency of a sound

rarefaction
a low-pressure region in a sound wave

resonance
the phenomenon of driving a system with a frequency equal to the system's natural frequency

resonate
to drive a system at its natural frequency

sonic boom
a constructive interference of sound created by an object moving faster than sound

sound
a disturbance of matter that is transmitted from its source outward by longitudinal waves

sound intensity
the power per unit area carried by a sound wave

sound intensity level
the level of sound relative to a fixed standard related to human hearing

SECTION SUMMARY

14.1 Speed of Sound, Frequency, and Wavelength

- Sound is one type of wave.
- Sound is a disturbance of matter that is transmitted from its source outward in the form of longitudinal waves.
- The relationship of the speed of sound v, its frequency f, and its wavelength λ is given by $v = f\lambda$, which is the same relationship given for all waves.
- The speed of sound depends upon the medium through which the sound wave is travelling.
- In a given medium at a specific temperature (or density), the speed of sound v is the same for all frequencies and wavelengths.

14.2 Sound Intensity and Sound Level

- The intensity of a sound is proportional to its amplitude squared.
- The energy of a sound wave is also proportional to its amplitude squared.
- Sound intensity level in decibels (dB) is more relevant for how humans perceive sounds than sound intensity (in W/m^2), even though sound intensity is the SI unit.

- Sound intensity level is not the same as sound intensity—it tells you the *level* of the sound relative to a reference intensity rather than the actual intensity.
- Hearing is the perception of sound and involves that transformation of sound waves into vibrations of parts within the ear. These vibrations are then transformed into neural signals that are interpreted by the brain.
- People create sounds by pushing air up through their lungs and through elastic folds in the throat called vocal cords.

14.3 Doppler Effect and Sonic Booms

- The Doppler effect is a shift in the observed frequency of a sound due to motion of either the source or the observer.
- The observed frequency is greater than the actual source's frequency when the source and the observer are moving closer together, either by the source moving toward the observer or the observer moving toward the source.
- A sonic boom is constructive interference of sound created by an object moving faster than sound.

14.4 Sound Interference and Resonance

- A system's natural frequency is the frequency at which the system will oscillate if not affected by driving or damping forces.
- A periodic force driving a harmonic oscillator at its natural frequency produces resonance. The system is said to resonate.
- Beats occur when waves of slightly different frequencies are superimposed.
- In air columns, the lowest-frequency resonance is called the fundamental, whereas all higher resonant frequencies are called overtones. Collectively, they are called harmonics.
- The resonant frequencies of a tube closed at one end are $f_n = n\frac{v}{4L},\ n = 1, 3, 5...$, where f_1 is the fundamental and L is the length of the tube.
- The resonant frequencies of a tube open at both ends are $f_n = n\frac{v}{2L},\ n = 1, 2, 3...$

KEY EQUATIONS

14.1 Speed of Sound, Frequency, and Wavelength

speed of sound $v = f\lambda$

14.2 Sound Intensity and Sound Level

intensity $I = \frac{P}{A}$

sound intensity $I = \frac{(\Delta p)^2}{2\rho v_w}$

sound intensity level $\beta\,(\text{dB}) = 10\log_{10}\left(\frac{I}{I_0}\right)$

14.3 Doppler Effect and Sonic Booms

Doppler effect observed frequency (moving source)
$f_{obs} = f_s\left(\frac{v_w}{v_w \pm v_s}\right)$

Doppler effect observed frequency (moving observer)

$$f_{obs} = f_s\left(\frac{v_w \pm v_{obs}}{v_w}\right)$$

14.4 Sound Interference and Resonance

beat frequency $f_B = |f_1 - f_2|$

resonant frequencies of a closed-pipe resonator
$f_n = n\frac{v}{4L},\ n = 1, 3, 5...$

resonant frequencies of an open-pipe resonator
$f_n = n\frac{v}{2L},\ n = 1, 2, 3...$