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YEAR OF COMMUNITY

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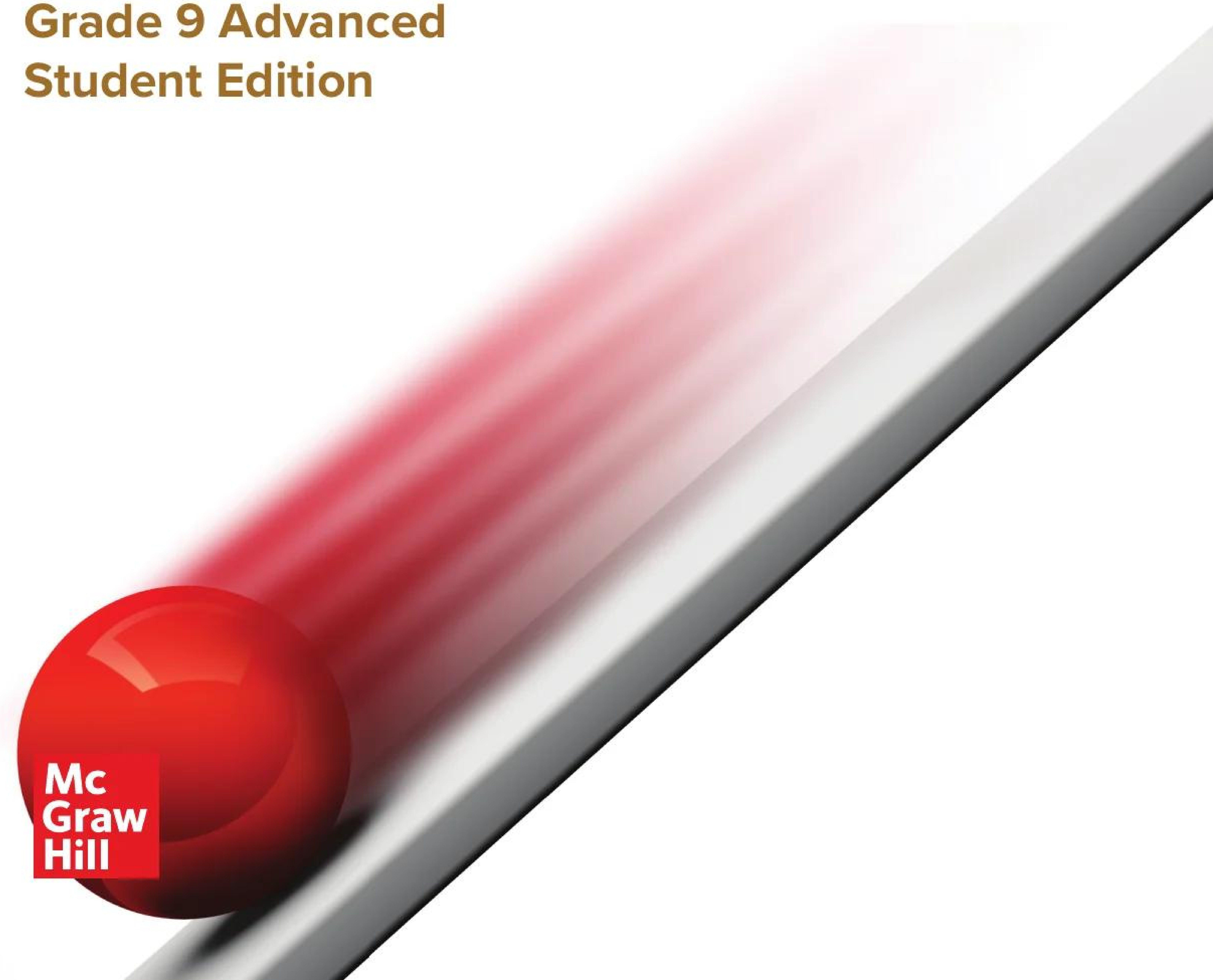
WE THE UAE
2031

2025-2026

Inspire Physics

UAE Edition
Grade 9 Advanced
Student Edition



Mc Graw Hill

McGraw-Hill Education

Physics

United Arab Emirates Edition

Grade 9 Advanced

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Physics
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MODULE 1
A PHYSICS TOOLKIT

ENCOUNTER THE PHENOMENON
What tools and skills do physicists use?

GO ONLINE to play a video about the way Newton studied light.

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

CER Claim, Evidence, Reasoning

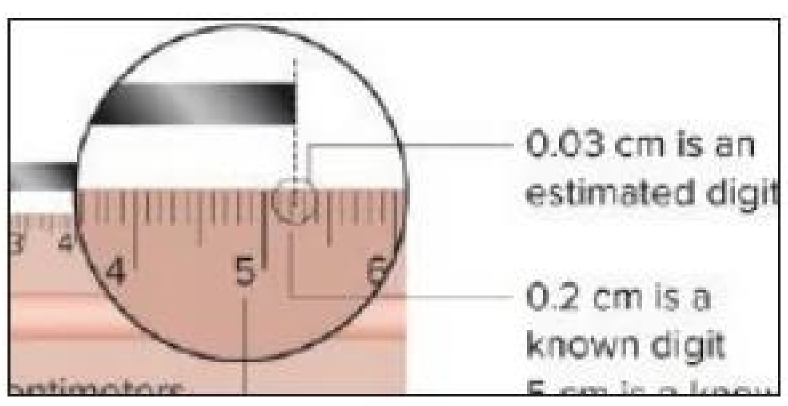
Make Your Claim Use your CER chart to make a claim about the tools and skills physicists use. Explain your reasoning.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.

LESSON 1: Explore & Explain: What is physics?



LESSON 2: Explore & Explain: Uncertainty in Data: Significant Figures

Smithsonian

Additional Resources

LESSON 1
METHODS OF SCIENCE

FOCUS QUESTION

What do physicists do?

What is physics?

Science is not just a subject in school. It is a process based on inquiry that helps develop explanations about events in nature. **Physics** is a branch of science that involves the study of the physical world: energy, matter, and how they are related.

When you see the word *physics* you might picture a chalkboard full of formulas and mathematics: $E = mc^2$, $I = \frac{V}{R}$, $x = \left(\frac{1}{2}\right)at^2 + v_0t + x_0$. Maybe you picture scientists in white lab coats or well-known figures such as Marie Curie and Albert Einstein. Alternatively, you might think of the many modern technologies created with physics, such as weather satellites, laptop computers, and lasers.

Physicists investigate the motions of electrons and rockets, the energy in sound waves and electric circuits, and the structure of the proton and of the universe. The goal of this course is to help you better understand the physical world.

People who study physics go on to many different careers. Some become scientists at universities and colleges, at industries, or in research institutes. Others go into related fields, such as engineering, computer science, teaching, medicine, or astronomy, as shown in **Figure 1.** Still others use the problem-solving skills of physics to work in finance, construction, or other very different disciplines. In the last 50 years, research in the field of physics has led to many new technologies, including satellite-based communications and high-speed microscanners used to detect disease.

Figure 1 Physicists may choose from a variety of careers.

inga spence/Alamy Stock Photo

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Quick Investigation: Measuring Change

Analyze data to find patterns that can be used for extrapolation.

Review the News

Obtain information from a current news story about current physics research. Evaluate your source and communicate your findings to your class.

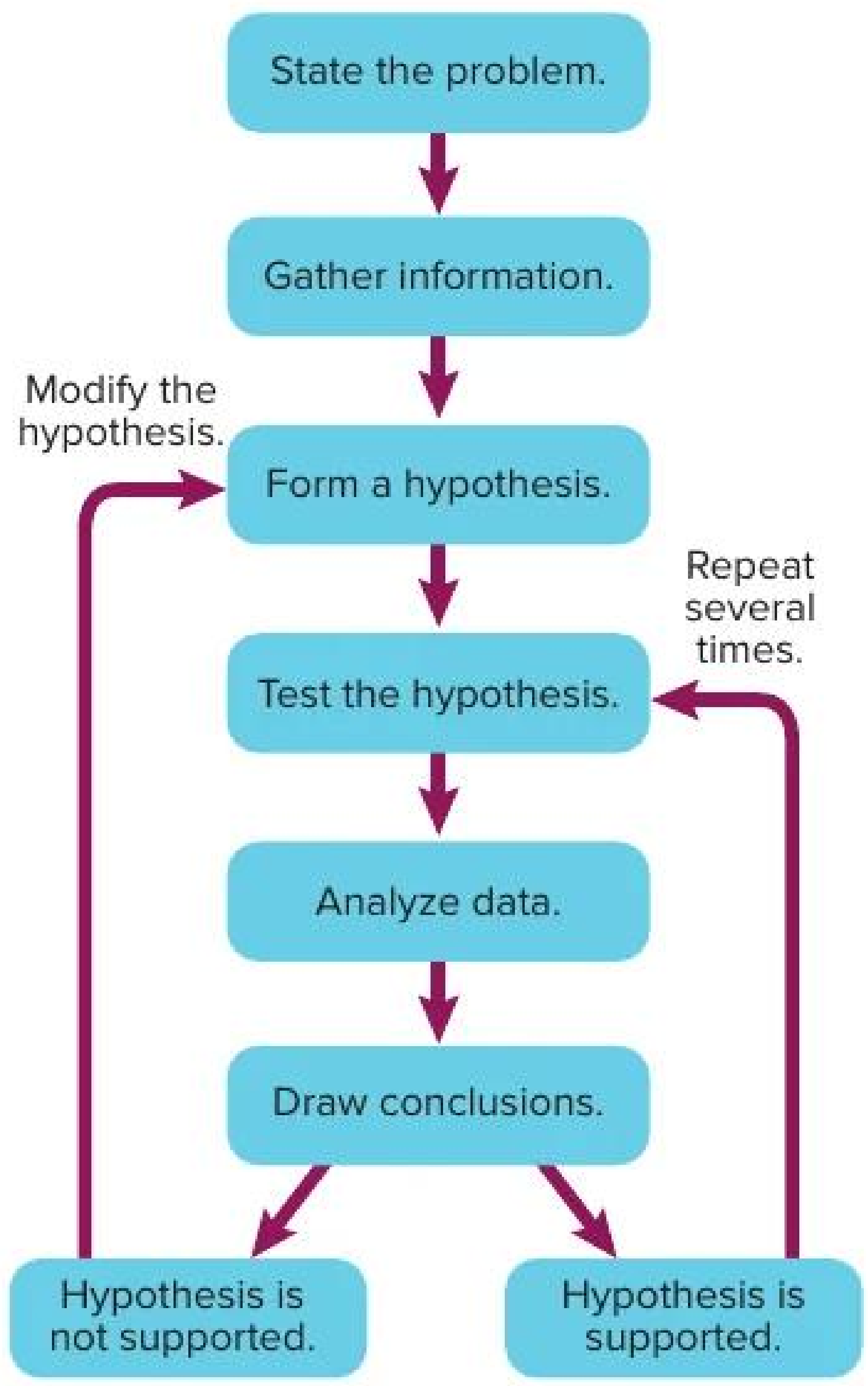


Figure 2 The series of procedures shown here is one way to use scientific methods to solve a problem.

Scientific Methods

Although physicists do not always follow a rigid set of steps, investigations often follow similar patterns called **scientific methods,** as shown in **Figure 2.** Depending on the particular investigation, a scientist might add new steps, repeat some steps, or skip steps altogether.

State the problem Investigations can begin when one observes an event in nature and wonders why or how it occurs. The question of "why" or "how" is the problem to be stated.

Sometimes a new question is posed during an investigation, leading to a new statement of a problem. In the 1940s, researcher Percy Spencer was trying to answer the question of how to mass-produce the magnetron tubes used in radar systems. When he stood in front of an operating magnetron, which produces microwaves, a candy bar in his pocket melted. The new question of how the magnetron was cooking food was then asked.

Research and gather information Before beginning an investigation, it is useful to research what is already known about the problem. Making and examining observations and interpretations from reliable sources helps fine-tune the question and form it into a hypothesis.

WORD ORIGINS

Science
comes from the Latin word *scientia*, which means *knowledge*

STEM CAREER Connection

Survey or Mapping Technician
Do you like being outside? Survey technicians spend most of their time outside in various weather conditions collecting geographic data such as elevation and contour. Mapping technicians use the data and sophisticated computer software to make maps of Earth's surface.

Form and test a hypothesis A **hypothesis** is a possible explanation for a problem using what you know and have observed. A scientific hypothesis can be tested through experimentation and observation. Sometimes scientists must wait for new technologies before a hypothesis can be tested. For example, the first hypotheses about the existence of atoms were developed more than 2300 years ago, but the technologies to test these hypotheses were not available for many centuries.

Some hypotheses can be tested by making observations. Others can be tested by building a model and relating it to real-life situations. One common way to test a hypothesis is to perform an experiment. An experiment tests the effect of one thing on another, using a control. Sometimes it is not possible to perform experiments; in these cases, investigations become descriptive in nature. For example, physicists cannot conduct experiments in deep space. They can, however, collect and analyze valuable data to help us learn more about events occurring there.

Analyze the data An important part of every investigation includes recording observations and organizing data into easy-to-read tables and graphs. Later in this module, you will study ways to display data. When you are making and recording observations, you should include all your results, even unexpected ones. Many important discoveries have been made from unexpected results. Scientific inferences are based on scientific observations. All possible scientific explanations must be considered. If the data are not organized in a logical manner, incorrect conclusions can be drawn.

When a scientist communicates and shares data, other scientists will examine those data and how the data were analyzed, and compare the data to the work of others. Scientists, such as the planetary scientist in **Figure 3,** share their data and analyses through reports, journals, and conferences.

Draw conclusions Based on the analysis of the data, the next step is to decide whether the hypothesis is supported. For the hypothesis to be considered valid and widely accepted, the results of the experiment must be the same every time it is repeated. If the experiment does not support the hypothesis, the hypothesis must be reconsidered. Perhaps the hypothesis needs to be revised, or maybe the experimenter's procedure needs to be refined.

Figure 3 An important part of scientific methods is to share data and results with other scientists. This scientist is sharing predicted planetary orbital data with colleagues.

Peer review Before it is made public, science-based information is reviewed by scientists' peers—scientists who are in the same field of study. Peer review is a process by which the procedures and results of an experiment are evaluated by peer scientists of those who conducted the research. Reviewing other scientists' work is a responsibility that many scientists have.

Being objective One also should be careful to reduce bias in scientific investigations. Bias can occur when the scientist's expectations affect how the results are analyzed or the conclusions are made. This might cause a scientist to select a result from one trial over those from other trials. Bias might also be found if the advantages of a product being tested are used in a promotion and the drawbacks are not presented. Scientists can lessen bias by running as many trials as possible and by keeping accurate notes of each observation made.

Models

Sometimes, scientists cannot see everything they are testing. They might be observing an object that is too large or too small, a process that takes too much time to see completely, or a material that is hazardous. In these cases, scientists use models. A **model** is a representation of an idea, event, structure, or object that helps people better understand it.

Models in history Models have been used throughout history. In the early 1900s, British physicist J.J. Thomson created a model of the atom that consisted of electrons embedded in a ball of positive charge. Several years later, physicist Ernest Rutherford created a model of the atom based on new research. Later in the twentieth century, scientists discovered that the nucleus is not a solid ball but is made of protons and neutrons. The present-day model of the atom is a nucleus made of protons and neutrons surrounded by an electron cloud. All three of these models are shown in **Figure 4.** Scientists use models of atoms to represent their current understanding because of the small size of an atom.

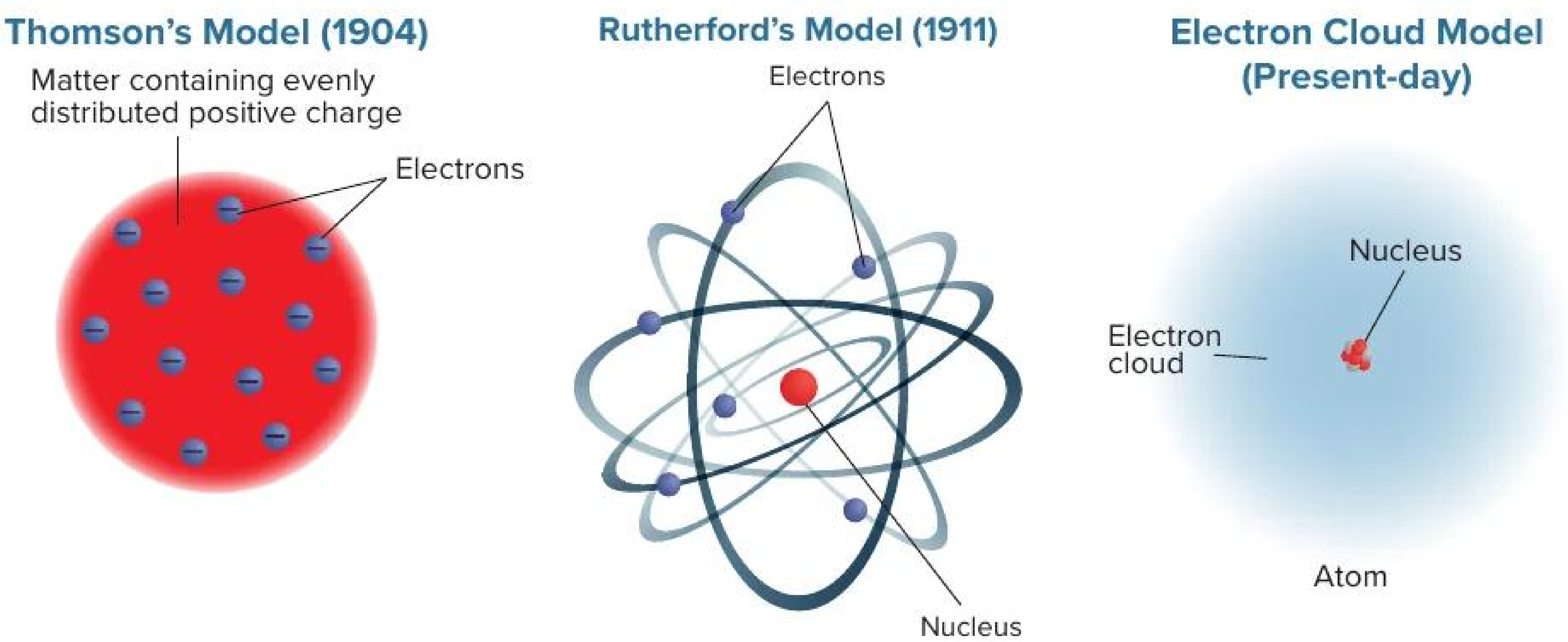


Figure 4 Throughout history, scientists have made models of the atom.

Infer *Why have models of the atom changed over the years?*

Get It?
Explain how the model shown at the beginning of this module is helpful.

High-tech models Both physical models and computers can be used in various ways to aid in the engineering design process. Computers are useful for a variety of purposes, such as running simulations to test different ways of solving a problem or to see which one is most efficient or economical; and in making a persuasive presentation to a client about how a given design will meet his or her needs. Computer software is designed to mimic the processes under study.

For instance, computer simulators, such as the one shown in **Figure 5,** help airplane pilots practice all aspects of flight without ever leaving the ground. In addition, computer simulations can simulate harsh weather conditions and other potentially dangerous in-flight challenges.

Figure 5 This is a flight simulator used to help train pilots. The image mimics what the pilot would see if flying a real plane.

Identify *other models around your classroom.*

Get It?

Discuss how computer simulations can help develop possible solutions to a problem.

Scientific Theories and Laws

A **scientific theory** is an explanation of things or events based on knowledge gained from many observations and investigations.

A theory is not a guess. If scientists repeat an investigation and the results always support the hypothesis, the hypothesis can be called a theory. Just because a scientific theory has data supporting it does not mean it will never change. As new information becomes available, theories can be refined or modified, as shown in **Figure 6** on the next page.

A **scientific law** is a statement about what happens in nature and seems to be true all the time. Laws tell you what will happen under certain conditions, but they don't explain why or how something happens. Gravity is an example of a scientific law. The law of gravity states that any one mass will attract another mass. To date, no experiments have been performed that disprove the law of gravity.

A theory can be used to explain a law, but theories do not become laws. For example, many theories have been proposed to explain how the law of gravity works. Even so, there are few accepted theories in science and even fewer laws.

CCC CROSSCUTTING CONCEPTS

Systems and System Models Models can be used to simulate systems. Choose a model not mentioned in this lesson. Remember that a model isn't necessarily a physical model, something you can build and touch, although it could be. Prepare a poster that shows how your model can help test a process or a procedure. What type of model will you use? What evidence supports your explanation?

Greek philosophers proposed that objects fall because they seek their natural places. The more massive the object, the faster it falls.

↓ **Revision**

Galileo showed that the speed at which an object falls depends on the amount of time for which that object has fallen and not on the object's mass.

↓ **Revision**

Newton provided an explanation for why objects fall. Newton proposed that objects fall because the object and Earth are attracted by a force. Newton also stated that there is a force of attraction between any two objects with mass.

↓ **Revision**

Einstein suggested that the force of attraction between two objects is due to mass causing the space around it to curve.

Figure 6 If experiments provide new insight and evidence about a theory, such as the theory describing the behavior of falling objects, the theory is modified accordingly.

The Limitations of Science

Science can help you explain many things about the world, but science cannot explain or solve everything. Scientists make guesses, but the guesses must be tested and verified. Questions about opinions, values, and emotions are not scientific because they cannot be tested. For example, some people may find a particular piece of art beautiful while others do not. Some people might think that certain foods, such as pizza, taste delicious while others do not. You might take a survey to gather opinions about such questions, but that would not prove that the opinions are true for everyone.

Check Your Progress

1. **Summarize** the steps you might use to carry out an investigation using scientific methods.
2. **Define** the term *hypothesis*. Identify three ways to test a hypothesis.
3. **Describe** why it is important for scientists to avoid bias.
4. **Explain** why scientists use models. Give an example of a scientific model not mentioned in this lesson, and explain how it is useful.
5. **Analyze** Your friend finds that 90 percent of students surveyed in the cafeteria like pizza. She says this scientifically proves that everyone likes pizza. How would you respond?
6. **Critical Thinking** An accepted value for free-fall acceleration is $9.8\ m/s^2$. In an experiment with pendulums, you calculate a value to be $9.4\ m/s^2$. Should the accepted value be tossed out because of your finding? Explain.

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LESSON 2
MATHEMATICS AND PHYSICS

FOCUS QUESTION

How is math helpful to physicists?

Mathematics in Physics

Physicists often use the language of mathematics. In physics, equations are important tools for modeling observations and for making predictions. Equations are one way of representing relationships between measurements. Physicists rely on theories and experiments with numerical results to support their conclusions. For example, you can predict that if you drop a penny, it will fall, but can you predict how fast it will be going when it strikes the ground? Different models of falling objects give different answers to how the speed of the object changes as it falls or on what the speed depends. By measuring how an object falls, you can compare the experimental data with the results predicted by different models. This tests the models, allowing you to pick the best one or to develop a new model.

SI Units

To communicate results, it is helpful to use units that everyone understands. The worldwide scientific community uses an adaptation of the metric system for measurements. **Table 1** shows that the Système International d'Unités, or SI, uses seven base quantities. Other units, called derived units, are formed by combining the base units in various ways. Velocity is measured in meters per second (m/s). Often, derived units are given their own names. For example, electric charge is measured in ampere-seconds (A·s), which are also called coulombs (C).

SI is regulated by the International Bureau of Weights and Measures in Sèvres, France. In the past, this bureau and the National Institute of Science and Technology (NIST) in Gaithersburg, Maryland, kept physical samples on which the standards were based.

Table 1 SI Base Units

Base Quantity	Base Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Amount of a substance	mole	mol
Electric current	ampere	A
Luminous intensity	candela	cd

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the Unit and Module questions?

However, the standards are being redefined in terms of phenomena. For example, the meter, as shown in **Figure 7,** is now defined as $\frac{1}{299,792,458}$, the distance that light travels in $\frac{1}{299,792,458}$ of a second.

The ease of switching between units is another convenient feature of SI. To convert between units, multiply or divide by the appropriate power of 10. Prefixes are used to change SI base units by powers of 10, as shown in **Table 2.** You often will encounter these prefixes in daily life, as in, for example, milligrams and centimeters.

Figure 7 You will use metersticks as your standard of measurement, but the official definition of a meter is $\frac{1}{299,792,458}$, the distance that light travels in $\frac{1}{299,792,458}$ of a second.

Describe *Why is it important to have standards for measurements?*

Dimensional Analysis

You often will need to manipulate a formula, or use a string of formulas, to solve a physics problem. One way to check whether you have set up a problem correctly is to write out the equation or set of equations you plan to use. Before doing calculations, check that the answer will be in the expected units. For example, if you are finding a car's speed and you see that your answer will have the units s/m or m/s^2, you have made an error in setting up the problem. This method of treating the units as algebraic quantities that can be canceled is called **dimensional analysis.** Knowing that your answer will be in the correct units is not a guarantee that your answer is right, but if you find that your answer has or will have the wrong units, you can be sure that you have made an error. Dimensional analysis also is used in choosing conversion factors. A conversion factor is a multiplier equal to 1.

Table 2 Prefixes Used with SI Units

Prefix	Symbol	Multiplier	Scientific Notation	Example
femto–	f	0.000000000000001	10^{-15}	femtosecond (fs)
pico–	p	0.000000000001	10^{-12}	picometer (pm)
nano–	n	0.000000001	10^{-9}	nanometer (nm)
micro–	μ	0.000001	10^{-6}	microgram (μg)
milli–	m	0.001	10^{-3}	milliamps (mA)
centi–	c	0.01	10^{-2}	centimeter (cm)
deci–	d	0.1	10^{-1}	deciliter (dL)
kilo–	k	1000	10^{3}	kilometer (km)
mega–	M	1,000,000	10^{6}	megagram (Mg)
giga–	G	1,000,000,000	10^{9}	gigameter (Gm)
tera–	T	1,000,000,000,000	10^{12}	terahertz (THz)

Get It?

Identify the prefix that would be used to express 2,000,000,000 bytes of computer memory.

For example, because 1 kg = 1000 g, you can construct the following conversion factors:

$$1 = \frac{1\,\text{kg}}{1000\,\text{g}} \quad \text{and} \quad 1 = \frac{1000\,\text{g}}{1\,\text{kg}}$$

Choose a conversion factor that will make the initial units cancel, leaving the answer in the desired units. For example, to convert a mass of 1.34 kg to grams, set up the conversion as shown below.

$$1.34\,\cancel{\text{kg}}\left(\frac{1000\,\text{g}}{1\,\cancel{\text{kg}}}\right) = 1340\,\text{g}$$

You also might need to do a series of conversions. To convert 43 km/h to m/s, do the following:

$$\left(\frac{43\,\cancel{\text{km}}}{1\,\cancel{\text{h}}}\right)\left(\frac{1000\,\text{m}}{1\,\cancel{\text{km}}}\right)\left(\frac{1\,\cancel{\text{h}}}{60\,\cancel{\text{min}}}\right)\left(\frac{1\,\cancel{\text{min}}}{60\,\text{s}}\right) = 12\,\text{m/s}$$

Significant Figures

Suppose you measure a pen and find that the end of the pen is just past 138 mm, as shown in **Figure 8.** You estimate that the pen is one-tenth of a millimeter past the last tick mark on the ruler and record the pen as being 138.1 mm long. This measurement has four valid digits: the first three digits are certain, and the last one is uncertain. The valid digits in a measurement are called **significant figures.** The last digit given for any measurement is the uncertain digit. All nonzero digits in a measurement are significant.

Are all zeros significant?

No. For example, in the measurement 0.0860 m, the first two zeros serve only to locate the decimal point and are not significant. The last zero, however, is the estimated digit and is significant. The measurement 172,000 m could have 3, 4, 5, or 6 significant figures. This ambiguity is one reason to use scientific notation. It is clear that the measurement 1.7200×10^5 m has five significant figures.

Arithmetic with significant figures

When you do any arithmetic operation, remember that the result never can be more precise than the least-precise measurement.

To add or subtract measurements, first do the operation, then round off the result to correspond to the least-precise value involved. For example, 3.86 m + 2.4 m = 6.3 m, not 6.26 m, because the least-precise measure is to one-tenth of a meter.

To multiply or divide measurements, first do the calculation, and then round to the same number of significant figures as the least-precise measurement. For example, $\frac{409.2\,\text{km}}{11.4\,\text{L}} = \frac{35.9\,\text{km}}{\text{L}}$, because the least-precise measurement has three significant figures. Some calculators display several additional digits, while others round at different points. Be sure to record your answers with the correct number of digits.

Solving Problems

Most practice problems in this course will be complex and require a strategy to solve. This textbook includes many example problems, each of which is solved using a three-step process. Example Problem 1 on the next page follows the steps to calculate a car's average speed using distance and time.

Figure 8 You recorded the length of this pen as 138.1 mm.
Infer *Why is the last digit uncertain?*

Richard Hutchings/Digital Light Source

EXAMPLE Problem 1

USING DISTANCE AND TIME TO FIND SPEED When a car travels 434 km in 4.5 h, what is the car's average speed?

1 ANALYZE AND SKETCH THE PROBLEM

The car's speed is unknown. The known values include the distance the car traveled and the time. Use the relationship among speed, distance, and time to solve for the car's speed.

Known	Unknown
distance = 434 km	speed = ?
time = 4.5 h	

2 SOLVE FOR THE UNKNOWN

distance = **speed** × time — State the relationship as an equation.

speed = $\frac{\text{distance}}{\text{time}}$ — Solve the equation for speed.

speed = $\frac{434\text{ km}}{4.5\text{ h}}$ — Substitute distance = 434 km and time = 4.5 h.

speed = 96.4 km/h — Calculate, and specify the units.

3 EVALUATE THE ANSWER

Check your answer by using it to calculate the distance the car traveled.

distance = speed × time = 96.4 km/$\cancel{\text{h}}$ × 4.5 $\cancel{\text{h}}$ = 434 km

The calculated distance matches the distance stated in the problem. This means that the calculated average speed is correct.

THE PROBLEM

1. Read the problem carefully.
2. Be sure you understand what is being asked.

ANALYZE AND SKETCH THE PROBLEM

1. Read the problem again.
2. Identify what you are given, and list the known data. If needed, gather information from graphs, tables, or figures.
3. Identify and list the unknowns.
4. Determine whether you need a sketch to help solve the problem.
5. Plan the steps you will follow to find the answer.

SOLVE FOR THE UNKOWN

1. If the solution is mathematical, write the equation and isolate the unknown factor.
2. Substitute the known quantities into the equation.
3. Solve the equation.
4. Continue the solution process until you solve the problem.

EVALUATE THE ANSWER

1. Reread the problem. Is the answer reasonable?
2. Check your math. Are the units and significant figures correct?

Check Your Progress

7. **Modeling** Why are concepts in physics described with formulas?
8. **Significant Figures** Solve the following problems, using the correct number of significant figures each time.
   a. 10.8 g – 8.264 g
   b. 4.75 m – 0.4168 m
   c. 139 cm × 2.3 cm
   d. 13.78 g / 11.3 mL
   e. 1.6 km + 1.62 m + 1200 cm
9. **Dimensional Analysis** How many seconds are in a leap year?
10. **Solving Problems** Rewrite $F = Bqv$ to find v in terms of F, q, and B.
11. **Critical Thinking** Using values given in a problem and the equation for distance, distance = speed × time, you calculate a car's speed to be 290 km/h. Is this answer reasonable? Explain. Under what circumstances might this be a reasonable answer?

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LESSON 3
MEASUREMENT

FOCUS QUESTION

Why is it important to make careful measurments?

What is measurement?

A **measurement** is a comparison between an unknown quantity and a standard. For example, if you measure the mass of a rolling cart used in an experiment, the unknown quantity is the mass of the cart and the standard is the gram, as defined by the balance or spring scale you use. If you do an experiment with a spring for which the length is unknown, the centimeter is the standard you might use for length. Measurements quantify our observations. For example, a person's blood pressure isn't just "pretty good"; it's $\frac{110}{60}$, the low end of the good range.

Comparing Results

As you learned in Lesson 1, scientists share their results. Before new data are fully accepted, other scientists examine the experiment, look for possible sources of error, and try to reproduce the results. Results often are reported with an uncertainty. A new measurement that is within the margin of uncertainty is in agreement with the old measurement.

For example, archaeologists use radiocarbon dating to determine the age of cave paintings, such as those from the Niaux cave in France, in **Figure 9,** and the Chauvet cave, also in France. Each radiocarbon date is reported with an uncertainty. Three radiocarbon ages from a panel in the Chauvet cave are 30,940 ± 610 years, 30,790 ± 600 years, and 30,230 ± 530 years. While none of the measurements matches, the uncertainties in all three overlap, and the measurements agree with each other.

Figure 9 These drawings are from the Niaux cave in France. Scientists estimate that the drawings were made about 17,000 years ago.

CAROLUS/Pixtal/age fotostock

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Mass and Volume

Carry out an investigation to determine the relationship between mass, volume, and density.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the Unit and Module questions?

Suppose three students performed an experiment several times starting with springs of the same length. With two washers on the spring, student 1 made repeated measurements, which ranged from 14.4 cm to 14.8 cm. The average of student 1's measurements was 14.6 cm, as shown in **Figure 10.** This result was reported as (14.6 ± 0.2) cm. Student 2 reported finding the spring's length to be (14.8 ± 0.3) cm. Student 3 reported a length of (14.0 ± 0.1) cm.

Could you conclude that the three measurements are in agreement? Is student 1's result reproducible? The ranges of the results of students 1 and 2 overlap between 14.5 cm and 14.8 cm. However, there is no overlap and, therefore, no agreement, between their results and the result of student 3.

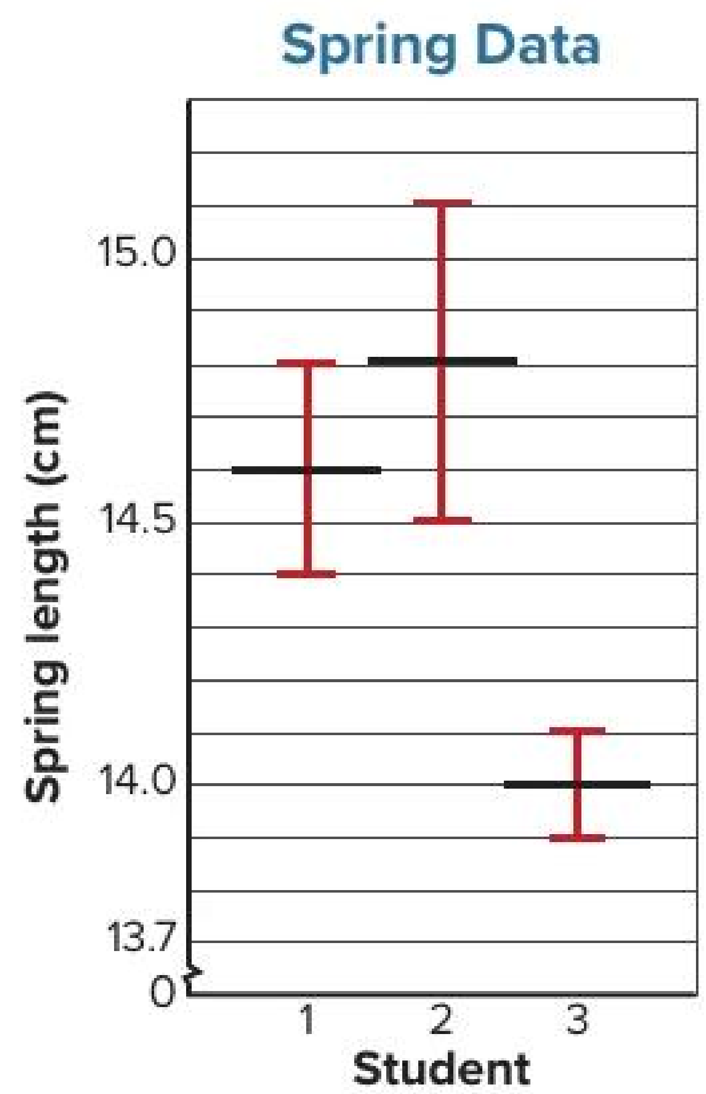

Figure 10 Three students took multiple measurements. The red bars show the uncertainty of each student's measurement.

Get It?
Explain Is student 3's result reproducible? Why or why not?

Precision Versus Accuracy

Both precision and accuracy are characteristics of measured values, as shown in **Figure 11.** How precise and accurate are the measurements of the three students above? The degree of exactness of a measurement is called its **precision.** In the example above, student 3's measurements are the most precise, within ± 0.1 cm. Both the measurements of student 1 and student 2 are less precise because they have a larger uncertainty (student 1 = ± 0.2 cm, student 2 = ± 0.3 cm).

Precision depends on the instrument and technique used to make the measurement. Generally, the device that has the finest division on its scale produces the most precise measurement. The precision of a measurement is one-half the smallest division of the instrument.

For example, suppose a graduated cylinder has divisions of 1 mL. You could measure an object to within 0.5 mL with this device. However, if the smallest division on a beaker is 50 mL, how precise would your measurements be compared to those taken with the graduated cylinder?

The significant figures in an answer show its precision. A measure of 67.100 g is precise to the nearest thousandth of a gram. Say you add 1.2 mL of acid to a beaker containing 2.4×10^2 mL of water—you cannot say you now have 2.412×10^2 mL of fluid because the volume of water was not measured to the nearest tenth of a milliliter, but to the nearest 10 mL.

Accuracy describes how well the results of a measurement agree with the "real" value; that is, the accepted value as measured by competent experimenters. **Figure 11** illustrates accuracy and precision.

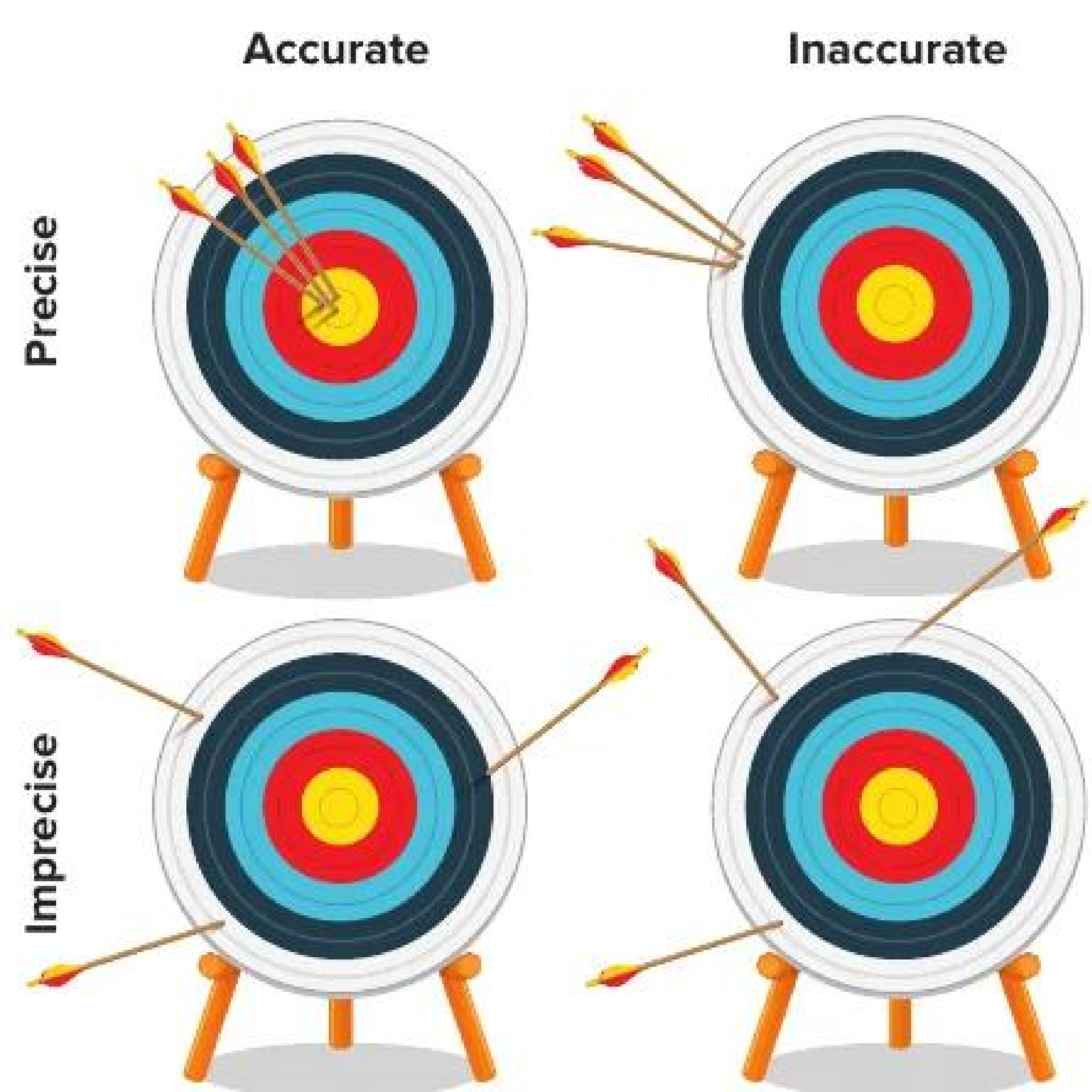

Figure 11 The yellow area in the center of each target represents an accepted value for a particular measurement. The arrows represent measurements taken by a scientist during an experiment.

If the length of the spring that the three students above measured had been 14.8 cm, then student 2 would have been most accurate and student 3 least accurate. What might have led someone to make inaccurate measurements? How could you check the accuracy of measurements?

A common method for checking the accuracy of an instrument is called the two-point calibration. First, does the instrument read zero when it should, as shown in **Figure 12?** Second, does it give the correct reading when it is measuring an accepted standard? Regular checks for accuracy are performed on critical measuring instruments, such as the radiation output of the machines used to treat cancer.

Get It?
Compare and contrast precision and accuracy.

Techniques of Good Measurement

To assure accuracy and precision, instruments also have to be used correctly. Measurements have to be made carefully if they are to be as precise as the instrument allows. One common source of error comes from the angle at which an instrument is read. Scales should be read with one's eye directly in front of the measure, as shown on the left of **Figure 13.** If the scale is read from an angle, as shown on the right of **Figure 13,** a different, less accurate, value will be obtained. The difference in the readings is caused by parallax, which is the apparent shift in the position of an object when it is viewed from different angles. To experiment with parallax, place your pen on a ruler and read the scale with your eye directly over the tip, then read the scale with your head shifted far to one side.

Figure 12 Accuracy is checked by zeroing an instrument before measuring.

Infer *Is this instrument accurate? Why or why not?*

Figure 13 By positioning the scale head-on (left), your results will be more accurate than if you read your measurements at an angle (right).

Identify *How far did parallax shift the measurement on the right?*

GPS

The Global Positioning System, or GPS, offers an illustration of accuracy and precision in measurement. The GPS consists of 24 satellites with transmitters in orbit and several receivers on Earth. The satellites send signals with the time, measured by highly accurate atomic clocks.

The receiver uses the information from at least four satellites to determine latitude, longitude, and elevation. (The clocks in the receivers are not as accurate as those on the satellites.)

Receivers have different levels of precision. A device in an automobile might give your position to within a few meters. Devices used by geophysicists and geologists, as in **Figure 14,** can measure movements of millimeters in Earth's crust.

The GPS was developed by the United States Department of Defense. It uses atomic clocks, which were developed to test Einstein's theories of relativity and gravity. The GPS eventually was made available for civilian use.

GPS signals now are provided worldwide free of charge and are used in navigation on land, at sea, and in the air, for mapping and surveying, by telecommunications and satellite networks, and for scientific research into earthquakes and plate tectonics.

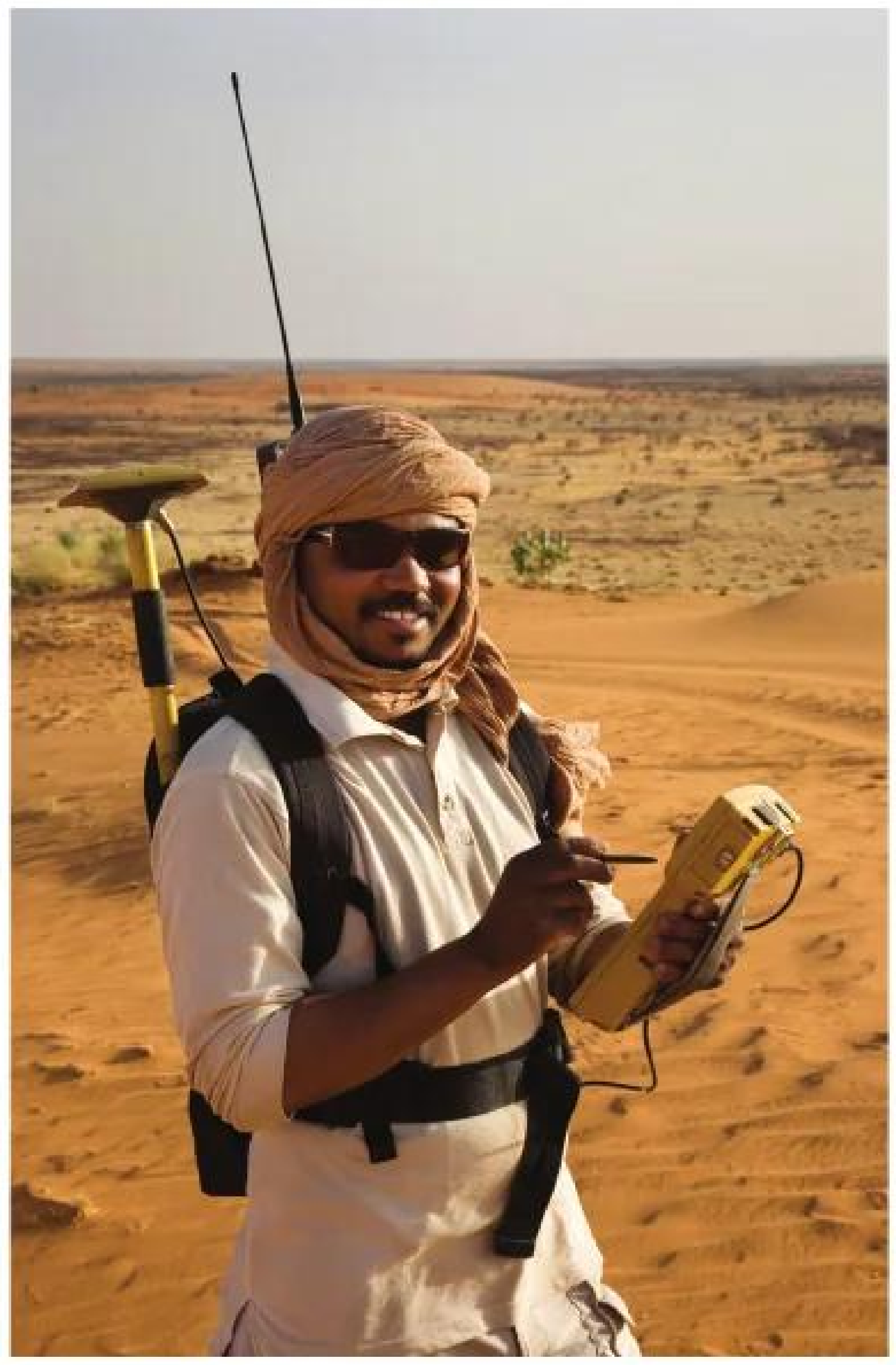

Figure 14 This geologist in the Mali Desert is using a highly accurate GPS receiver to record and analyze the movements of continental plates. His findings will help in the search for oil deposits.

Check Your Progress

12. **Precision and Accuracy** You find a micrometer (a tool used to measure objects to the nearest 0.001 mm) that has been bent. How does it compare to a new, high-quality meter-stick in its precision and accuracy?
13. **Accuracy** Some wooden rulers do not start with 0 at the edge, but have it set in a few millimeters. How could this improve the accuracy of the ruler?
14. **Parallax** Does parallax affect the precision of a measurement that you make? Explain.
15. **Uncertainty** Your friend tells you that his height is 182 cm. In your own words, explain the range of heights implied by this statement.
16. **Precision** A box has a length of 18.1 cm, a width of 19.2 cm, and is 20.3 cm tall.
    a. What is its volume?
    b. How precise is the measurement of length? Of volume?
    c. How tall is a stack of 12 of these boxes?
    d. How precise is the measurement of the height of one box? Of 12 boxes?
17. **Critical Thinking** Your friend states in a report that the average time required for a car to circle a 2.4-km track was 65.414 s. This was measured by timing 7 laps using a clock with a precision of 0.1 s. How much confidence do you have in the results of the report? Explain.

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LESSON 4

GRAPHING DATA

FOCUS QUESTION

How do graphs help scientists analyze data?

Identifying Variables

When you perform an experiment, it is important to change only one factor at a time. For example, **Table 3** gives the length of a spring with different masses attached. Only the mass varies; if different masses were hung from different types of springs, you wouldn't know how much of the difference between two data pairs was due to the different masses and how much was due to the different springs.

Independent and dependent variables

A variable is any factor that might affect the behavior of an experimental setup. The factor that is manipulated during an investigation is the **independent variable.** In the experiment that gave the data in **Table 3,** the mass was the independent variable. The factor that depends on the independent variable is the **dependent variable.** In this investigation, the amount the spring stretched depended on the mass, so the amount of stretch was the dependent variable.

Line of best fit

A line graph shows how the dependent variable changes with the independent variable. The data from **Table 3** are graphed in **Figure 15** on the next page. The line in blue, drawn as close to all the data points as possible, is called a **line of best fit.** The line of best fit is a better model for predictions than any one point along the line. **Figure 15** gives detailed instructions on how to construct a graph, plot data, and sketch a line of best fit.

A well-designed graph allows patterns that are not immediately evident in a list of numbers to be seen quickly and simply. The graph in **Figure 15** shows that the length of the spring increases as the mass suspended from the spring increases.

Table 3 Length of a Spring for Different Masses

Mass Attached to Spring (g)	Length of Spring (cm)
0	13.7
5	14.1
10	14.5
15	14.9
20	15.3
25	15.7
30	16.0
35	16.4

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

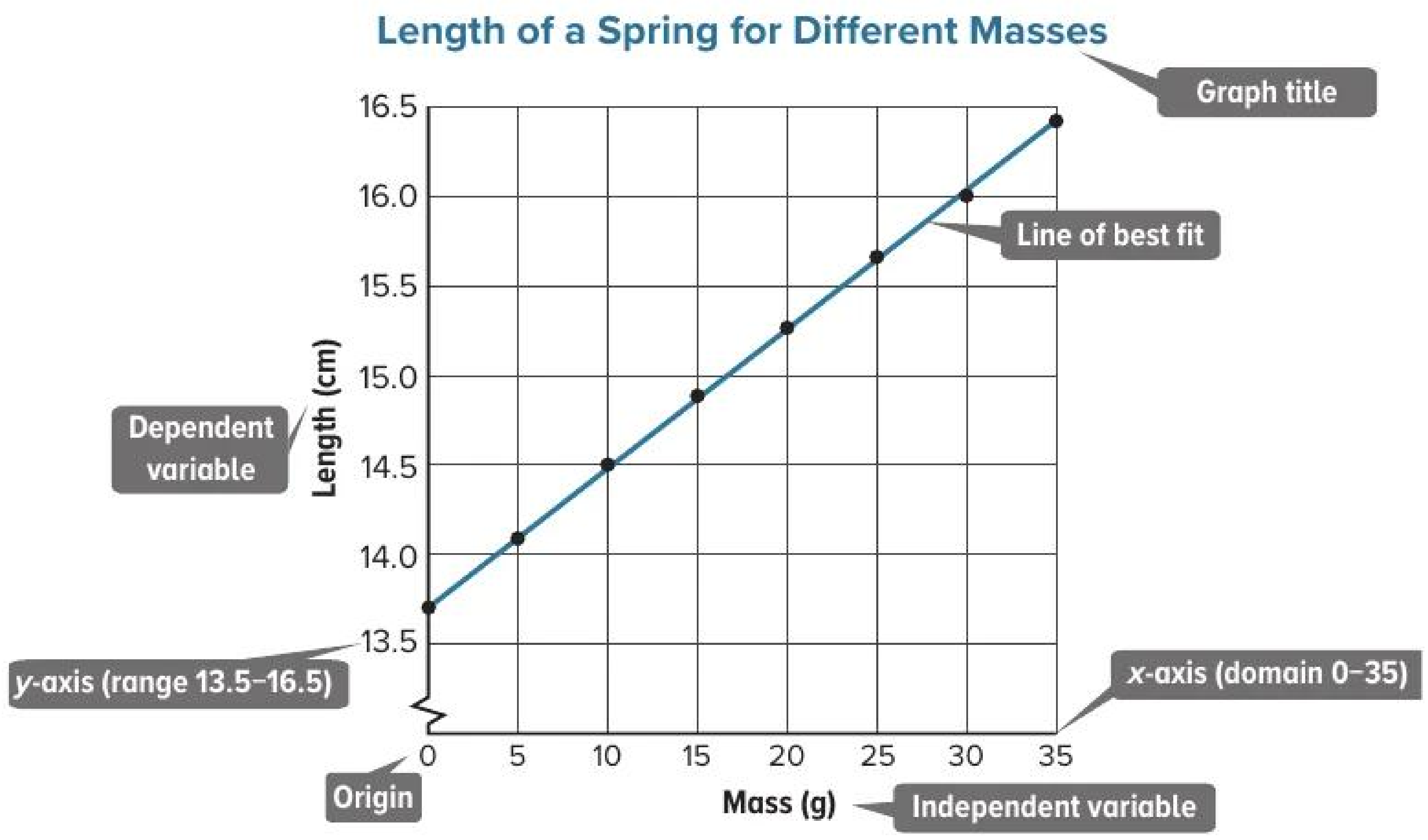
INVESTIGATE

GO ONLINE to find these activities and more resources.

Forensics Lab: It's in the Blood
Analyze and interpret data to determine cause and effect at a crime scene.

Review the News
Obtain information from a current news story where graphs are used to present data. Evaluate your source and communicate your findings to your class.

Figure 15 Use the steps outlined here to plot line graphs from data tables.



1. Identify the independent variable and the dependent variable in your data. In this example, the independent variable is mass (g) and the dependent variable is length (cm). The independent variable is plotted on the horizontal axis, the *x*-axis. The dependent variable is plotted on the vertical axis, the *y*-axis.
2. Determine the range of the independent variable to be plotted. In this case the range is 0–35.
3. Decide whether the origin (0, 0) is a valid data point.
4. Spread the data out as much as possible. Let each division on the graph paper stand for a convenient unit. This usually means units that are multiples of 2, 5, or 10.
5. Number and label the horizontal axis. The label should include the name of the variable and its units, for example, Mass (g).
6. Repeat steps 2–5 for the dependent variable.
7. Plot the data points on the graph.
8. Draw the best-fit straight line or smooth curve that passes through as many data points as possible. This is sometimes called *eyeballing*. Do not use a series of straight-line segments that connect the dots. The line that looks like the best fit to you may not be exactly the same as someone else's. There is a formal procedure, which many graphing calculators use, called the least-squares technique, that produces a unique best-fit line, but that is beyond the scope of this textbook.
9. Give the graph a title that clearly tells what the graph represents.

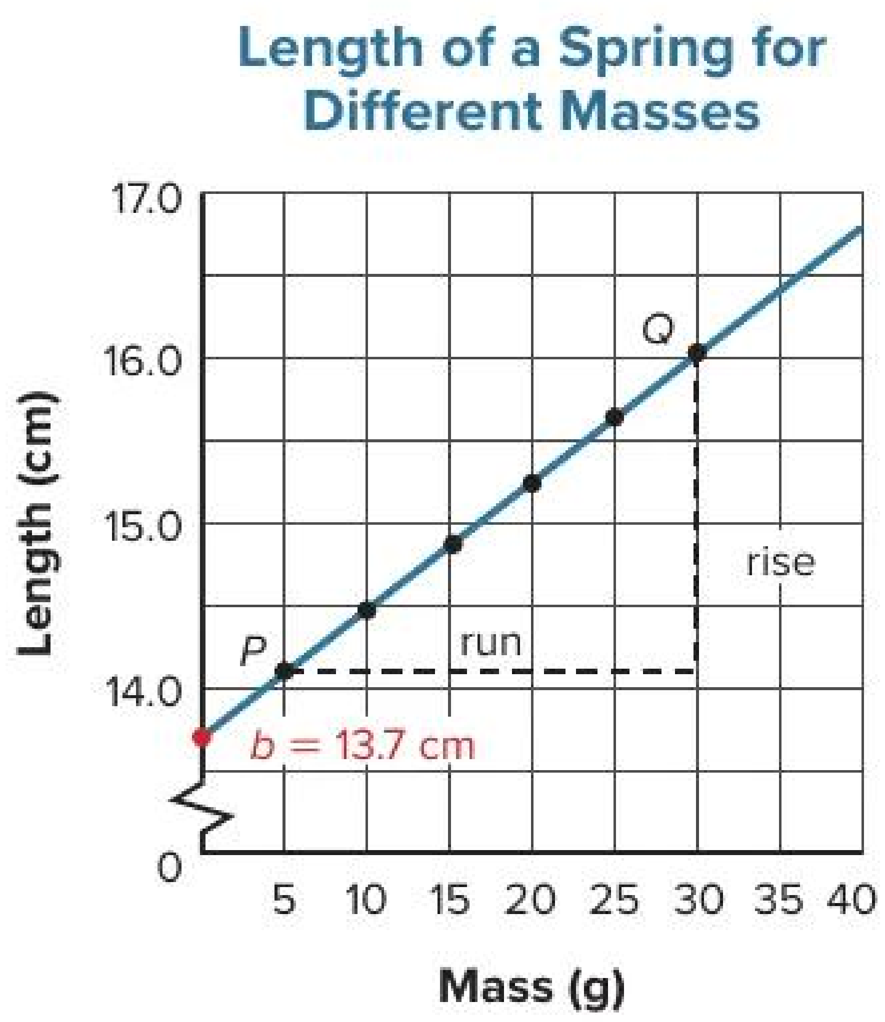


Figure 16 In a linear relationship, the dependent variable—in this case, length—varies linearly with the independent variable. The independent variable in this experiment is mass.

Describe *What happens to the length of the spring as mass decreases?*

Linear Relationships

Scatter plots of data take many different shapes, suggesting different relationships. Three of the most common relationships are linear relationships, quadratic relationships, and inverse relationships. You probably are familiar with them from math class.

When the line of best fit is a straight line, as in **Figure 15,** there is a linear relationship between the variables. In a **linear relationship,** the dependent variable varies linearly with the independent variable. The relationship can be written as the following equation.

Linear Relationship Between Two Variables

$$y = mx + b$$

Here, m is the slope of the line, or the ratio of the vertical change to the horizontal change, and b is the y-intercept, the point at which the line crosses the vertical axis. To find the slope, select two points, P and Q, far apart on the line—they may or may not be data points. The vertical change, or rise (Δy), is the difference between the vertical values of P and Q, as shown in **Figure 16.** The horizontal change, or run (Δx), is the difference between the horizontal values of P and Q.

Slope

The slope of a line is equal to the rise divided by the run, which also can be expressed as the vertical change divided by the horizontal change.

$$m = \frac{rise}{run} = \frac{\Delta y}{\Delta x}$$

In **Figure 16:** $m = \frac{(16.0 \text{ cm} - 14.1 \text{ cm})}{(30 \text{ g} - 5 \text{ g})} = 0.08 \text{ cm/g}$

If y gets smaller as x gets larger, then $\frac{\Delta y}{\Delta x}$ is negative, and the line slopes downward from left to right. The y-intercept, or the y-value when the value of x is zero, in this example is $b = 13.7$ cm (**Figure 16**). So, when no mass is suspended by the spring, it has a length of 13.7 cm. When $b = 0$, or $y = mx$, y is said to vary directly with x. In physics, the slope of the line and the y-intercept always contain information about the physical system that is described by the graph.

Nonlinear Relationships

Figure 17 graphs the distance a brass ball falls versus time. Note that the graph is not a straight line, meaning the relationship is not linear. There are many types of nonlinear relationships in science. Two of the most common are quadratic and inverse relationships.

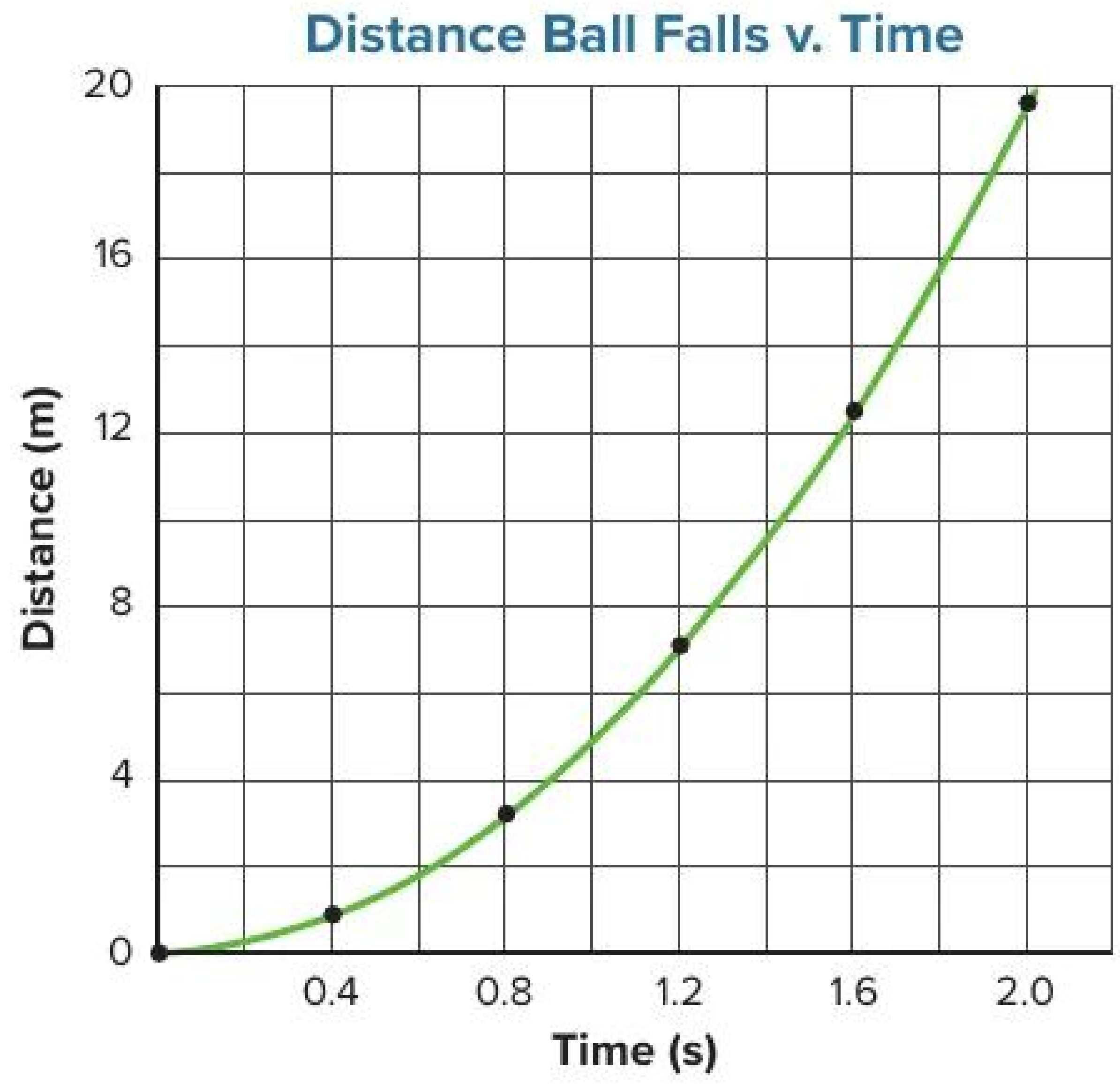


Figure 17 The quadratic, or parabolic, relationship shown here is an example of a nonlinear relationship.

Quadratic relationships

The graph in **Figure 17** is a quadratic relationship, represented by the equation below. A **quadratic relationship** exists when one variable depends on the square of another.

Quadratic Relationship Between Two Variables

$$y = ax^2 + bx + c$$

A computer program or graphing calculator can easily find the values of the constants a, b, and c in the above equation. In **Figure 17,** the equation is $d = 5t^2$. See the Math Skill Handbook in the back of this book or online for more on making and using line graphs.

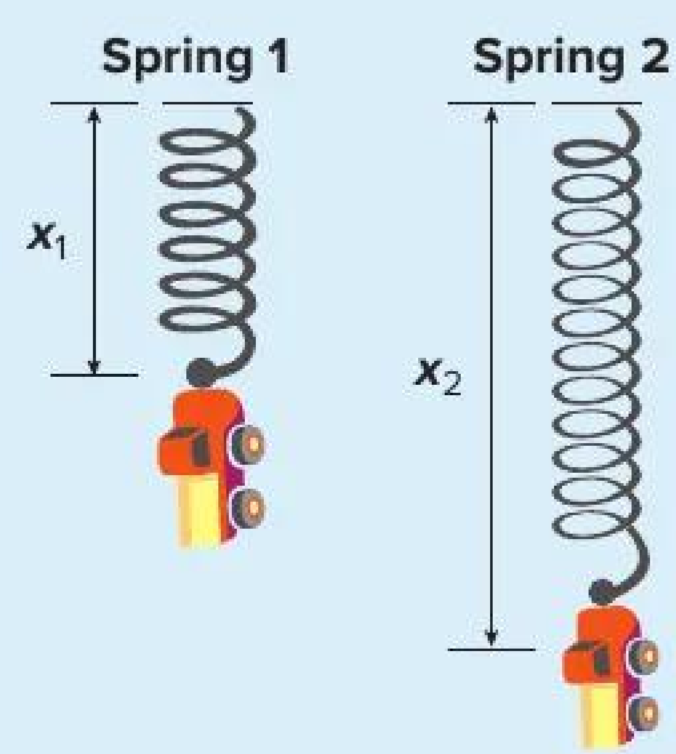
Get It?

Explain how two variables are related to each other in a quadratic relationship.

PHYSICS Challenge

An object is suspended from spring 1, and the spring's elongation (the distance it stretches) is x_1. Then the same object is removed from the first spring and suspended from a second spring. The elongation of spring 2 is x_2. x_2 is greater than x_1.

1. On the same axes, sketch the graphs of the mass versus elongation for both springs.
2. Should the origin be included in the graph? Why or why not?
3. Which slope is steeper?
4. At a given mass, $x_2 = 1.6\ x_1$. If $x_2 = 5.3$ cm, what is x_1?



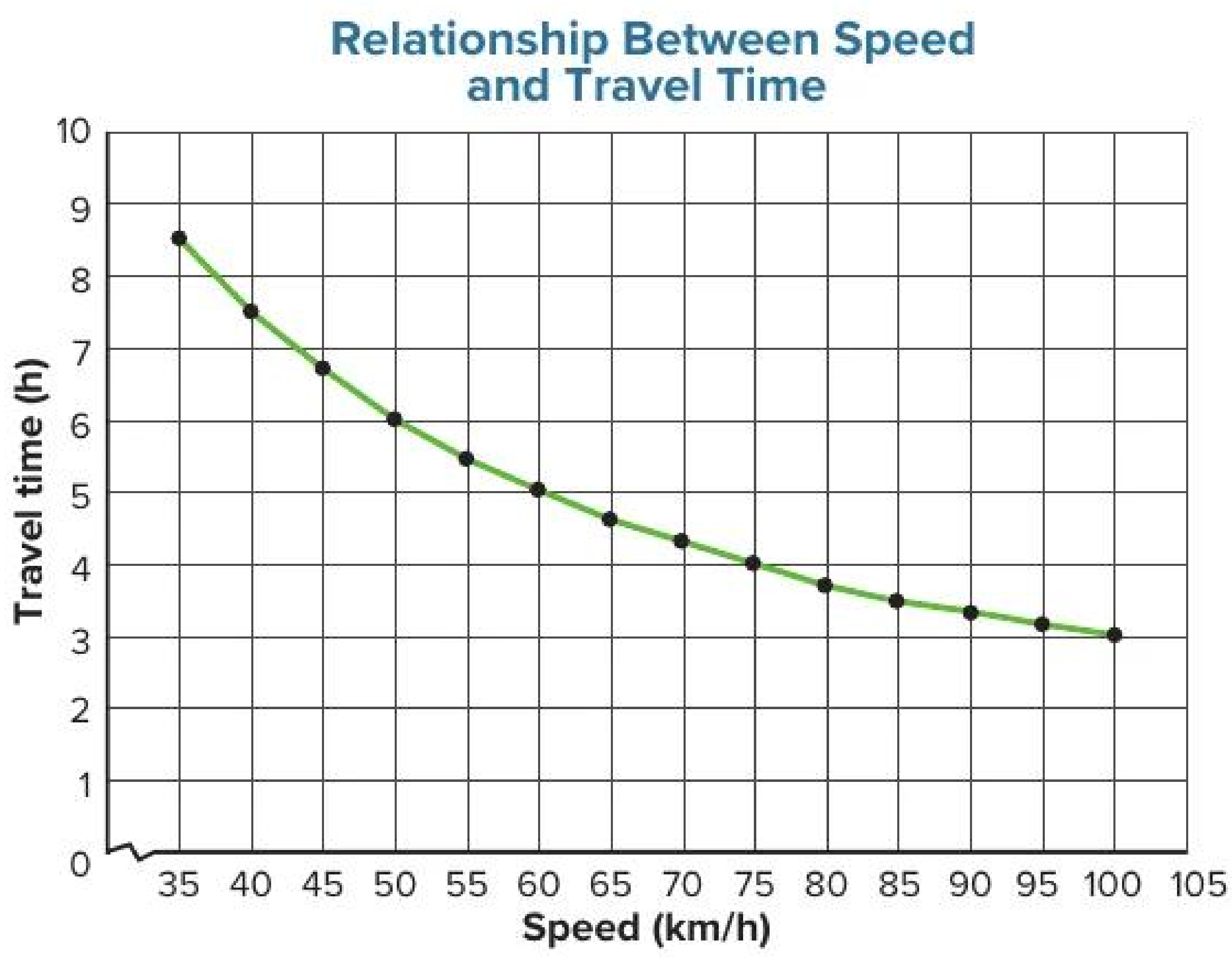


Figure 18 This graph shows the inverse relationship between speed and travel time.

Describe *How does travel time change as speed increases?*

Inverse relationships

The graph in **Figure 18** shows how the time it takes to travel 300 km varies as a car's speed increases. This is an example of an inverse relationship, represented by the equation below. An **inverse relationship** is a hyperbolic relationship in which one variable depends on the inverse of the other variable.

Inverse Relationship Between Two Variables

$$y = \frac{a}{x}$$

The three relationships you have learned about are a sample of the relations you will most likely investigate in this course. Many other mathematical models are used. Important examples include sinusoids, used to model cyclical phenomena, and exponential growth and decay, used to study radioactivity. Combinations of different mathematical models represent even more complex phenomena.

Get It?

Explain how two variables are related to each other in an inverse relationship.

PRACTICE Problems

ADDITIONAL PRACTICE

18. Refer to the data listed in **Table 4.**

a. Plot mass versus volume, and draw the curve that best fits all points. Describe the curve.

b. What type of relationship exists between the mass of the gold nuggets and their volume?

c. What is the value of the slope of this graph? Include the proper units.

d. Write the equation showing mass as a function of volume for gold.

e. Write a word interpretation for the slope of the line.

Table 4 Mass of Pure Gold Nuggets

Volume (cm^3)	Mass (g)
1.0	19.4
2.0	38.6
3.0	58.1
4.0	77.4
5.0	96.5

Predicting Values

When scientists discover relationships like the ones shown in the graphs in this lesson, they use them to make predictions. For example, the equation for the linear graph in **Figure 16** is as follows:

$$y = (0.08 \text{ cm/g})x + 13.7 \text{ cm}$$

Relationships, either learned as formulas or developed from graphs, can be used to predict values you haven't measured directly. How far would the spring in **Table 3** stretch with 49 g of mass?

$$y = (0.08 \text{ cm/g})(49 \text{ g}) + 13.7 \text{ cm}$$
$$= 18 \text{ cm}$$

It is important to decide how far you can extrapolate from the data you have. For example, 90 g is a value far outside the ones measured and displayed in **Table 3,** and the spring might break rather than stretch that far.

Physicists use models to accurately predict how systems will behave: what circumstances might lead to a solar flare (an immense outburst of material from the Sun's surface into space) or how changes to a grandfather clock's pendulum will change its ability to keep accurate time. People in all walks of life use models in many ways. One example is shown in **Figure 19.** With the tools you have learned in this module, you can answer questions and produce models for the physics questions you will encounter in the rest of this textbook.

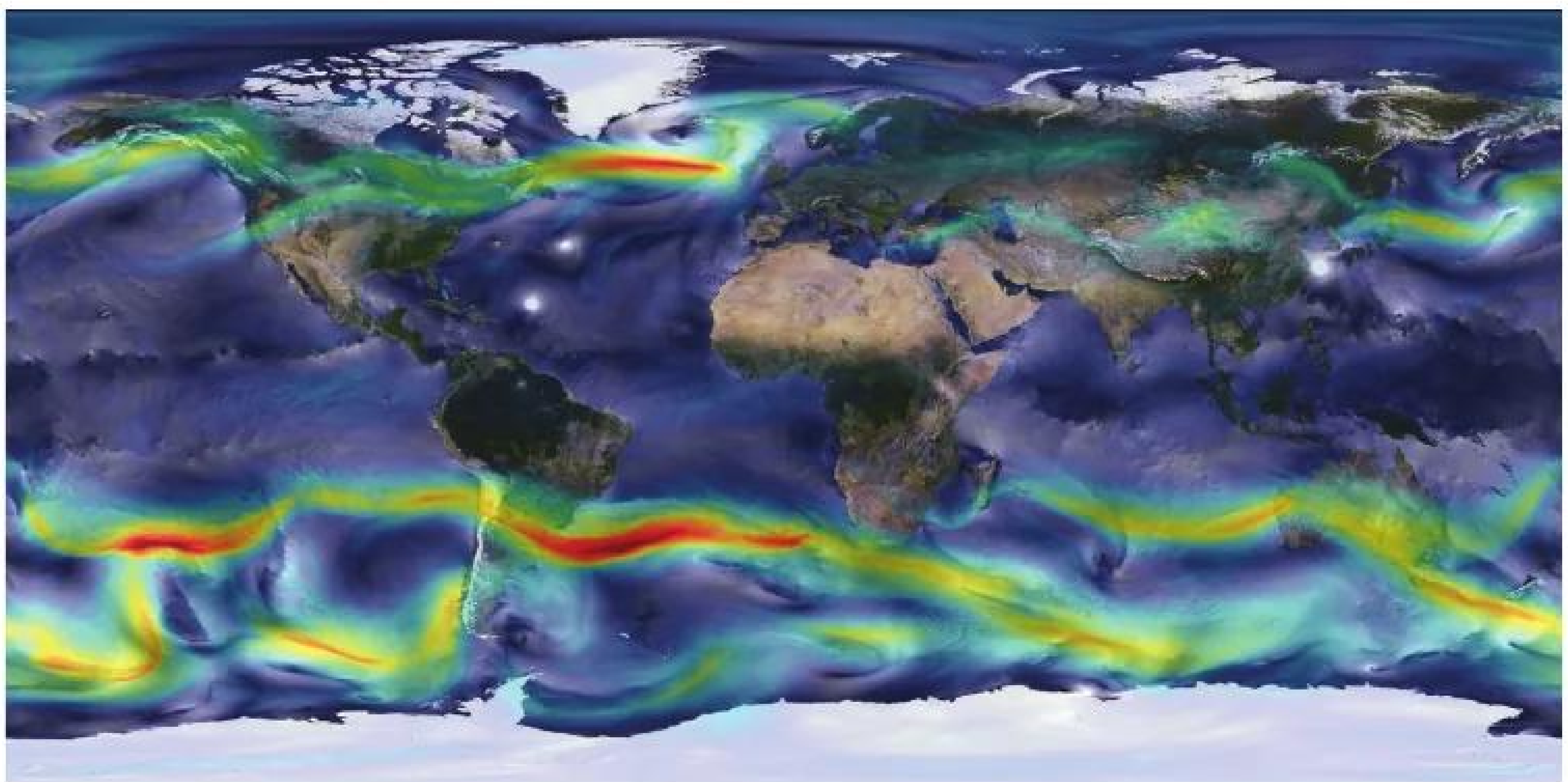


Figure 19 In order to create a realistic model, computer animators use mathematical models of the real world to help visualize global atmospheric conditions.

Check Your Progress

19. **Make a Graph** Graph the following data. Time is the independent variable.

Time (s)	0	5	10	15	20	25	30	35
Speed (m/s)	12	10	8	6	4	2	2	2

20. **Interpret a Graph** What would be the meaning of a nonzero *y*-intercept in a graph of total mass versus volume?

21. **Predict** Use the relationship illustrated in **Figure 16** to determine the mass required to stretch the spring 15 cm.

22. **Predict** Use the relationship shown in **Figure 18** to predict the travel time when speed is 110 km/h.

23. **Critical Thinking** Look again at the graph in **Figure 16.** In your own words, explain how the spring would be different if the line in the graph were shallower or had a smaller slope.

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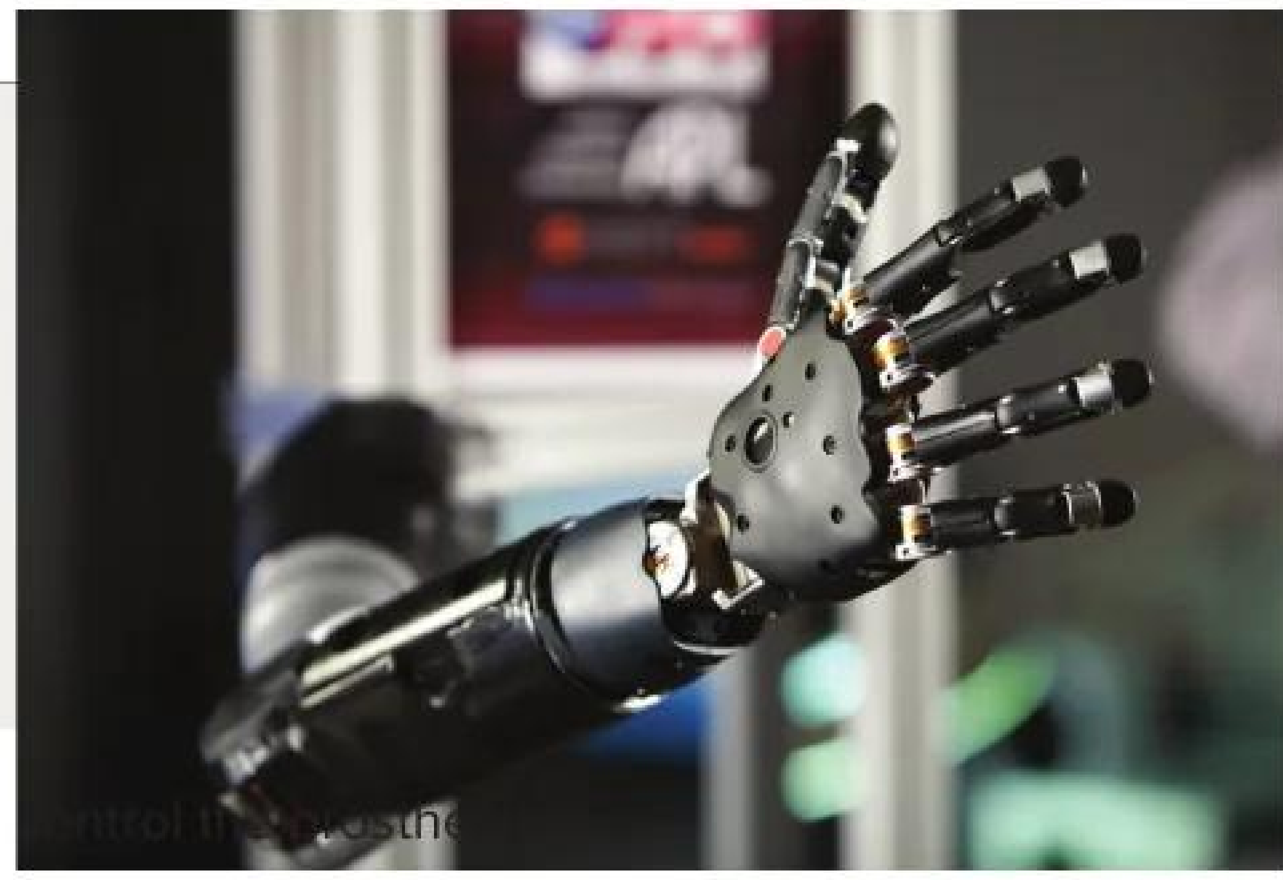
ENGINEERING & TECHNOLOGY

A Step in the Right Direction

Prosthetics, or artificial body parts, have been in use since ancient Greek times. Most prostheses of the past, however, were more decorative than functional. They were made mainly of metal and wood, and were attached to the body with straps or harnesses made of leather. Prosthetics have come a long way over the last few decades. Today's prosthetic limbs can transform people's lives.



Some prosthetics can be attached directly to the patient's body, rather than being attached with slings or harnesses.

New materials, new look

The prostheses of today look and function more like biological limbs than ever before. The inner structure of a prosthesis, called a pylon, is now commonly made of carbon-fiber composites and new types of plastics. These materials make the prosthesis stronger, but also lighter, than metal or wood prostheses.

Electronic components give users better control over a prosthesis. For example, myoelectric prostheses use the electric signals generated by muscles to control a prosthesis. A person with a myoelectric prosthetic hand can move muscles in his or her arm to signal the hand to move or grip in different ways, with varying amounts of force.

Targeted muscle reinnervation (TMR) is another new method of giving people more control over cutting-edge prostheses, specifically arms. The nerves in a person's residual limb, which once controlled the amputated limb, are surgically "reassigned" to

Another game-changing advance in prosthetic technology is a change in the socket, the part of a prosthesis that connects to a person's residual limb. When prostheses are attached with slings or harnesses, the socket is sometimes uncomfortable. It can cause sores, blisters, and pain, and it can damage the tissues under the skin. To combat this problem, some new prostheses are mounted directly into the bone marrow of a person's residual limb. This method of attachment increases the person's comfort, as well as his or her control of the prosthesis.

Some prosthetic advances are still making the transition from prototypes to patient care. But scientists are determined to speedily move these new technologies into the everyday lives of patients.

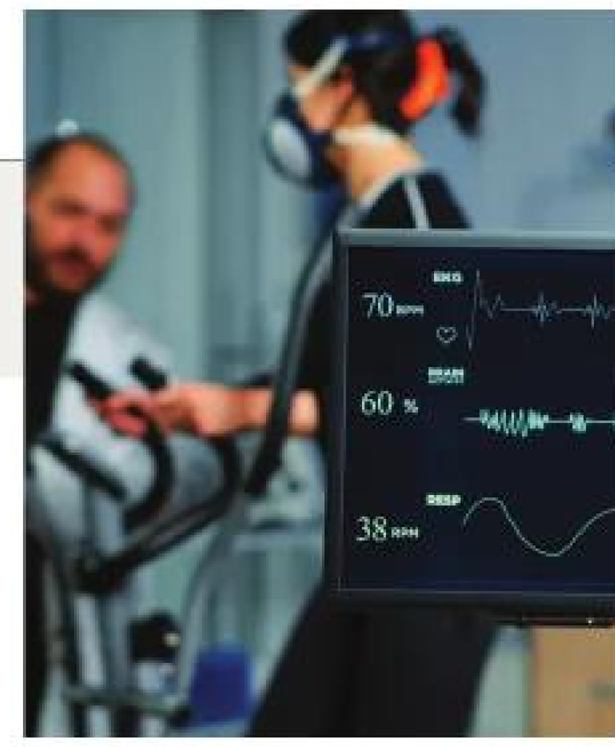
COMMUNICATE TECHNICAL INFORMATION

Use print or online sources to research an advance in prosthetics that was not discussed in this feature. Share the results of your research with your class.

STEM AT WORK

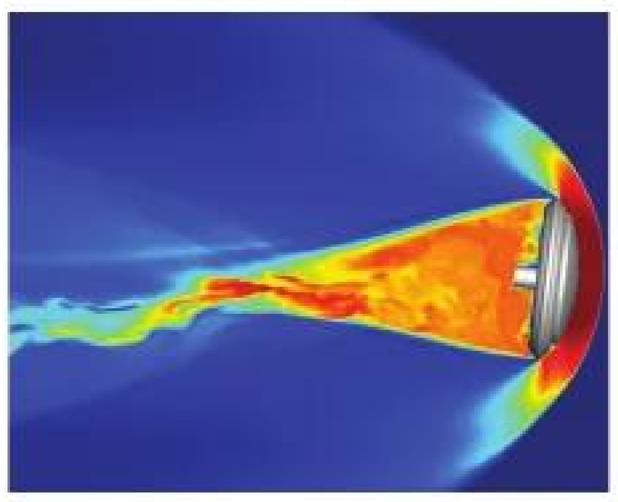
What do physicists study?

Physicist study a wide range of topics from the tiniest particles to stars, galaxies, and the universe itself.



Mechanics is the branch of physics that studies motion and forces.

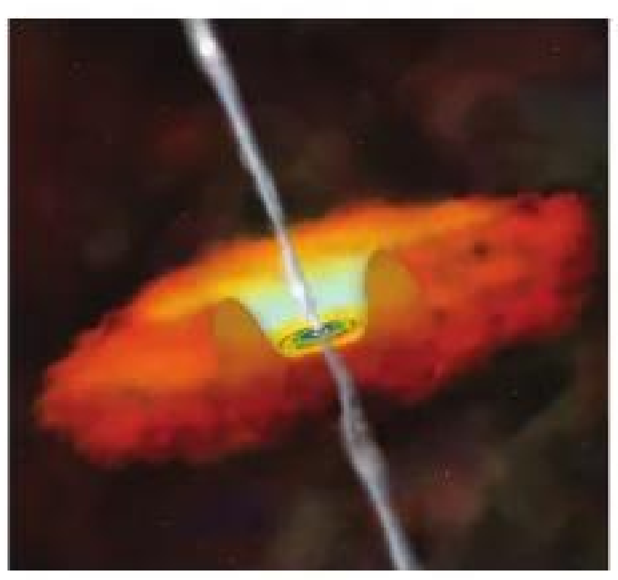
Physicists often work with other branches of science. For example, geophysics is the study of Earth's physical properties and processes. Another area of collaboration is biomechanics, which is the study of the motion of living things. The researcher in the photo at the right is collecting data about the motion of an athlete.



Thermodynamics is the study of the energy of a system's particles. It includes the study of temperature, heat, and the relationship between the characteristics of a system's particles and the macroscopic characteristics of the system. Because systems contain very large numbers of particles, physics often use computer models to study thermodynamics. The NASA model on the left allows scientists to predict how heat shields will perform in the atmosphere.

Electromagnetism is the study of electricity, magnetism, and the relationship between them. By understanding how currents produce magnetic fields, physicists and engineers can design and build electromagnets, like the one on the right.

Nuclear and Particle Physics Nuclear physicists study the atomic nucleus. Particle physicists will use this superconducting electromagnet in a particle accelerator to study even smaller structures—the elementary particles that make up universe.



Optics is the study of the generation, transmission, and detection of visible, infrared, ultraviolet, and microwave radiation.

Astrophysics and Cosmology are, respectively, the study of the physical properties of celestial bodies such as the active galactic nucleus on the left and the development and overall structure of the universe.

OBTAIN AND COMMUNICATE INFORMATION

Choose one of the fields of physics that interests you. Research your chosen field, and identify a related career, what a person does in that career, and the types of education and training required. Develop a presentation in which you are recruiting candidates for a job opening in that career.

(t to b, l to r)DC Studio/Shutterstock; Joe Brock, NASA Ames Research Center; Cultura Creative(RF)/Alamy Stock Photo; NASA/CXC/M.Weiss

MODULE 1
STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 METHODS OF SCIENCE

- Scientific methods include making observations and asking questions about the natural world.
- Scientists use models to represent things that may be too small or too large, processes that take too much time to see completely, or a material that is hazardous.
- A scientific theory is an explanation of things or events based on knowledge gained from observations and investigations. A scientific law is a statement about what happens in nature, which seems to be true all the time.
- Science can't explain or solve everything. Questions about opinions and values cannot be tested.

- physics
- scientific methods
- hypothesis
- model
- scientific theory
- scientific law

Lesson 2 MATHEMATICS AND PHYSICS

- Using SI, an adaptation of the metric system, helps scientists around the world communicate more easily.
- Dimensional analysis is used to check that an answer is in the correct units.
- Significant figures are the valid digits in a measurement.

- dimensional analysis
- significant figures

Lesson 3 MEASUREMENT

- Measurements are reported with uncertainty because a new measurement that is within the margin of uncertainty confirms the old measurement.
- Precision is the degree of exactness with which a quantity is measured. Accuracy is the extent to which a measurement matches the true value.
- A common source of error that occurs when making a measurement is the angle at which an instrument is read. If the scale of an instrument is read at an angle, as opposed to at eye level, the measurement will be less accurate.

- measurement
- precision
- accuracy

Lesson 4 GRAPHING DATA

- Graphs contain information about the relationships between variables. Patterns that are not immediately evident in a list of numbers are seen more easily when the data are graphed.
- Common relationships shown in graphs are linear relationships, quadratic relationships, and inverse relationships. In a linear relationship, the dependent variable varies linearly with the independent variable. A quadratic relationship occurs when one variable depends on the square of another. In an inverse relationship, one variable depends on the inverse of the other variable.
- Scientists use models and relationships between variables to make predictions.

- independent variable
- dependent variable
- line of best fit
- linear relationship
- quadratic relationship
- inverse relationship

THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

What tools and skills do physicists use?

CER Claim, Evidence, Reasoning

Explain Your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

GO FURTHER

SEP Data Analysis Lab

How is string length and square of the period of a pendulum related?

A group of students planned and carried out an investigation into the relationship between string length L and the time it took for one complete swing of a pendulum (its period) T.

Data and Observations Their measurements are given in the table.

String Length L (m)	Period T (s)
0.07	0.53
0.10	0.63
0.20	0.90
0.40	1.27
0.55	1.49
0.70	1.68
0.90	1.90

CER Analyze and Interpret Data

One of the students used the data to investigate the relationship between the string length L and the square of the period T^2.

1. **Calculate and record** the values of T^2.
2. **Construct a Model** Plot the values of L and T^2 and draw the best-fit curve. Write an equation that describes the curve.
3. **Claim** What is the relationship between the square of the period of a pendulum and the length of the string?
4. **Evidence and Reasoning** Use your graph as evidence and

Aurora Photos/Alamy Stock Photo

MODULE 2

REPRESENTING MOTION

ENCOUNTER THE PHENOMENON

How does a GPS unit know where you are?

GO ONLINE to play a video about how GPS works.

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

CER Claim, Evidence, Reasoning

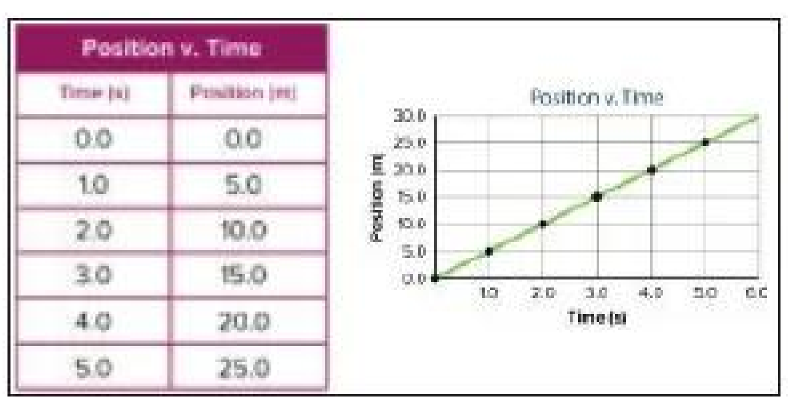
Make Your Claim Use your CER chart to make a claim about how a GPS unit knows where you are. Explain your reasoning.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.

LESSON 2: Explore & Explain: Coordinates and Vectors



LESSON 3: Explore & Explain: Velocity and Speed

Smithsonian

Additional Resources

LESSON 1
PICTURING MOTION

FOCUS QUESTION

How do you know that something is moving?

All Kinds of Motion

You have learned about scientific processes that will be useful in your study of physics. You will now begin to use these tools to analyze motion. In subsequent modules, you will apply these processes to many kinds of motion. You will use words, sketches, diagrams, graphs, and equations.

Changes in position What comes to your mind when you hear the word motion? A spinning ride at an amusement park? A baseball soaring over a fence for a home run? Motion is all around you—from fast trains and speedy skiers to slow breezes and lazy clouds. Objects move in many different ways, such as the straight-line path of a bowling ball in a bowling lane's gutter, the curved path of a car rounding a turn, the spiral of a falling kite, and swirls of water circling a drain. When an object is in motion, such as the train in **Figure 1,** its position changes.

Some types of motion are more complicated than others. When beginning a new area of study, it is generally a good idea to begin with the least complicated situation, learn as much as possible about it, and then gradually add more complexity to that simple model. In the case of motion, you will begin your study with movement along a straight line.

Ingram Publishing

Figure 1 The train appears blurry in the photograph because its position changed during the time the camera shutter was open.

Get It?

Describe how the picure in **Figure 1** would be different if the train were sitting still.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Motion Diagrams

Use a model to identify patterns in motion.

Review the News

Obtain information from a current news story about motion capture technology. Evaluate your source and communicate your findings to your class.

Movement along a straight line

In general, an object can move along many different kinds of paths, but straight-line motion follows a path directly between two points without turning left or right. For example, you might describe an object's motion as forward and backward, up and down, or north and south. In each of these cases, the object moves along a straight line.

Suppose you are reading this textbook at home. As you start to read, you glance over at your pet hamster and see that it is sitting in a corner of the cage. Sometime later you look over again, and you see that it now is sitting next to the food dish in the opposite corner of the cage. You can infer that your hamster has moved from one place to another in the time between your observations. What factors helped you make this inference about the hamster's movement?

The description of motion is a description of place and time. You must answer the questions of where an object is located and when it is at that position in order to describe its motion.

Get It?

Identify two factors you must know to describe the motion of an object along a straight line.

Motion Diagrams

Consider the following example of straight-line motion: a runner jogs along a straight path. One way of representing the runner's motion is to create a series of images showing the runner's position at equal time intervals. You can do this by photographing the runner in motion to obtain a sequence of pictures. Each photograph will show the runner at a point that is farther along the straight path.

Consecutive images

Suppose you point a camera in a direction and a runner crosses the camera's field of view. Then you take a series of photographs of the runner at equal time intervals, without moving the camera. **Figure 2** shows what a series of consecutive images for a runner might look like. Notice that the runner is in a different position in each image, but everything in the background remains in the same position. This indicates that, relative to the camera and the ground, only the runner is in motion.

Figure 2 You can tell that the runner is in motion because her position changes relative to the tree and the ground.

Richard Hutchings/Digital Light Source

Combining images Suppose that you layered the four images of the runner from **Figure 2** one on top of the other, as shown in **Figure 3**. A series of images showing the positions of a moving object at equal time intervals is called a **motion diagram.**

Particle Models

Keeping track of the runner's motion is easier if you disregard the movement of her arms and her legs and instead concentrate on a single point at the center of her body. In a **particle model,** you replace the object or objects with single points.

To use the particle model, the object's size must be much less than the distance it moves. In the photographic motion diagram, you could identify a central point at her waistline, and draw a dot to represent the position at different times. The bottom of **Figure 3** shows the particle model for the runner's motion.

Get It?

Describe how you would model the motion of the hiker at the beginning of this module.

Figure 3 Combining the images from **Figure 2** produces this motion diagram of the runner's movement. The series of dots at the bottom of the figure is a particle model that corresponds to the motion diagram.

Explain *how the particle model shows that the runner's speed is not changing.*

Check Your Progress

1. **Representing Motion** How does a motion diagram represent an object's motion?
2. **Bike Motion Diagram** Draw a particle model motion diagram for a bike rider moving at a constant pace along a straight path.
3. **Car Motion Diagram** Draw a particle motion diagram corresponding to the motion in **Figure 4** for a car coming to a stop at a stop sign. What point on the car did you use to represent the car?

Figure 4

4. **Bird Motion Diagram** Draw a particle model motion diagram corresponding to the motion diagram in **Figure 5.** What point on the bird did you choose to represent the bird?

Figure 5

5. **Critical Thinking** Draw particle model motion diagrams for two runners during a race in which the first runner crosses the finish line as the other runner is three-fourths of the way to the finish line.

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LESSON 2

WHERE AND WHEN?

FOCUS QUESTION

What are some different ways of describing and representing motion?

Coordinate Systems

Is it possible to measure distance and time on a motion diagram? Before photographing a runner, you could place a long measuring tape on the ground to show where the runner is in each image. A stop-watch within the camera's view could show the time. But where should you place the end of the measuring tape? When should you start the stopwatch?

Position and distance It is useful to identify a system in which you have chosen where to place the zero point of the measuring tape and when to start the stopwatch. A **coordinate system** gives the location of the zero point of the variable you are studying and the direction in which the values of the variable increase, as shown in the diagram in **Figure 6.**

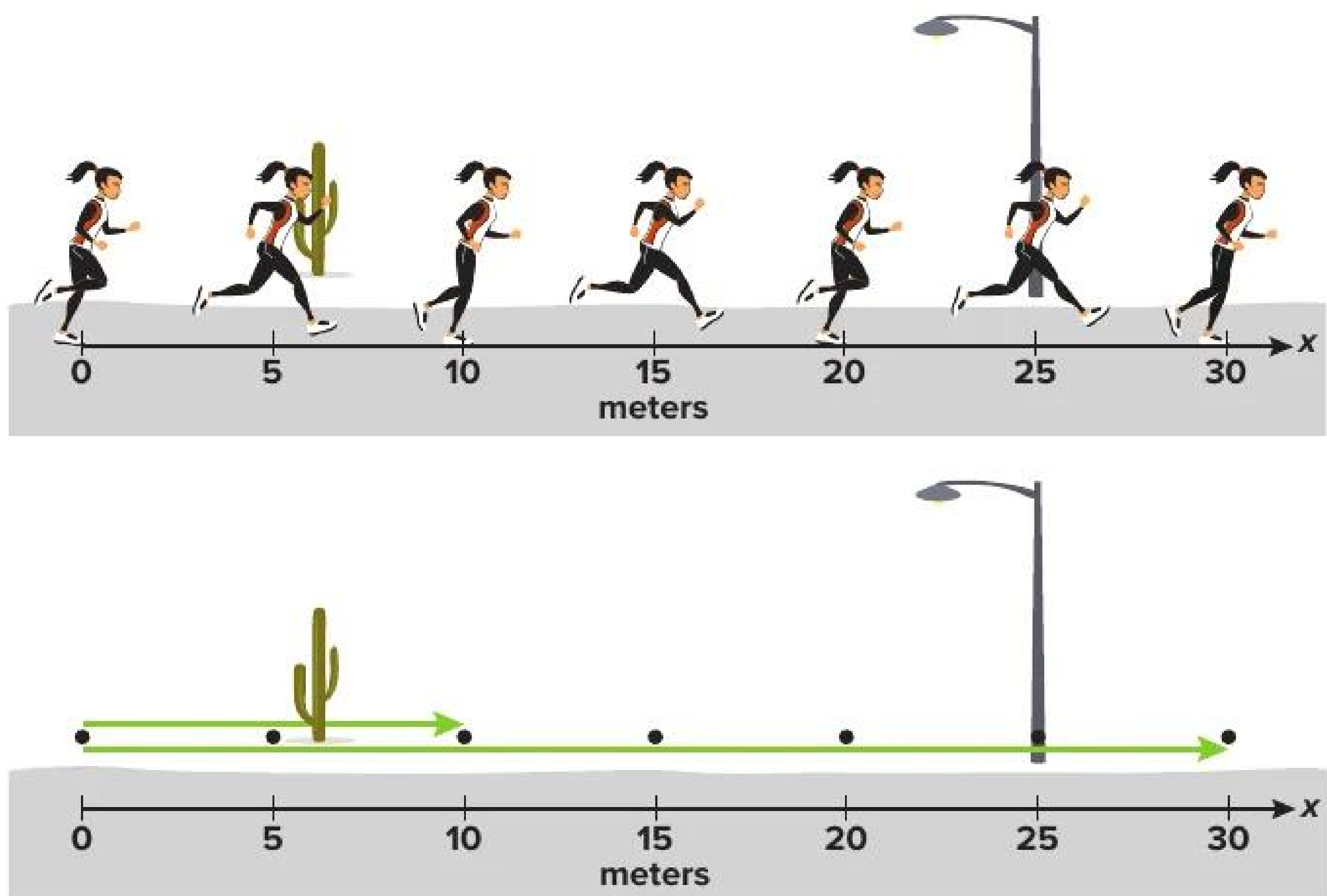


Figure 6 A simplified motion diagram uses dots to represent a moving object and arrows to indicate positions.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Quick Investigation: Vector Models
Develop and use a model to visualize the result of adding vector quantities in one dimension.

Revisit the Encounter the Phenomenon Question
What information from this lesson can help you answer the Unit and Module questions?

The **origin** is the point at which all variables in a coordinate system have the value zero. In the example of the runner shown in **Figure 6,** the origin, which is the zero point of the measuring tape, could be 6 m to the left of the cactus. Because the motion is in a straight line, your measuring tape should lie along this line. The straight line is an axis of the coordinate system.

You can indicate how far the runner in **Figure 6** is from the origin at a certain time on the motion diagram by drawing an arrow from the origin to the point that represents the runner, shown at the bottom of **Figure 6**. This arrow represents the runner's **position,** the distance and direction from the origin to the object. In general, **distance** is the entire length of an object's path, even if the object moves in many directions. Because the motion in **Figure 6** is in one direction, the arrow lengths represent distance.

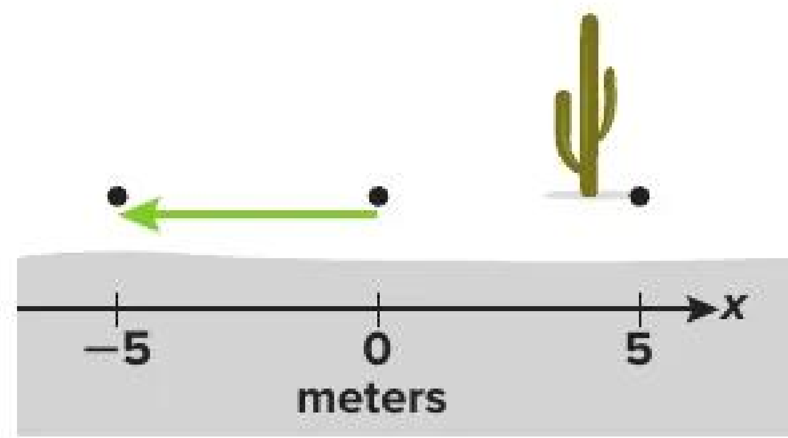


Figure 7 The green arrow indicates a negative position of −5 m, if the direction right of the origin is chosen as positive.

Infer *What position would the arrow indicate if you chose the direction left of the origin as positive?*

Negative position

Is there such a thing as a negative position? Suppose you chose the coordinate system just described but this time placed the origin 4 m left of the cactus with the *x*-axis extending in a positive direction to the right. A position 9 m left of the cactus, or 5 m left of the origin, would be a negative position, as shown in **Figure 7.**

Get It?
Explain how positive and negative positions are determined.

Vectors and Scalars

As you might imagine, there are many kinds of measurements and numbers used to represent or describe motion. If you needed to describe how far you ran, you might say that you ran 1.6 km. If you needed to run to a specific location, you might say that you need to run 1.6 km north. Many quantities in physics have both size, also called **magnitude,** and direction. A quantity that has both magnitude and direction is called a **vector.** You can represent a vector with an arrow. The length of the arrow represents the magnitude of the vector, and the direction of the arrow represents the direction of the vector. A quantity that is just a number without any direction, such as distance, time, or temperature, is called a **scalar.** In this textbook, we will use boldface letters to represent vector quantities and regular letters to represent scalars.

Get It?
Describe the difference between a vector and a scalar.

SCIENCE USAGE V. COMMON USAGE

Magnitude
Science usage: a measure of size
When drawing vectors, the magnitude of a vector is proportional to that vector's length.
Common usage: great size or extent
The magnitude of the Grand Canyon is difficult to capture in photographs.

CCC CROSSCUTTING CONCEPTS

Systems and System Models Vectors represent a form of modeling. With a partner, create a vector drawing representing motion from one location to another. Add explanations to your drawing that explain how your motion was modeled.

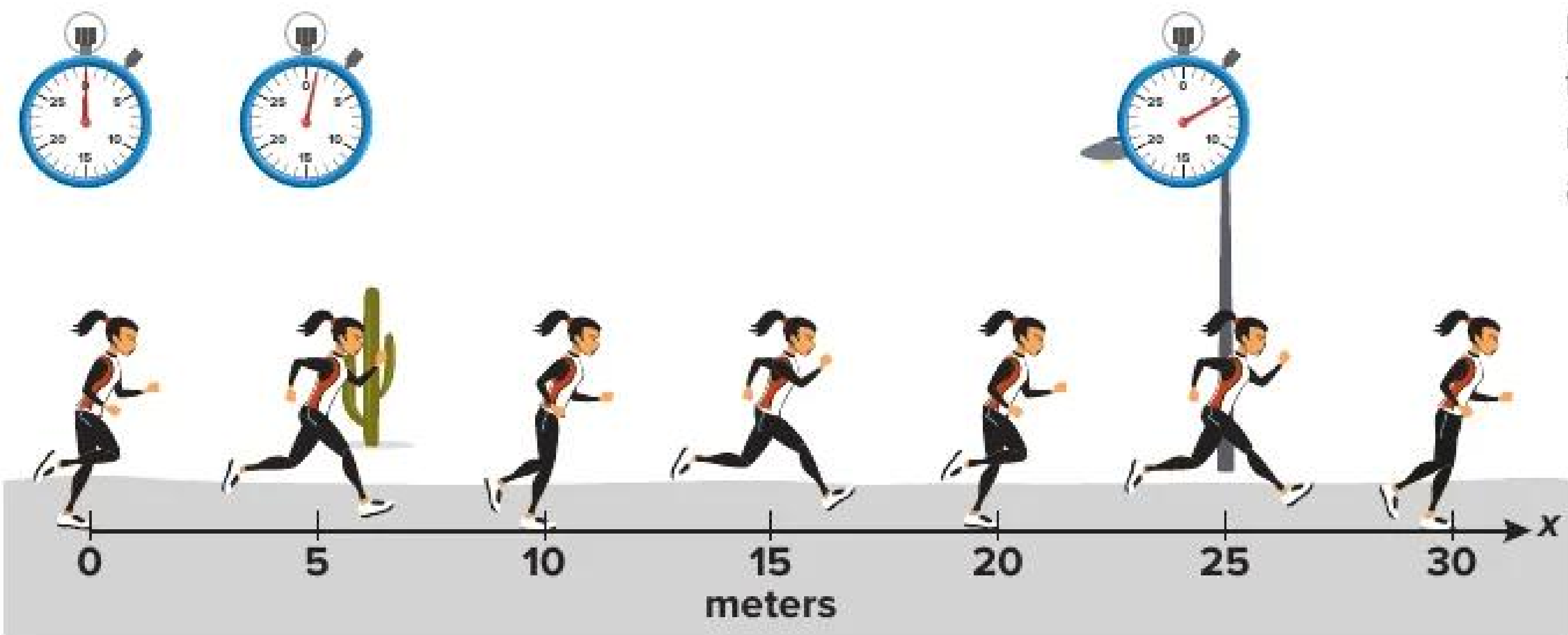


Figure 8 You can use the clocks in the figure to calculate the time interval (Δt) for the runner's movement from one position to another.

Time intervals are scalars. When analyzing the runner's motion in **Figure 8,** you might want to know how long it took her to travel from the cactus to the lamppost. You can obtain this value by finding the difference between the stopwatch reading at the cactus and the stopwatch reading at the lamppost. **Figure 8** shows these stopwatch readings. The difference between two times is called a **time interval.**

A common symbol for a time interval is Δt, where the Greek letter delta (Δ) is used to represent a change in a quantity. Let t_i represent the initial (starting) time, when the runner was at the cactus. Let t_f represent the final (ending) time of the interval, when the runner was at the lamppost. We define a time interval mathematically as follows.

Time Interval

The time interval is equal to the change in time from the initial time to the final time.

$$\Delta t = t_f - t_i$$

The subscripts i and f represent the initial and final times, but they can be the initial and final times of any time interval you choose. In the example of the runner, the time it takes for her to go from the cactus to the lamppost is $t_f - t_i = 5.0\text{ s} - 1.0\text{ s} = 4.0\text{ s}$. You could instead describe the time interval for the runner to go from the origin to the lamppost. In this case, the time interval would be $t_f - t_i = 5.0\text{ s} - 0.0\text{ s} = 5.0\text{ s}$. The time interval is a scalar because it has no direction. Is the runner's position a scalar?

Positions and displacements are vectors. You have already seen how a position can be described as negative or positive in order to indicate whether that position is to the left or the right of a coordinate system's origin. This suggests that position is a vector because position has direction—either right or left in this case.

STEM CAREER Connection

Geographic Information Systems (GIS) Manager

Would you like to work with computers, maps, and logistics? Then, a GIS manager might be a career for you. GIS managers work with teams that produce geographical information systems that are used for road traffic management, health care delivery, defense planning, market research, and community services such as garbage collection and utilities delivery.

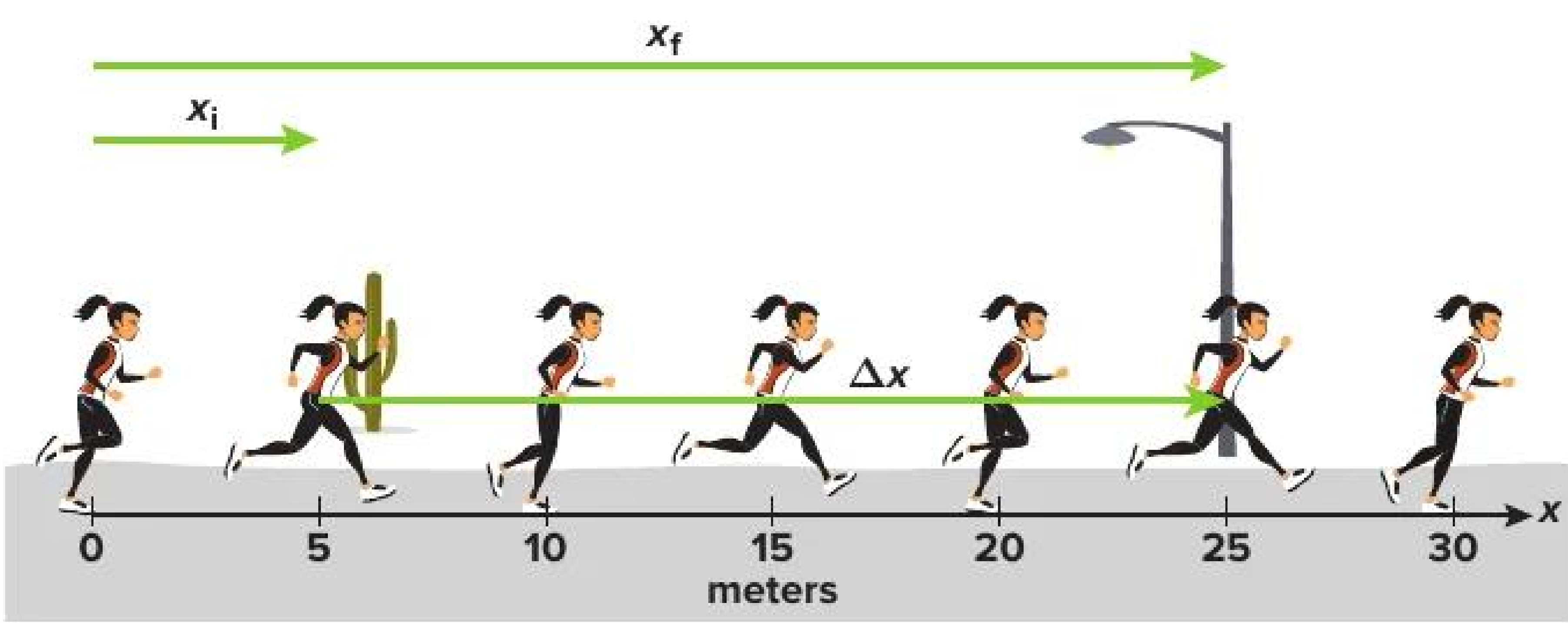


Figure 9 The vectors $\boldsymbol{x}_i$ and $\boldsymbol{x}_f$ represent positions. The vector $\Delta \boldsymbol{x}$ represents displacement from $\boldsymbol{x}_i$ to $\boldsymbol{x}_f$.

Describe *the displacement from the lamppost to the cactus.*

Figure 9 shows the position of the runner at both the cactus and the lamppost. Notice that you can draw an arrow from the origin to the location of the runner in each case. These arrows have magnitude and direction. In common speech, a position refers to a certain place, but in physics, the definition of a position is more precise. A position is a vector with the arrow's tail at the origin of a coordinate system and the arrow's tip at the place.

You can use the symbol $\boldsymbol{x}$ to represent position vectors mathematically. In **Figure 9**, the symbol $\boldsymbol{x}_i$ represents the position at the cactus, and the symbol $\boldsymbol{x}_f$ represents the position at the lamppost. The symbol $\Delta \boldsymbol{x}$ represents the change in position from the cactus to the lamppost. Because a change in position is described and analyzed so often in physics, it has a special name. In physics, a change in position is called a **displacement.** Because displacement has both magnitude and direction, it is a vector.

What was the runner's displacement when she ran from the cactus to the lamppost? By looking at **Figure 9**, you can see that this displacement is 20 m to the right. Notice also, that the displacement from the cactus to the lamppost ($\Delta \boldsymbol{x}$) equals the position at the lamppost ($\boldsymbol{x}_f$) minus the position at the cactus ($\boldsymbol{x}_i$). This is true in general; displacement equals final position minus initial position.

Displacement

Displacement is the change in position from initial position to final position.

$$\Delta \boldsymbol{x} = \boldsymbol{x}_f - \boldsymbol{x}_i$$

Remember that the initial and final positions are the start and the end of any interval you choose. Although position is a vector, sometimes the magnitude of a position is described without the boldface. In this case, a plus or minus sign might be used to indicate direction.

Vector addition and subtraction You will learn about many different types of vectors in physics, including velocity, acceleration, and momentum. Often, you will need to find the sum of two vectors or the difference between two vectors. A vector that represents the sum of two other vectors is called a **resultant.** **Figure 10** on the next page shows how to add and subtract vectors in one dimension. In a later module, you will learn how to add and subtract vectors in two dimensions.

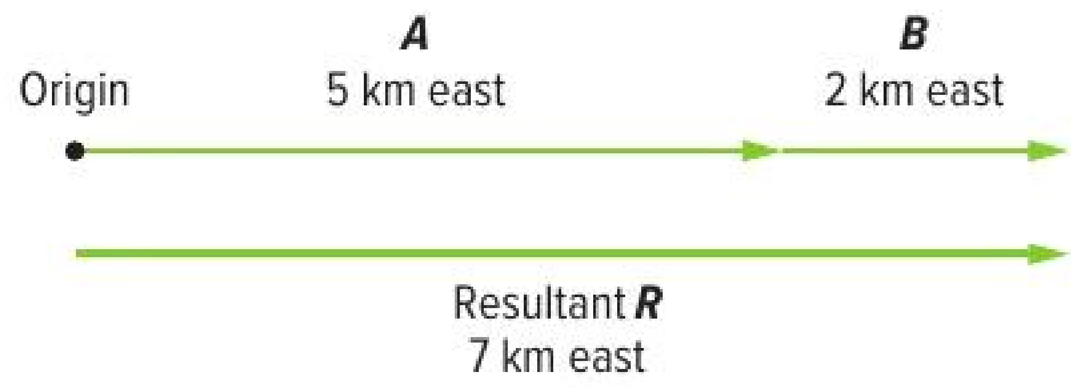
Figure 10 You can use a diagram or an equation to combine vectors.

Analyze *What is the sum of a vector 12 m north and a vector 8 m north?*

COLOR CONVENTION

Displacement (*x*) green

Example of Vector Addition



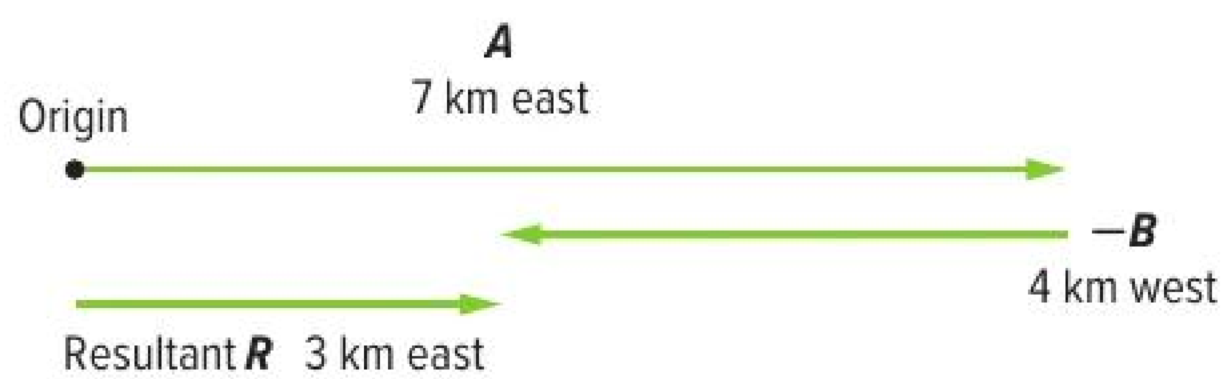
$R = A + B$
$= 5 \text{ km} + 2 \text{ km}$
$= 7 \text{ km}$

$\mathbf{R} = \mathbf{A} + \mathbf{B}$
$= 7 \text{ km east}$

Examples of Vector Subtraction

$R = A - B$
$= 4 \text{ km} - 6 \text{ km}$
$= -2 \text{ km}$

$\mathbf{R} = \mathbf{A} - \mathbf{B}$
$= \mathbf{A} + (-\mathbf{B})$
$= 2 \text{ km west}$



$R = A - B$
$= 7 \text{ km} - 4 \text{ km}$
$= 3 \text{ km}$

$\mathbf{R} = \mathbf{A} - \mathbf{B}$
$= \mathbf{A} + (-\mathbf{B})$
$= 3 \text{ km east}$

Check Your Progress

6. **Coordinate System** Identify a coordinate system you could use to describe the motion of a girl swimming across a rectangular pool.
7. **Displacement** The motion diagram for a car traveling on an interstate highway is shown below. The starting and ending points are indicated.

   Start • • • • • • End

   Make a copy of the diagram. Draw a vector to represent the car's displacement from the starting time to the end of the third time interval.
8. **Position** Two students added a vector for a moving object's position at $t = 2$ s to a motion diagram. When they compared their diagrams, they found that their vectors did not point in the same direction. Explain.
9. **Displacement** The motion diagram for a boy walking to school is shown below.

   Home • • • • • • • • • • School

   Make a copy of this motion diagram, and draw vectors to represent the displacement between each pair of dots.

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LESSON 3
POSITION-TIME GRAPHS

FOCUS QUESTION
What can you learn from position-time graphs?

Finding Positions

When analyzing complex motion, it often is useful to represent the motion in a variety of ways. A motion diagram contains information about an object's position at various times. Tables and graphs can also show this same information. Review the motion diagrams in **Figure 8** and **Figure 9**. You can use these diagrams to organize the times and corresponding positions of the runner, as in **Table 1.**

Plotting data The data listed in **Table 1** can be presented on a **position-time graph,** in which the time data is plotted on a horizontal axis and the position data is plotted on a vertical axis. The graph of the runner's motion is shown in **Figure 11**. To draw this graph, first plot the runner's positions. Then, draw a line that best fits the points.

Table 1 Position v. Time

Time (s)	Position (m)
0.0	0.0
1.0	5.0
2.0	10.0
3.0	15.0
4.0	20.0
5.0	25.0

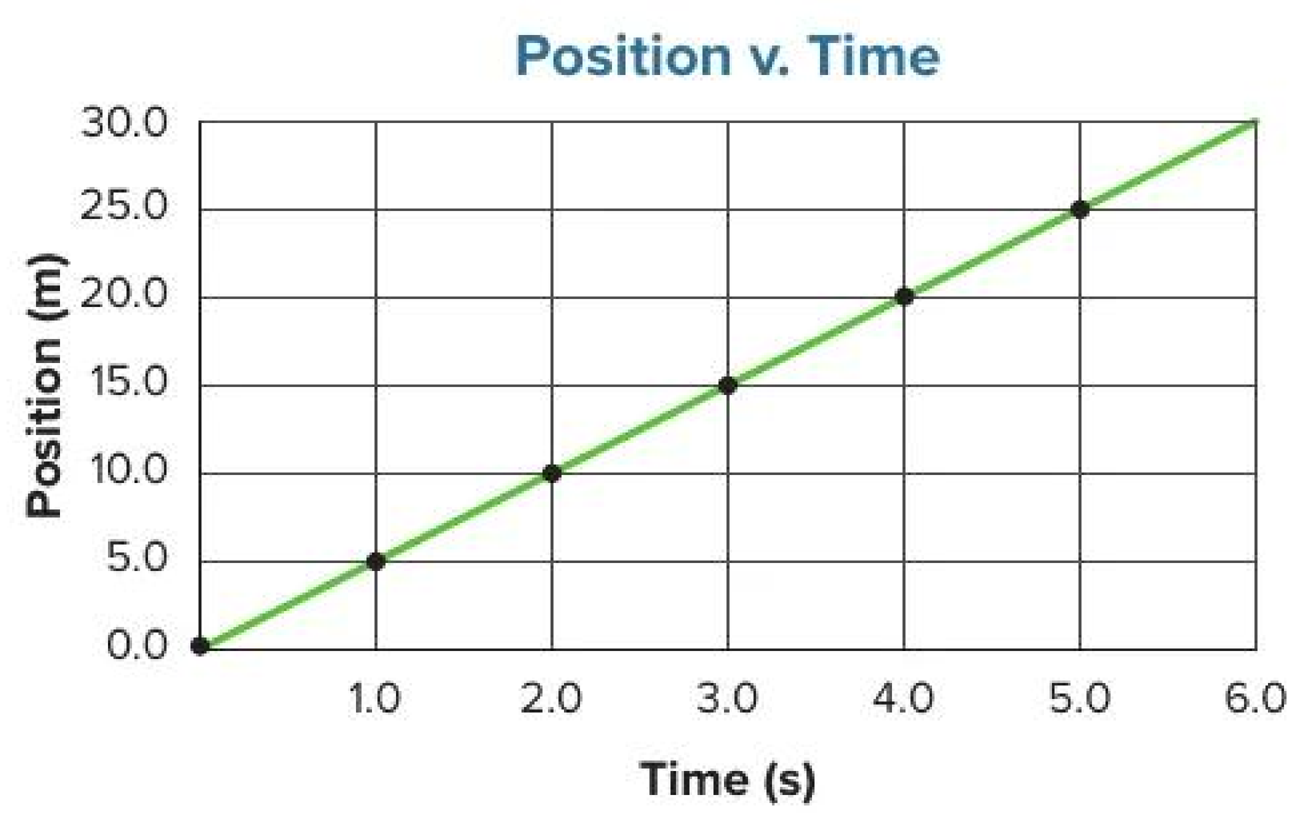

Figure 11 You can create a position-time graph by plotting the positions and times from the table. By drawing a best-fit line, you can estimate other times and positions.

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COLLECT EVIDENCE
Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE
GO ONLINE to find these activities and more resources.

CCC **Identify Crosscutting Concepts**
Create a table of the crosscutting concepts and fill in examples you find as you read.

Revisit the Encounter the Phenomenon Question
What information from this lesson can help you answer the Unit and Module questions?

Estimating time and position Notice that the graph is not a picture of the runner's path—the graphed line is sloped, but the runner's path was horizontal. Instead, the line represents the most likely positions of the runner at the times between the recorded data points. Even though there is no data point exactly when the runner was 12.0 m beyond her starting point or where she was at t = 4.5 s, you can use the graph to estimate the time or her position. The example problem on the next page shows how.

Instantaneous position How long did the runner spend at any location? Each position has been linked to a time, but how long did that time last? You could say "an instant," but how long is that? If an instant lasts for any finite amount of time, then the runner would have stayed at the same position during that time, and she would not have been moving. An instant is not a finite period of time, however. It lasts zero seconds. The symbol x represents the runner's **instantaneous position**—the position at a particular instant. Instantaneous position is usually simply called position.

Equivalent representations As shown in **Figure 12**, you now have several different ways to describe motion. You might describe motion using words, pictures (or pictorial representations), motion diagrams, data tables, or position-time graphs. All of these representations contain the same information about the runner's motion. However, depending on what you want to learn about an object's motion, some types of representations will be more useful than others.

Table 1 Position v. Time

Time (s)	Position (m)
0.0	0.0
1.0	5.0
2.0	10.0
3.0	15.0
4.0	20.0
5.0	25.0

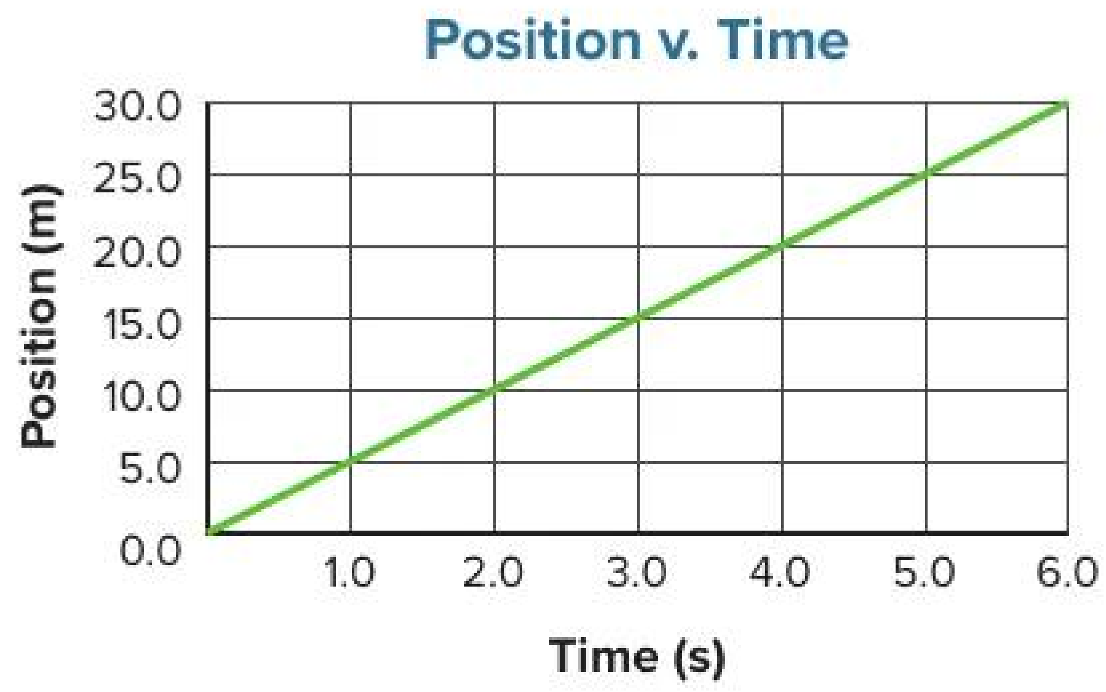


Figure 12 You can describe the runner's motion using the data table, the graph, and the motion diagram.

Identify *one benefit the table has over the graph.*

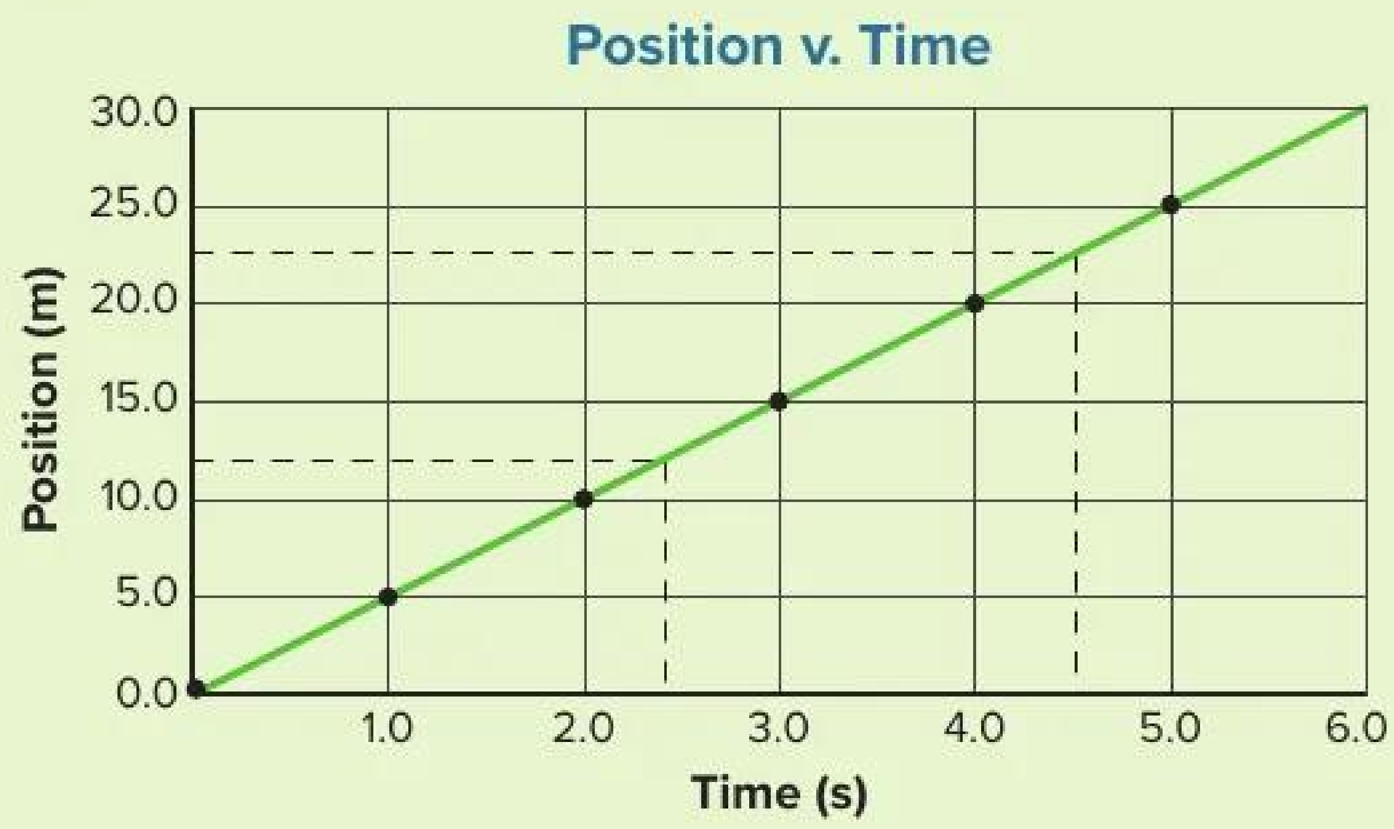
PHYSICS Challenge

POSITION-TIME GRAPHS Natana, Olivia, and Phil all enjoy exercising and often go to a path along the river for this purpose. Natana bicycles at a very consistent 40.25 km/h, Olivia runs south at a constant speed of 16.0 km/h, and Phil walks south at a brisk 6.5 km/h. Natana starts biking north at noon from the waterfalls. Olivia and Phil both start at 11:30 A.M. at the canoe dock, 20.0 km north of the falls.

1. Draw position-time graphs for each person.
2. At what time will the three exercise enthusiasts be located within the smallest distance interval from each other?
3. What is the length of that distance interval?

EXAMPLE Problem 1

ANALYZE A POSITION-TIME GRAPH When did the runner whose motion is described in **Figure 11** reach 12.0 m beyond the starting point? Where was she after 4.5 s?



1 ANALYZE THE PROBLEM

Restate the questions.

Question 1: At what time was the magnitude of the runner's position (x) equal to 12.0 m?

Question 2: What was the runner's position at time $t = 4.5$ s?

2 SOLVE FOR THE UNKNOWN

Question 1

Examine the graph to find the intersection of the best-fit line with a horizontal line at the 12.0 m mark. Next, find where a vertical line from that point crosses the time axis. The value of t there is 2.4 s.

Question 2

Find the intersection of the graph with a vertical line at 4.5 s (halfway between 4.0 s and 5.0 s on this graph). Next, find where a horizontal line from that point crosses the position axis. The value of x is approximately 22.5 m.

PRACTICE Problems

ADDITIONAL PRACTICE

*For problems 10–12, refer to **Figure 13**.*

10. The graph in **Figure 13** represents the motion of a car moving along a straight highway. Describe in words the car's motion.

11. Draw a particle model motion diagram that corresponds to the graph.

12. Answer the following questions about the car's motion. Assume that the positive x-direction is east of the origin and the negative x-direction is west of the origin.

a. At what time was the car's position 25.0 m east of the origin?

b. Where was the car at time $t = 1.0$ s?

c. What was the displacement of the car between times $t = 1.0$ s and $t = 3.0$ s?

13. The graph in **Figure 14** represents the motion of two pedestrians who are walking along a straight sidewalk in a city. Describe in words the motion of the pedestrians. Assume that the positive direction is east of the origin.

14. CHALLENGE Ari walked down the hall at school from the cafeteria to the band room, a distance of 100.0 m. A class of physics students recorded and graphed his position every 2.0 s, noting that he moved 2.6 m every 2.0 s. When was Ari at the following positions?

a. 25.0 m from the cafeteria

b. 25.0 m from the band room

c. Create a graph showing Ari's motion.

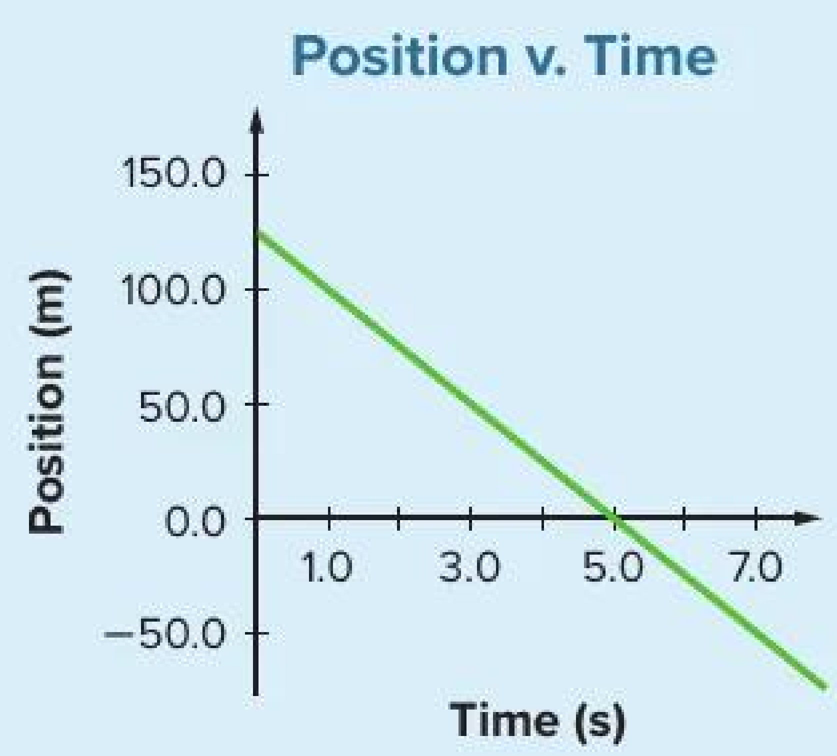


Figure 13

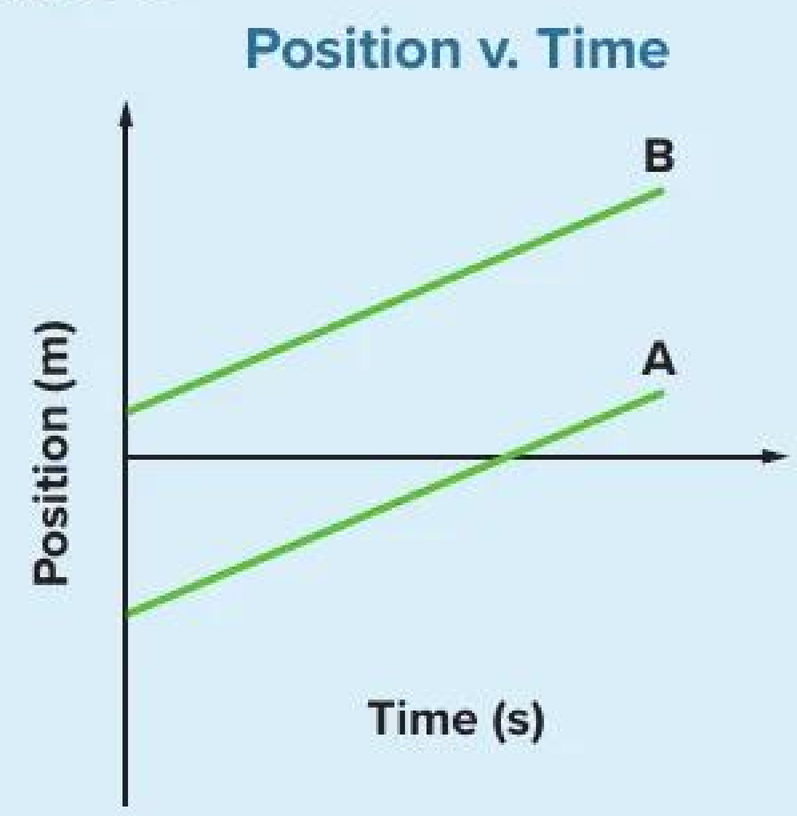


Figure 14

Multiple Objects on a Position-Time Graph

A position-time graph for two different runners is shown in Example Problem 2 below. Notice that runner A is ahead of runner B at time $t = 0$, but the motion of each runner is different. When and where does one runner pass the other? First, you should restate this question in physics terms: At what time are the two runners at the same position? What is their position at this time? You can evaluate these questions by identifying the point on the position-time graph at which the lines representing the two runners' motions intersect.

The intersection of two lines on a position-time graph tells you when objects have the same position, but does this mean that they will collide? Not necessarily. For example, if the two objects are runners and if they are in different lanes, they will not collide, even though they might be the same distance from the starting point.

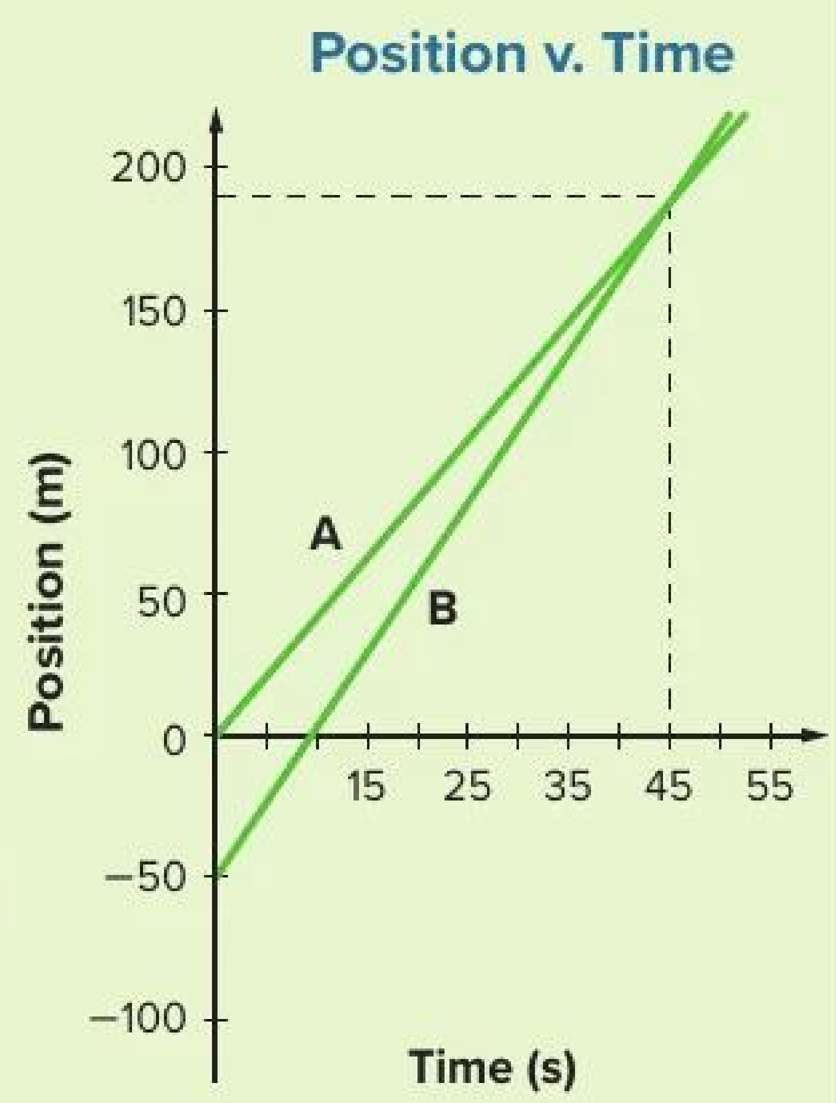
Get It?

Explain what the intersection of two lines on a position-time graph means.

What else can you learn from a position-time graph? Notice in Example Problem 2 that the lines on the graph have different slopes. What does the slope of the line on a position-time graph tell you? In the next lesson, you will use the slope of a line on a position-time graph to determine the velocity of an object. When you study accelerated motion, you will draw other motion graphs and learn to interpret the areas under the plotted lines. In later studies, you will continue to refine your skills with creating and interpreting different types of motion graphs.

EXAMPLE Problem 2

INTERPRETING A GRAPH The graph to the right describes the motion of two runners moving along a straight path. The lines representing their motion are labeled A and B. When and where does runner B pass runner A?



1 ANALYZE THE PROBLEM

Restate the questions.

Question 1: At what time are runner A and runner B at the same position?

Question 2: What is the position of runner A and runner B at this time?

2 SOLVE FOR THE UNKNOWN

Question 1

Examine the graph to find the intersection of the line representing the motion of runner A with the line representing the motion of runner B. These lines intersect at time 45 s.

Question 2

Examine the graph to determine the position when the lines representing the motion of the runners intersect. The position of both runners is about 190 m from the origin.

Runner B passes runner A about 190 m beyond the origin, 45 s after A has passed the origin.

PRACTICE Problems

ADDITIONAL PRACTICE

For problems 15–18, refer to the figure in Example Problem 2 on the previous page.

15. Where was runner A located at $t = 0$ s?

16. Which runner was ahead at $t = 48.0$ s?

17. When runner A was at 0.0 m, where was runner B?

18. How far apart were runners A and B at $t = 20.0$ s?

19. CHALLENGE Juanita goes for a walk to the north. Later her friend Heather starts to walk after her. Their motions are represented by the position-time graph in **Figure 15.**

a. How long had Juanita been walking when Heather started her walk?

b. Will Heather catch up to Juanita? How can you tell?

c. What was Juanita's position at $t = 0.2$ h?

d. At what time was Heather 5.0 km from the start?

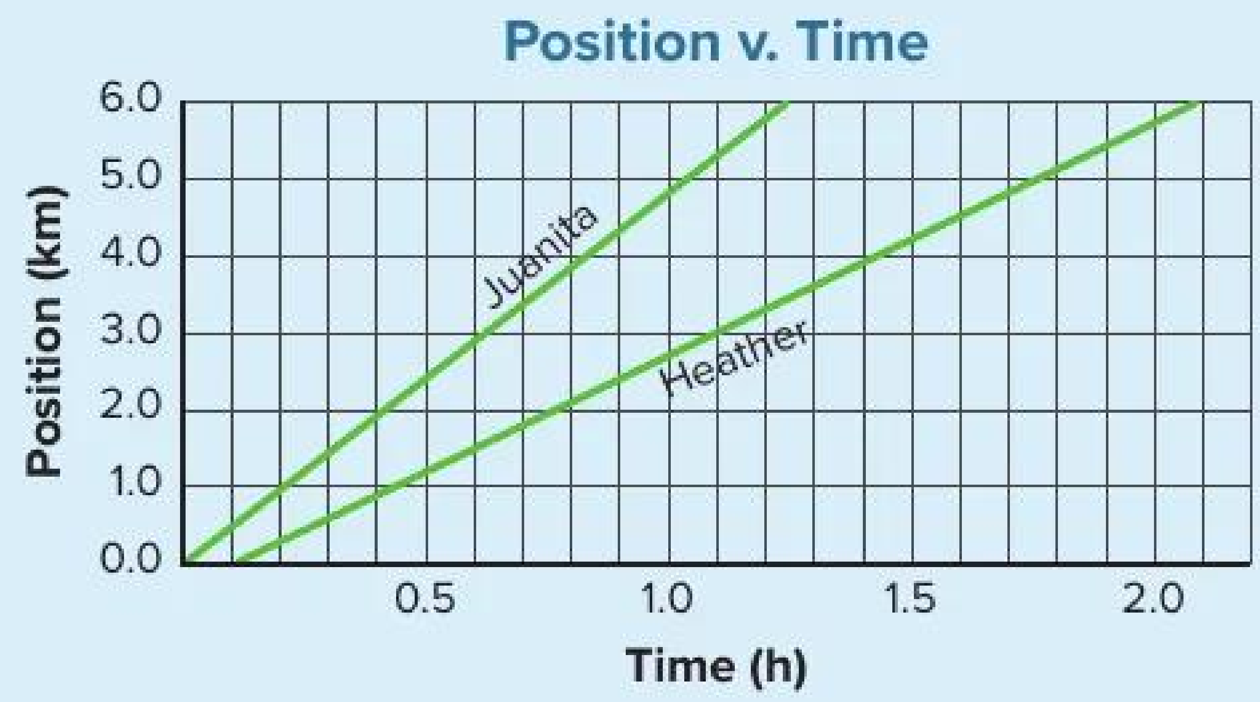


Figure 15

Check Your Progress

20. **Particle Diagram** Using the particle model motion diagram in **Figure 16** of a baby crawling across a kitchen floor, plot a position-time graph to represent the motion. The time interval between dots on the diagram is 1 s.

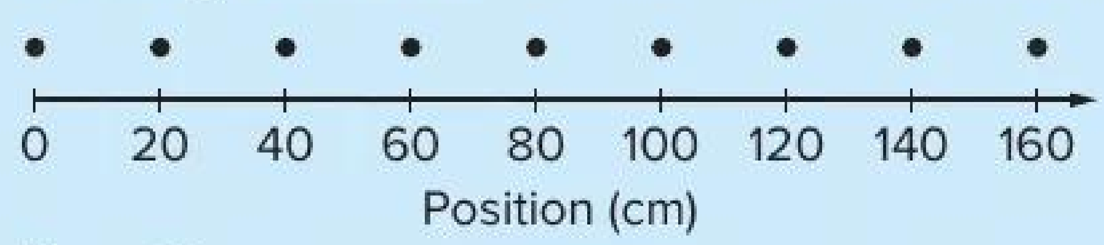


Figure 16

Figure 17

*For problems 21–24, refer to **Figure 17.***

21. **Particle Model** Create a particle model motion diagram from the position-time graph of a hockey puck gliding across the ice.

22. **Time** Use the hockey puck's position-time graph to determine the time when the puck was 10.0 m beyond the origin.

23. **Distance** Use the position-time graph to determine how far the hockey puck moved between 0.0 s and 5.0 s.

24. **Time Interval** Use the position-time graph for the hockey puck to determine the time it took for the puck to go from 40.0 m beyond the origin to 80.0 m beyond the origin.

25. **Critical Thinking** Look at the diagram and graph shown in **Figure 18**. Do they describe the same motion? Explain. The time intervals in the particle model diagram are 2 s.

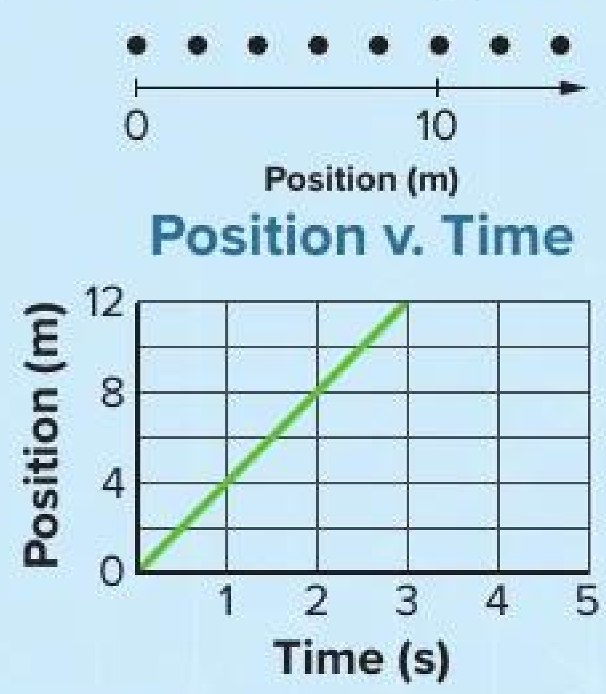


Figure 18

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LESSON 4

HOW FAST?

FOCUS QUESITON

How do you describe how fast something is moving?

Velocity and Speed

Suppose you recorded the motion of two joggers on one diagram, as shown by the graph in **Figure 19.** The position of the jogger wearing red changes more than that of the jogger wearing blue. For a fixed time interval, the magnitude of the displacement (Δx) is greater for the jogger in red because she is moving faster. Now, suppose that each jogger travels 100 m. The time interval (Δt) for the 100 m would be smaller for the jogger in red than for the one in blue.

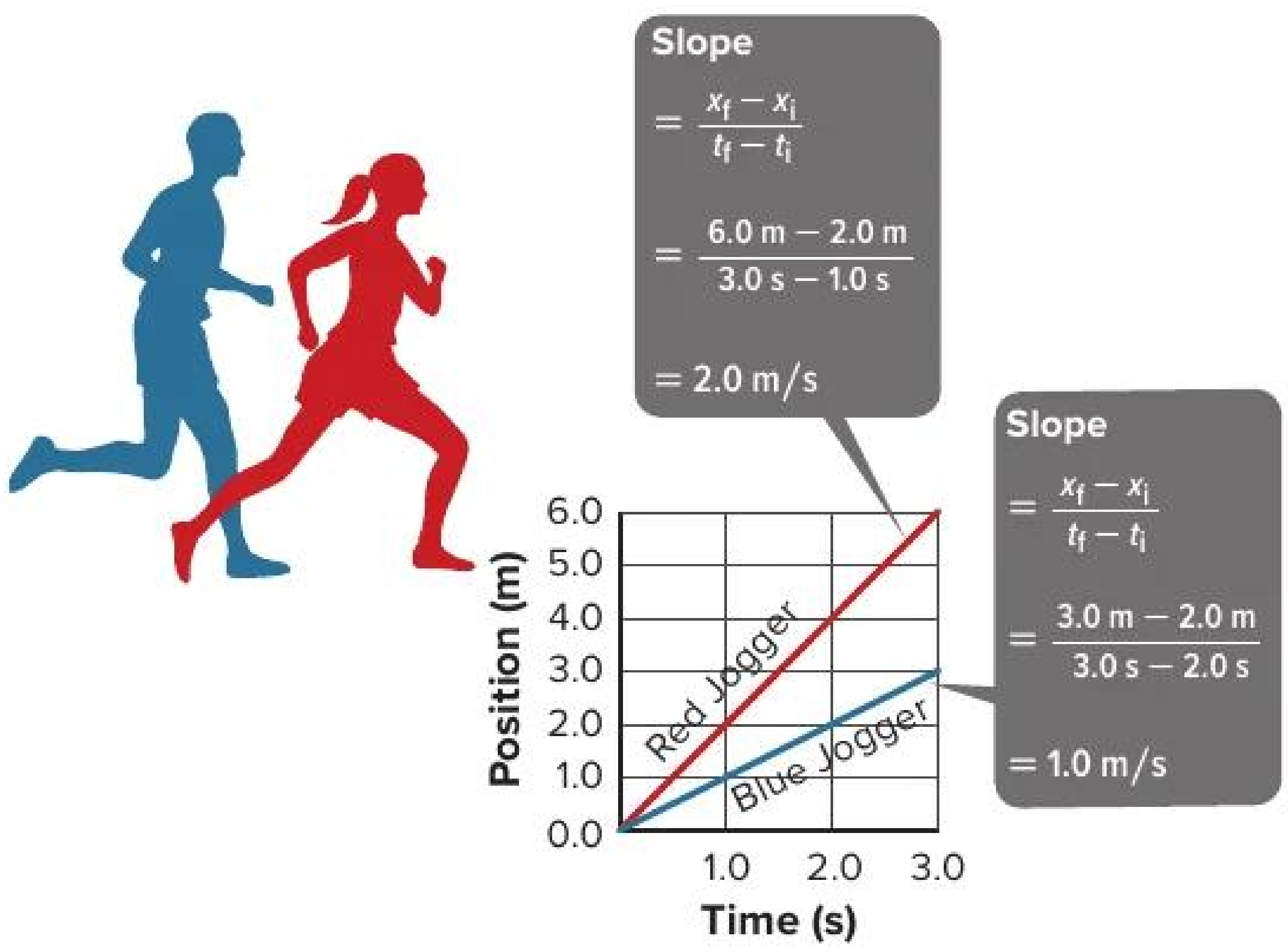

Figure 19 A greater slope shows that the red jogger traveled faster.

Analyze *How much farther did the red jogger travel than the blue jogger in the 3 s interval described by the graph?*

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COLLECT EVIDENCE

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INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Constant Speed

Plan and carry out an investigation to relate distance, speed, and time interval.

Review the News

Obtain information from a current news story about speed or velocity. Evaluate your source and communicate your findings to your class.

Slope on a position-time graph Compare the lines representing the joggers in the graph in **Figure 19.** The slope of the red jogger's line is steeper, indicating a greater change in position during each time interval. Recall that you find the slope of a line by first choosing two points on the line. Next, you subtract the vertical coordinate (x in this case) of the first point from the vertical coordinate of the second point to obtain the rise of the line. After that, you subtract the horizontal coordinate (t in this case) of the first point from the horizontal coordinate of the second point to obtain the run. The rise divided by the run is the slope.

Get It?

Explain In the graph in **Figure 19**, the graph for each jogger starts at the coordinates (0, 0). Explain what this means in terms of position.

Average velocity Notice that the slope of the faster runner's line in **Figure 19** is a greater number. A greater slope indicates a faster speed. Also notice that the slope's units are meters per second. Looking at how the slope is calculated, you can see that slope is the change in the magnitude of the position divided by the time interval during which that change took place: $\frac{x_f - x_i}{t_f - t_i}$ or $\frac{\Delta x}{\Delta t}$. When Δx gets larger, the slope gets larger; when Δt gets larger, the slope gets smaller. This agrees with the interpretation given on the previous page of the speeds of the red and blue joggers. **Average velocity** is the ratio of an object's change in position to the time interval during which the change occurred. If the object is in uniform motion, so that its speed does not change, then its average velocity is the slope of its position-time graph.

Average velocity

Average velocity is defined as the change in position divided by the time during which the change occurred.

$$\bar{\boldsymbol{v}} \equiv \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i}$$

The symbol ≡ means that the left-hand side of the equation is defined by the right-hand side.

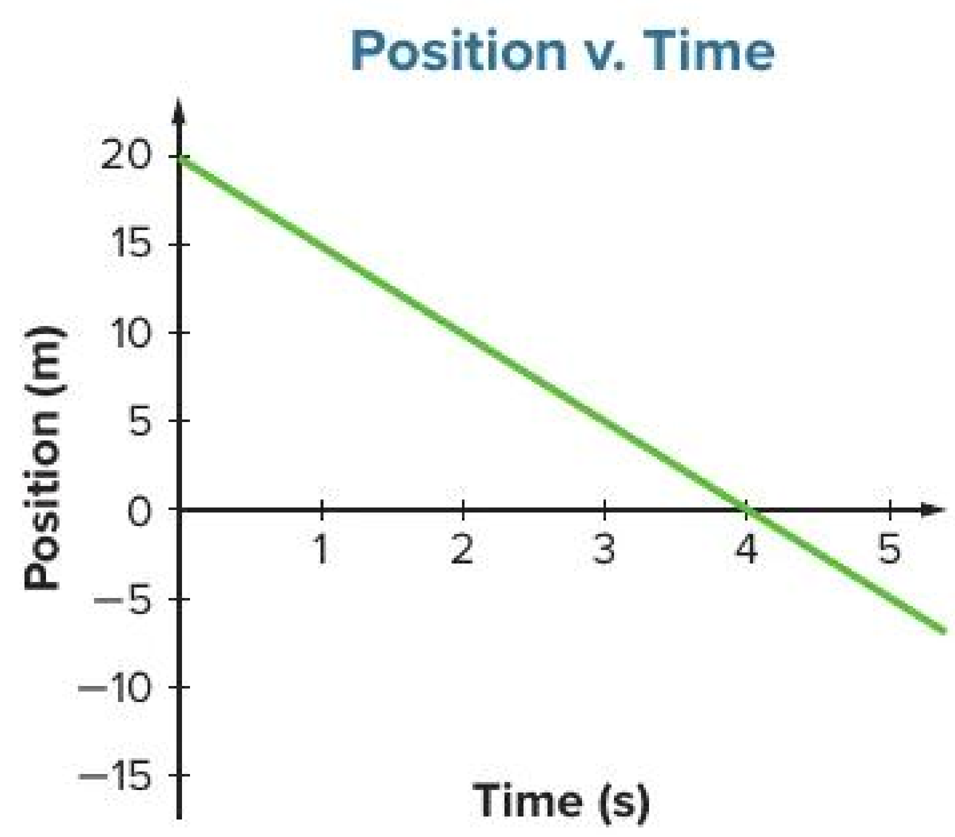
Interpreting slope The position-time graph's slope in **Figure 20** is –5.0 m/s. Notice that the slope of the graph indicates both magnitude and direction. By calculating the slope from the rise divided by the run between two points, you find that the object whose motion is represented by the graph has an average velocity of –5.0 m/s. The object started out at a positive position and moves toward the origin. After 4 s, it passes the origin and continues moving in the negative direction at a rate of 5.0 m/s.

Get It?

Explain the meaning of an upward and a downward slope of a position-time graph both above and below the x-axis.

Figure 20 The downward slope of this position-time graph shows that the motion is in the negative direction.

Analyze *What would the graph look like if the motion were at the same speed, but in the positive direction?*



Average speed The slope's absolute value is the object's **average speed,** 5.0 m/s, which is the distance traveled divided by the time taken to travel that distance. For uniform motion, average speed is the absolute value of the slope of the object's position-time graph. The combination of an object's average speed ($\bar{v}$) and the direction in which it is moving is the average velocity ($\bar{\mathbf{v}}$). Remember that if an object moves in the negative direction, its change in position is negative. This means that an object's displacement and velocity are both always in the same direction.

Real-World Physics

The fastest bird is the peregrine falcon. It can dive at a speed of 240 mph when hunting. The fastest land animal is the cheetah. It can run between 60–75 mph in short bursts.

Instantaneous velocity Why do we call the quantity $\frac{\Delta x}{\Delta t}$ average velocity? Why don't we just call it velocity? A motion diagram shows the position of a moving object at the beginning and end of a time interval. It does not, however, indicate what happened within that time interval. During the time interval, the object's speed could have remained the same, increased, or decreased. The object may have stopped or even changed direction. You can find the average velocity for each time interval in the motion diagram, but you cannot find the speed and the direction of the object at any specific instant. The speed and the direction of an object at a particular instant is called the **instantaneous velocity.** In this textbook, the term velocity will refer to instantaneous velocity, represented by the symbol $\mathbf{v}$.

Get It?
Explain how average velocity is different from velocity.

Average velocity on motion diagrams When an object moves between two points, its average velocity is in the same direction as its displacement. The two quantities are also proportional—when displacement is greater during a given time interval, so is average velocity. A motion diagram indicates the average velocity's direction and magnitude.

Imagine two cars driving down the road at different speeds. A video camera records the motion of the cars at the rate of one frame every second. Imagine that each car has a paintbrush attached to it that automatically descends and paints a red line on the ground for half a second every second. The faster car would paint a longer line on the ground. The vectors you draw on a motion diagram to represent the velocity are like the lines that the paintbrushes make on the ground below the cars. In this book, we use red to indicate velocity vectors on motion diagrams. **Figure 21** shows motion diagrams with velocity vectors for two cars. One is moving to the right, and the other is moving to the left.

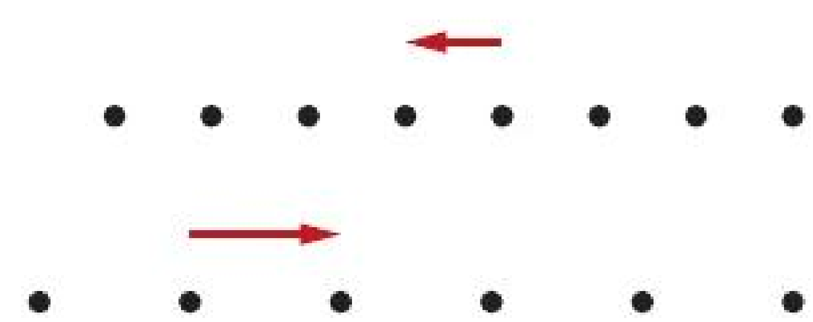
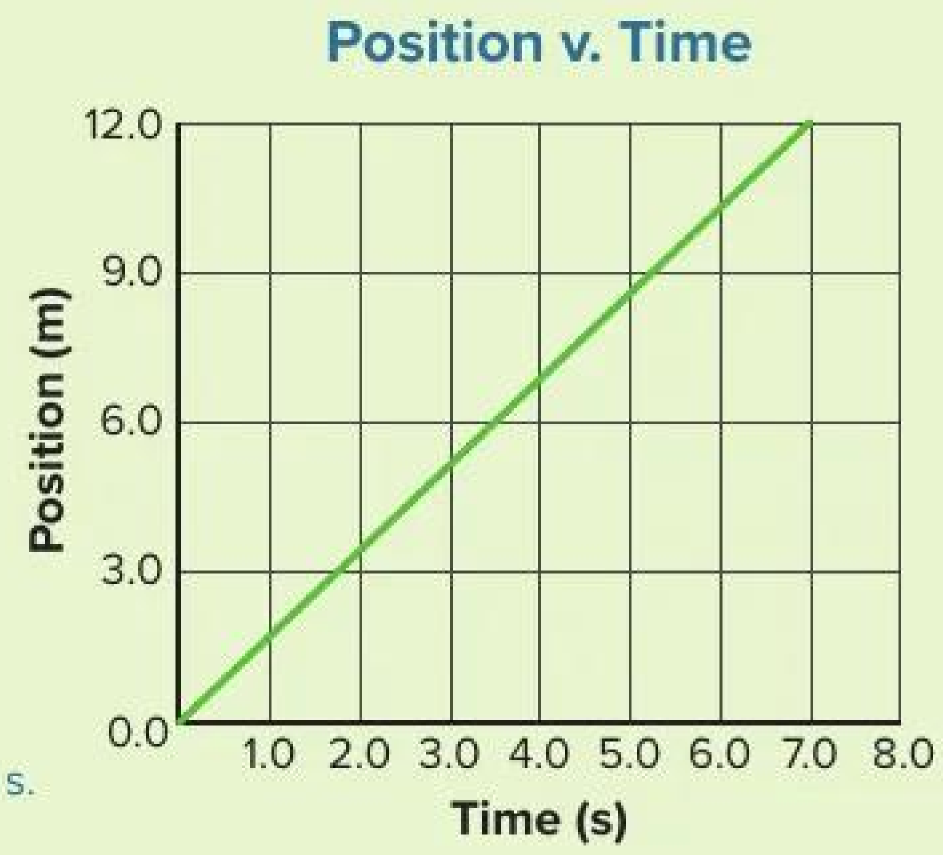


Figure 21 The length of each velocity vector is proportional to the magnitude of the velocity that it represents.

Get It?
Identify what the lengths of velocity vectors mean.

EXAMPLE Problem 3

AVERAGE VELOCITY The graph at the right describes the straight-line motion of a student riding her skateboard along a smooth, pedestrian-free sidewalk. What is her average velocity? What is her average speed?



1 ANALYZE AND SKETCH THE PROBLEM

Identify the graph's coordinate systems.

UNKNOWN

$\bar{v} = ?$ $\qquad \bar{v} = ?$

2 SOLVE FOR THE UNKNOWN

Find the average velocity using two points on the line.

$$\bar{v} = \frac{\Delta x}{\Delta t}$$

$$= \frac{x_f - x_i}{t_f - t_i}$$

$$= \frac{12.0\ \text{m} - 0.0\ \text{m}}{7.0\ \text{s} - 0.0\ \text{s}}$$ Substitute $x_f = 12.0$ m, $x_i = 0.0$ m, $t_f = 7.0$ s, $t_i = 0.0$ s.

$\bar{v} = 1.7$ m/s in the positive direction

The average speed ($\bar{v}$) is the absolute value of the average velocity, or 1.7 m/s.

3 EVALUATE THE ANSWER

- **Are the units correct?** The units for both velocity and speed are meters per second.
- **Do the signs make sense?** The positive sign for the velocity agrees with the coordinate system. No direction is associated with speed.

PRACTICE Problems

26. The graph in **Figure 22** describes the motion of a cruise ship drifting slowly through calm waters. The positive *x*-direction (along the vertical axis) is defined to be south.

a. What is the ship's average speed?

b. What is its average velocity?

27. Describe, in words, the cruise ship's motion in the previous problem.

28. What is the average velocity of an object that moves from 6.5 cm to 3.7 cm relative to the origin in 2.3 s?

29. The graph in **Figure 23** represents the motion of a bicycle.

a. What is the bicycle's average speed?

b. What is its average velocity?

30. Describe, in words, the bicycle's motion in the previous problem.

31. CHALLENGE When Marshall takes his pet dog for a walk, the dog walks at a very consistent pace of 0.55 m/s. Draw a motion diagram and a position-time graph to represent Marshall's dog walking the 19.8-m distance from in front of his house to the nearest stop sign.

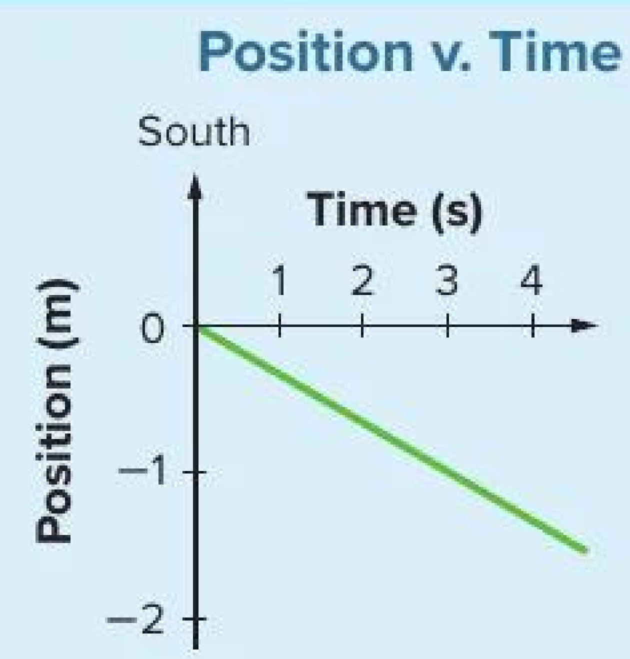


Figure 22

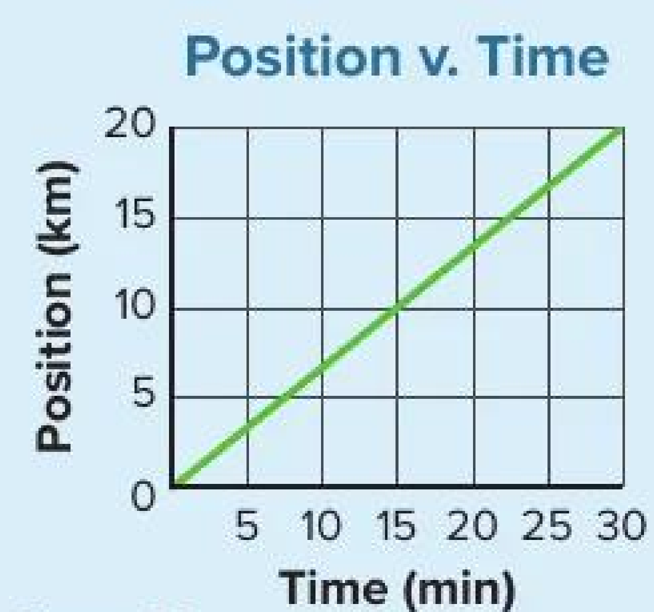


Figure 23

Equation of Motion

Often it is more efficient to use an equation, rather than a graph, to solve problems. Any time you graph a straight line, you can find an equation to describe it. Take another look at the graph in **Figure 20** for the object moving with a constant velocity of −5.0 m/s. Recall that you can represent any straight line with the equation $y = mx + b$, where y is the quantity plotted on the vertical axis, m is the line's slope, x is the quantity plotted on the horizontal axis, and b is the line's y-intercept.

For the graph in **Figure 20**, the quantity plotted on the vertical axis is position, represented by the variable $\boldsymbol{x}$. The line's slope is −5.0 m/s, which is the object's average velocity ($\bar{\boldsymbol{v}}$). The quantity plotted on the horizontal axis is time (t). The y-intercept is 20.0 m. What does this 20.0 m represent? This shows that the object was at a position of 20.0 m when $t = 0.0$ s. This is called the initial position of the object and it is designated $\boldsymbol{x}_i$.

A summary is given below of how the general variables in the straight-line formula are changed to the specific variables you have been using to describe motion. The table also shows the numerical values for the average velocity and initial position. Consider the graph shown in **Figure 20.** The mathematical equation for the line graphed is as follows:

$$y = (-5.0\ \text{m/s})x + 20.0\ \text{m}$$

You can rewrite this equation, using $\boldsymbol{x}$ for position and t for time.

$$\boldsymbol{x} = (-5.0\ \text{m/s})t + 20.0\ \text{m}$$

It might be confusing to use y and x in math but use $\boldsymbol{x}$ and t in physics. You do this because there are many types of graphs in physics, including position v. time graphs, velocity v. time graphs, and force v. position graphs. For a position v. time graph, the math equation $y = mx + b$ can be rewritten as follows:

Position

An object's position is equal to the average velocity multiplied by time plus the initial position.

$$\boldsymbol{x} = \bar{\boldsymbol{v}}t + \boldsymbol{x}_i$$

This equation gives you another way to represent motion. Note that a graph of x v. t would be a straight line.

CONNECTING MATH to Physics

Lines and Graphs Symbols used in the point-slope equation of a line relate to symbols used for motion variables on a position-time graph.

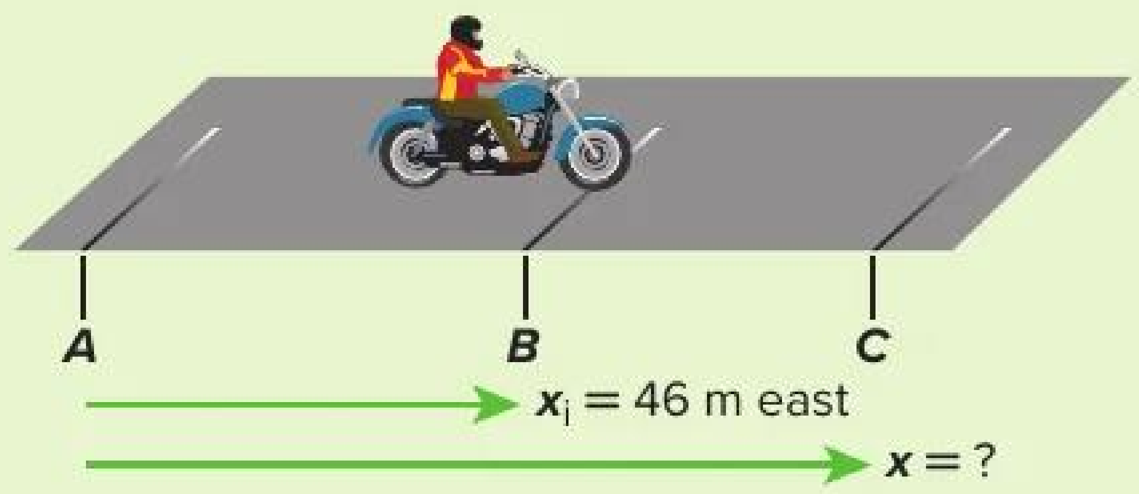
General Variable	Specific Motion Variable	Value in Figure 20
y	$\boldsymbol{x}$	
m	$\bar{\boldsymbol{v}}$	−5.0 m/s
x	t	
b	$\boldsymbol{x}_i$	20.0 m

EXAMPLE Problem 4

POSITION The figure shows a motorcyclist traveling east along a straight road. After passing point ***B***, the cyclist continues to travel at an average velocity of 12 m/s east and arrives at point ***C*** 3.0 s later. What is the position of point ***C***?

1 ANALYZE THE PROBLEM

Choose a coordinate system with the origin at ***A***.



KNOWN	UNKNOWN
$\bar{v}$ = 12 m/s east	x = ?
x_i = 46 m east	
t = 3.0 s	

2 SOLVE FOR THE UNKNOWN

$x = \bar{v}t + x_i$ — Use magnitudes for the calculations.

$= (12\text{ m/s})(3.0\text{ s}) + 46\text{ m}$ — Substitute $\bar{v}$ = 12 m/s, t = 3.0 s, and x_i = 46 m.

$= 82\text{ m}$

x = 82 m east

3 EVALUATE THE ANSWER

- **Are the units correct?** Position is measured in meters.
- **Does the direction make sense?** The motorcyclist is traveling east the entire time.

PRACTICE Problems

*For problems 32–35, refer to **Figure 24**.*

32. The diagram at the right shows the path of a ship that sails at a constant velocity of 42 km/h east. What is the ship's position when it reaches point ***C***, relative to the starting point, ***A***, if it sails from point ***B*** to point ***C*** in exactly 1.5 h?

33. Another ship starts at the same time from point ***B***, but its average velocity is 58 km/h east. What is its position, relative to ***A***, after 1.5 h?

34. What would a ship's position be if that ship started at point ***B*** and traveled at an average velocity of 35 km/h west to point ***D*** in a time period of 1.2 h?

35. CHALLENGE Suppose two ships start from point ***B*** and travel west. One ship travels at an average velocity of 35 km/h for 2.2 h. Another ship travels at an average velocity of 26 km/h for 2.5 h. What is the final position of each ship?

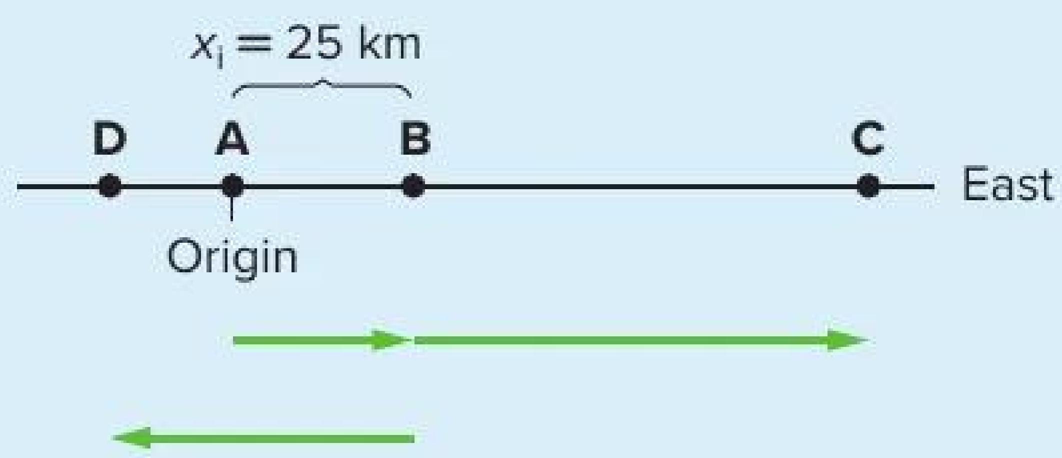


Figure 24

After your study of this lesson, you probably realize how closely linked physics is to mathematics. Algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another. For example, you can predict the change in average velocity of an object by examining the change in position over time. Using mathematics to model motion is a useful tool for physicists and physics students.

Check Your Progress

36. **Velocity and Position** How is an object's velocity related to its position?

*For problems 37–39, refer to **Figure 25.***

37. **Ranking Task** Rank the position-time graphs according to the average speed, from greatest average speed to least average speed. Specifically indicate any ties.

38. **Contrast Average Velocities** Describe differences in the average velocities shown on the graph for objects A and B. Describe differences in the average velocities shown on the graph for objects C and D.

39. **Ranking Task** Rank the graphs in **Figure 25** according to each object's initial position, from most positive position to most negative position. Specifically indicate any ties. Would your ranking be different if you ranked according to initial distance from the origin?

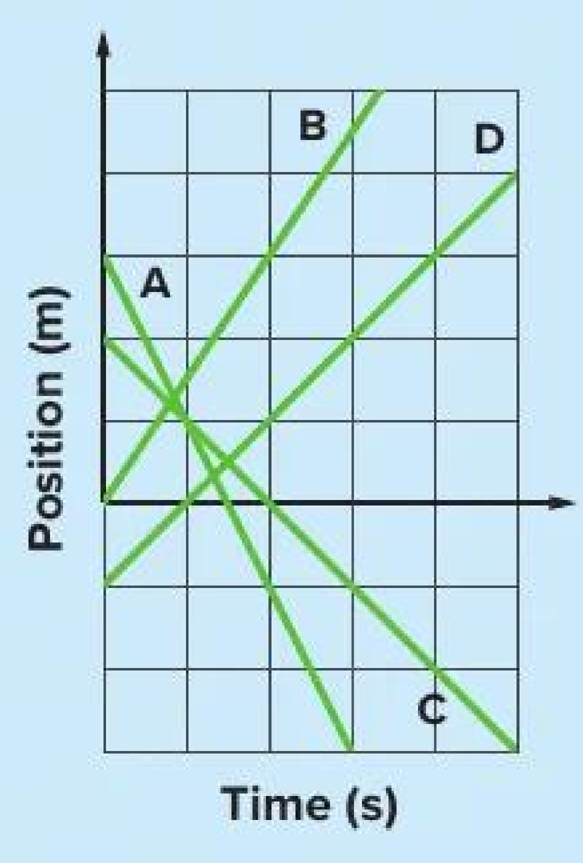


Figure 25

40. **Average Speed and Average Velocity** Explain how average speed and average velocity are related to each other for an object in uniform motion.

41. **Position** Two cars are traveling along a straight road, as shown in **Figure 26.** They pass each other at point B and then continue in opposite directions. The orange car travels for 0.25 h from point B to point C at a constant velocity of 32 km/h east. The blue car travels for 0.25 h from point B to point D at a constant velocity of 48 km/h west. How far has each car traveled from point B? What is the position of each car relative to the origin, point A?

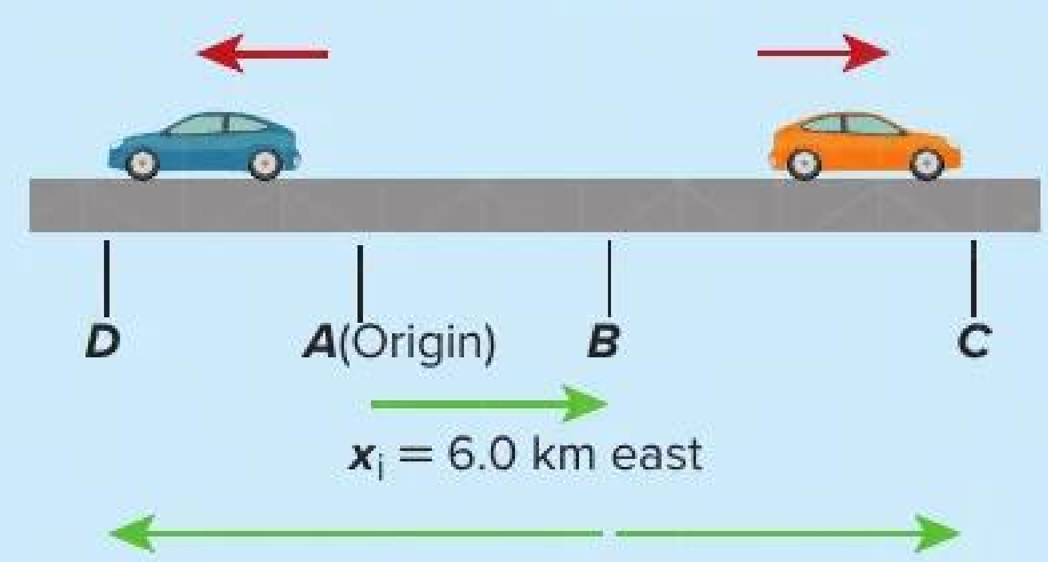


Figure 26

42. **Position** A car travels north along a straight highway at an average speed of 85 km/h. After driving 2.0 km, the car passes a gas station and continues along the highway. What is the car's position relative to the start of its trip 0.25 h after it passes the gas station?

43. **Critical Thinking** In solving a physics problem, why is it important to create pictorial and physical models before trying to solve an equation?

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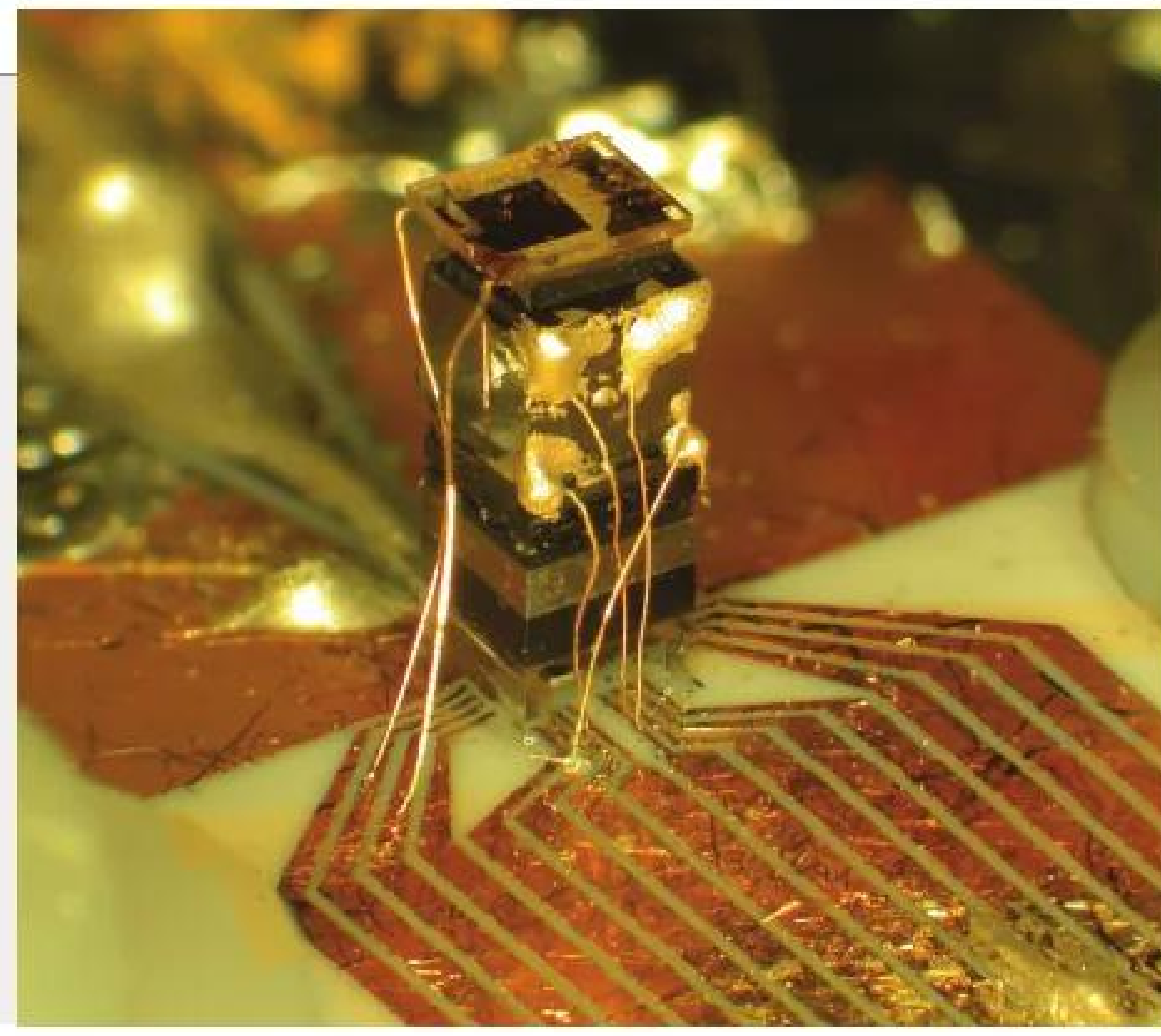
SCIENTIFIC BREAKTHROUGHS

In the Nick of Time

Global Positioning System (GPS) and other navigation systems rely on satellites with extremely accurate atomic clocks to keep track of time. However, some navigation systems must operate in environments—such as inside buildings, in the depths of canyons, or deep under water—where radio signals from satellites cannot reach them. Navigation systems that rely on satellites are also susceptible to intentional interference due to hacking or jamming. To address this problem, scientists have developed tiny atomic clocks for navigation systems small enough to be carried by a person.



Chip-scale atomic clocks (CSACs) allow for astoundingly accurate and precise time-keeping in a very small package.

Chip-scale atomic clocks

Old-fashioned clocks count the seconds by the swings of a pendulum. Mechanical clocks—and even digital clocks, which use the electrical oscillations in power lines or the oscillations of quartz crystals to keep time—are not completely accurate and precise. So, in 1949, scientists at the National Institute of Standards and Technology (NIST) took a step toward solving this problem by developing the first atomic clock.

Atomic clocks count the seconds by oscillations between atomic energy states of various elements, including cesium, rubidium, and strontium. Over the years, advances in technology have led to the creation of atomic clocks that are more and more accurate and precise. The most current models can keep perfect time for the next 15 billion years.

In the early 2000s, NIST began working with the U.S. Department of Defense's Defense Advanced Research Projects Agency (DARPA) to create atomic clocks small enough to work in portable navigation systems. In 2004, they introduced the first chip-scale atomic clock (CSAC) which, as the name implies, is the size of a computer chip. Today, the CSAC is used in portable navigation systems, telecommunications systems, and other applications, both civilian and military.

Even CSACs have vulnerabilities, such as temperature fluctuations that cause variations in atomic frequencies. In 2016, DARPA kicked off the Atomic Clocks with Enhanced Stability (ACES) project with the goal of creating an atomic clock that performs 1,000 times better than the original CSAC.

USE A MODEL TO ILLUSTRATE

Use print or online sources to find a diagram of an atomic clock or a CSAC. Study the diagram and then use it to write a short text explaining how the device works.

NIST

MODULE 2
STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 PICTURING MOTION

- A motion diagram shows the position of an object at successive equal time intervals.
- In a particle model motion diagram, an object's position at successive times is represented by a series of dots. The spacing between dots indicates whether the object is moving faster or slower.

- motion diagram
- particle model

Lesson 2 WHERE AND WHEN?

- A coordinate system gives the location of the zero point of the variable you are studying and the direction in which the values of the variable increase.
- A vector drawn from the origin of a coordinate system to an object indicates the object's position in that coordinate system. The directions chosen as positive and negative on the coordinate system determine whether the objects' positions are positive or negative in the coordinate system.
- A time interval is the difference between two times.

$$\Delta t = t_f - t_i$$

- Change in position is displacement, which has both magnitude and direction.

$$\Delta x = x_f - x_i$$

- On a motion diagram, the displacement vector's length represents how far the object was displaced. The vector points in the direction of the displacement, from x_i to x_f

- coordinate system
- origin
- position
- distance
- magnitude
- vector
- scalar
- time interval
- displacement
- resultant

Lesson 3 POSITION-TIME GRAPHS

- Position-time graphs provide information about the motion of objects. They also might indicate where and when two objects meet.
- The line on a position-time graph describes an object's position at each time.
- Motion can be described using words, motion diagrams, data tables, or graphs.

- position-time graph
- instantaneous position

Lesson 4 HOW FAST?

- An object's velocity tells how fast it is moving and in what direction it is moving.
- Speed is the magnitude of velocity.
- Slope on a position-time graph describes the average velocity of the object.

$$\bar{v} \equiv \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i}$$

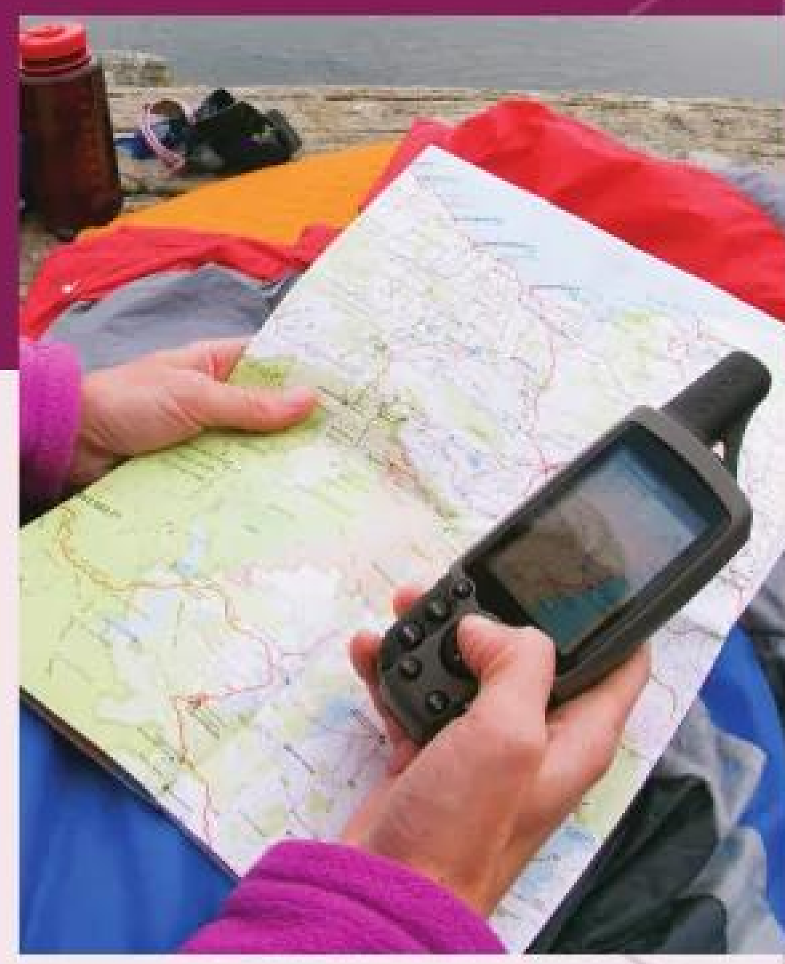
- A simple equation relates an object's initial position (x_i), its constant average velocity ($\bar{v}$), its position (x), and the time (t) since the object was at its initial position.

$$x = \bar{v}t + x_i$$

- average velocity
- average speed
- instantaneous velocity

THREE-DIMENSIONAL THINKING

Module Wrap-Up



REVISIT THE PHENOMENON

How does a GPS unit know where you are?

CER Claim, Evidence, Reasoning

Explain Your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

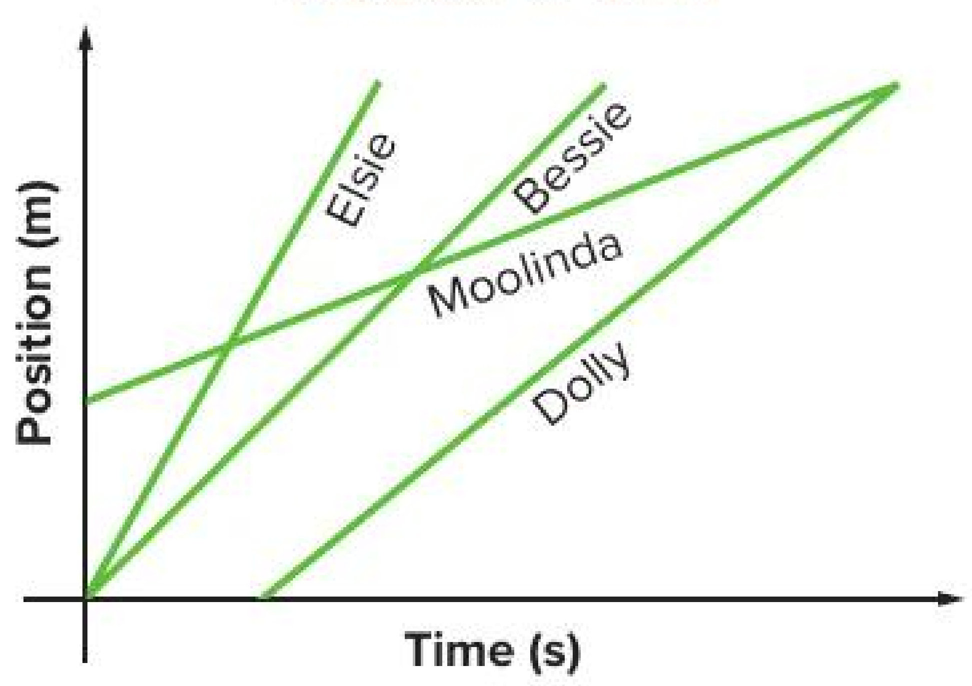
GO FURTHER

SEP Data Analysis Lab

How can you rank velocity from a graph?

Four cows were walking back to the barn at the end of the day. The position-time graph shows the motion of the four cows.

Position v. Time



CER Analyze and Interpret Data

1. **Compare and contrast the average velocities of the cows.**
2. **Claim** Rank the cows according to their average velocities.
3. **Evidence and Reasoning** Explain the evidence you obtained from the position-time graph and your reasoning to justify your ranking.

MODULE 3

ACCELERATED MOTION

Steve Whittington/Moment/Getty Images

MODULE 3
ACCELERATED MOTION

ENCOUNTER THE PHENOMENON

Why do sudden changes in the direction or speed of jet planes affect pilots?

GO ONLINE to play a video about the effects of acceleration on pilots.

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

CER Claim, Evidence, Reasoning

Make Your Claim Use your CER chart to make a claim about why sudden changes in the direction or speed of jet planes affect pilots. Explain your reasoning.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.

LESSON 1: Explore & Explain: Calculating Acceleration

LESSON 3: Explore & Explain: Galileo's Discovery

Smithsonian

Additional Resources

LESSON 1

ACCELERATION

FOCUS QUESTION

What are two ways velocity can change?

Nonuniform Motion Diagrams

An object in uniform motion moves along a straight line with an unchanging velocity, but few objects move this way all the time. More common is nonuniform motion, in which velocity is changing. In this module, you will study nonuniform motion along a straight line. Examples include balls rolling down hills, cars braking to a stop, and falling objects. In later modules you will analyze nonuniform motion that is not confined to a straight line, such as motion along a circular path and the motion of thrown objects, such as baseballs.

Describing nonuniform motion Uniform motion feels smooth. If you close your eyes, it feels as if you are not moving at all. In contrast, when you move around a curve or up and down a roller coaster hill, you feel pushed or pulled.

In the first diagram in **Figure 1**, the single image indicates that the person is motionless, like a runner waiting for the signal at the start of a race. In the other diagrams, the distances between successive positions change in different ways. In the second diagram, the distances are the same, which indicates that the jogger is in uniform motion at a constant velocity. In the third diagram, the distance increases because the jogger speeds up. In the fourth diagram, the distance decreases because the jogger slows down.

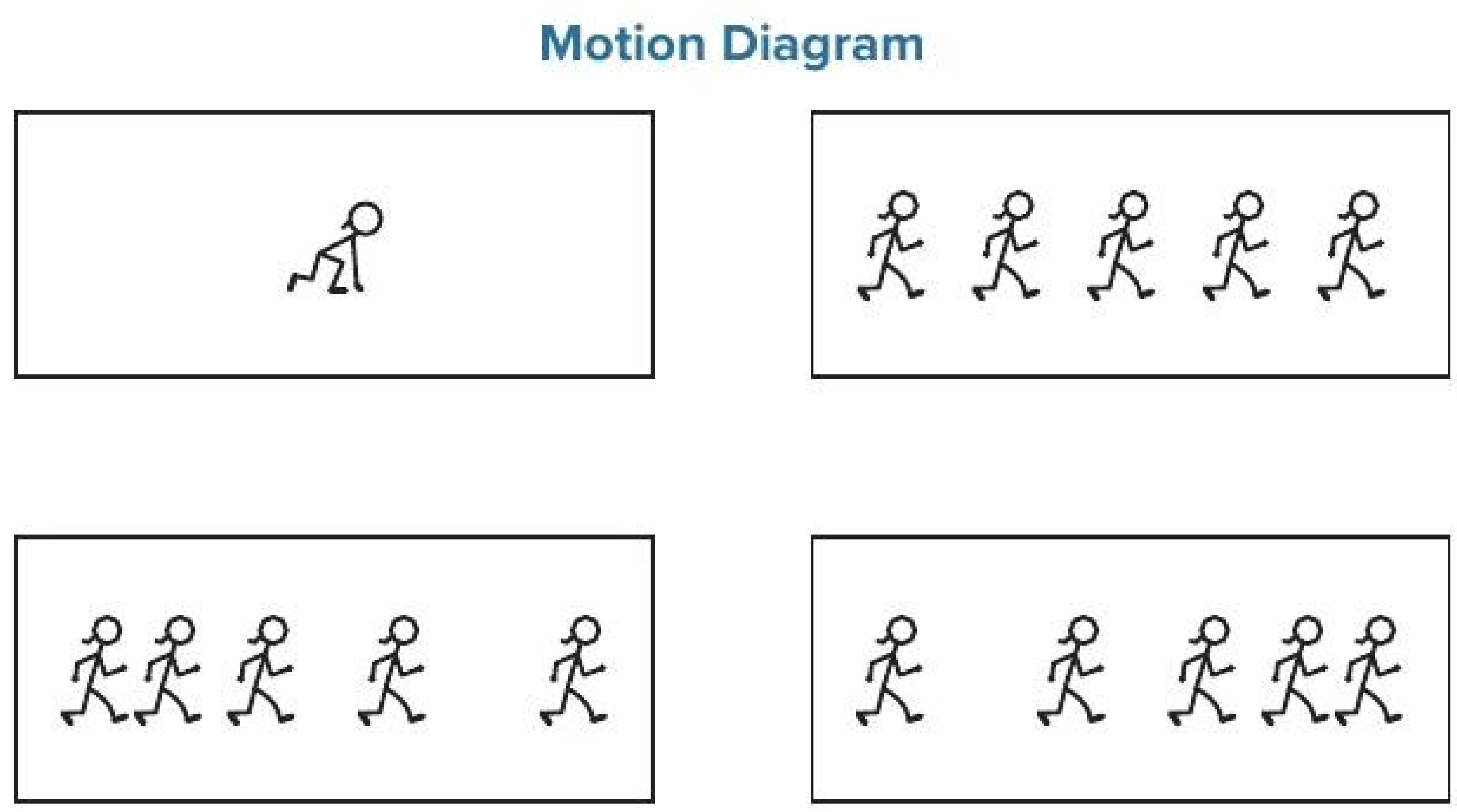


Figure 1 The distance the jogger moves in each time interval indicates the type of motion.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Virtual Investigation: Accelerated Motion
Use a computer model to relate acceleration, change in velocity, and time.

Probeware Lab: Tossed Ball Motion
Carry out an investigation to determine how the position, velocity, and acceleration of a tossed ball change over time.

Particle model diagram What does a particle model motion diagram look like for an object with changing velocity? **Figure 2** shows particle model motion diagrams below the motion diagrams of the jogger when she is speeding up and slowing down. There are two major indicators of the change in velocity in this form of the motion diagram. The change in the spacing of the dots and the differences in the lengths of the velocity vectors indicate the changes in velocity. If an object speeds up, each subsequent velocity vector is longer, and the spacing between dots increases. If the object slows down, each vector is shorter than the previous one, and the spacing between dots decreases. Both types of motion diagrams indicate how an object's velocity is changing.

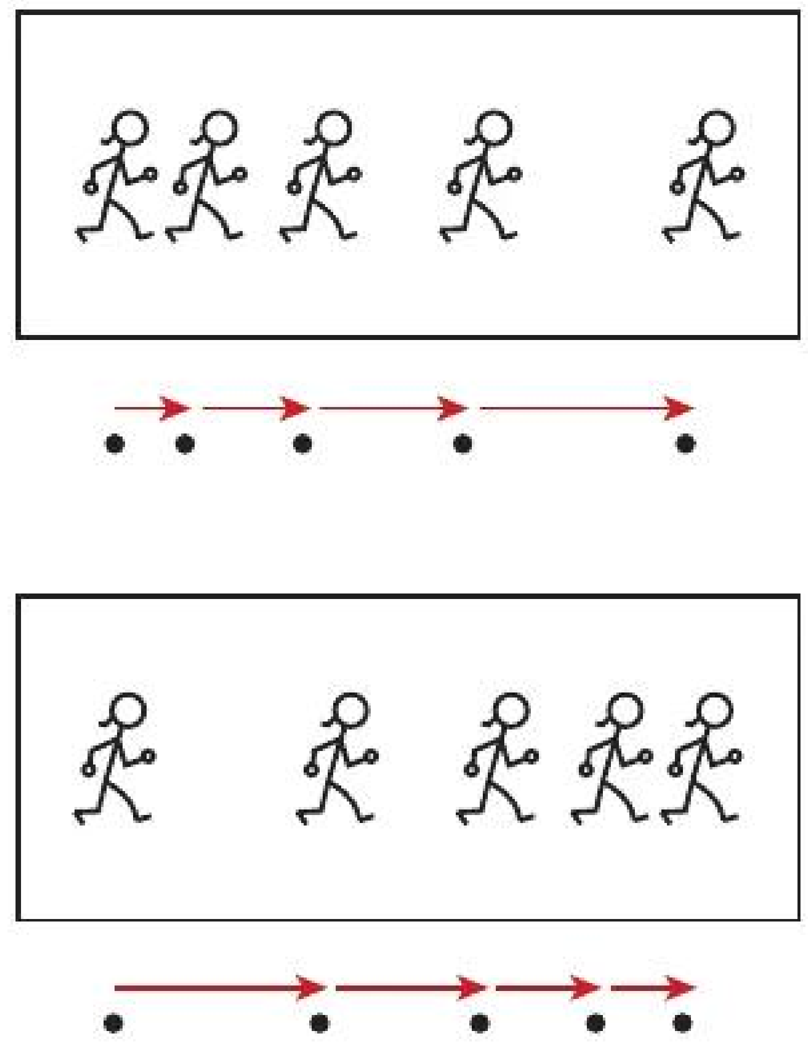


Figure 2 The change in length of the velocity vectors on these motion diagrams indicates whether the jogger is speeding up or slowing down.

Get It?

Analyze What do increasing and decreasing lengths of velocity vectors indicate on a motion diagram?

Displaying acceleration on a motion diagram For a motion diagram to give a full picture of an object's movement, it should contain information about the rate at which the object's velocity is changing. The rate at which an object's velocity changes is called the **acceleration** of the object. By including acceleration vectors on a motion diagram, you can indicate the rate of change for the velocity.

Figure 3 shows a particle motion diagram for an object with increasing velocity. Notice that the lengths of the red velocity vectors get longer from left to right along the diagram. The figure also describes how to use the diagram to draw an acceleration vector for the motion. The acceleration vector that describes the increasing velocity is shown in violet on the diagram.

Notice in the figure that if the object's acceleration is constant, you can determine the length and direction of an acceleration vector by subtracting two consecutive velocity vectors and dividing by the time interval. That is, first find the change in velocity, $\Delta v = v_f - v_i = v_f + (-v_i)$, where v_i and v_f refer to the velocities at the beginning and the end of the chosen time interval. Then divide by the time interval (Δt). The time interval between each dot in **Figure 3** is 1 s. You can draw the acceleration vector from the tail of the final velocity vector to the tip of the initial velocity vector.

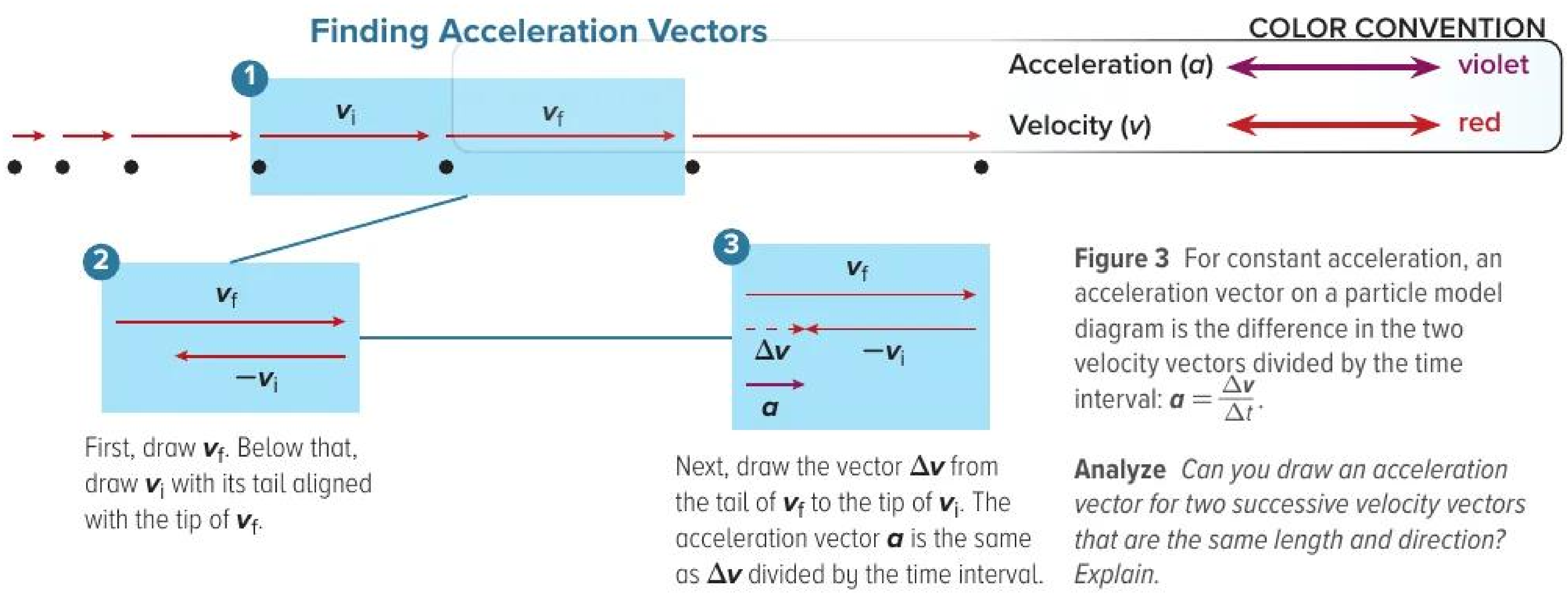


Figure 3 For constant acceleration, an acceleration vector on a particle model diagram is the difference in the two velocity vectors divided by the time interval: $a = \frac{\Delta v}{\Delta t}$.

Analyze *Can you draw an acceleration vector for two successive velocity vectors that are the same length and direction? Explain.*

Direction of Acceleration

Consider the four situations shown in **Figure 4** in which an object can accelerate by changing speed. The first motion diagram shows the car moving in the positive direction and speeding up. The second motion diagram shows the car moving in the positive direction and slowing down. The third shows the car speeding up in the negative direction, and the fourth shows the car slowing down as it moves in the negative direction. The figure also shows the velocity vectors for the second time interval of each diagram, along with the corresponding acceleration vectors. Note that Δt is equal to 1 s.

In the first and third situations, when the car is speeding up, the velocity and acceleration vectors point in the same direction. In the other two situations, in which the acceleration vector is in the opposite direction from the velocity vectors, the car is slowing down. In other words, when the car's acceleration is in the same direction as its velocity, the car's speed increases. When they are in opposite directions, the speed of the car decreases.

Both the direction of an object's velocity and its direction of acceleration are needed to determine whether it is speeding up or slowing down. An object has a positive acceleration when the acceleration vector points in the positive direction and a negative acceleration when the acceleration vector points in the negative direction. It is important to notice that the sign of acceleration alone does not indicate whether the object is speeding up or slowing down.

Get It?

Describe the motion of an object if its velocity and acceleration vectors have opposite signs.

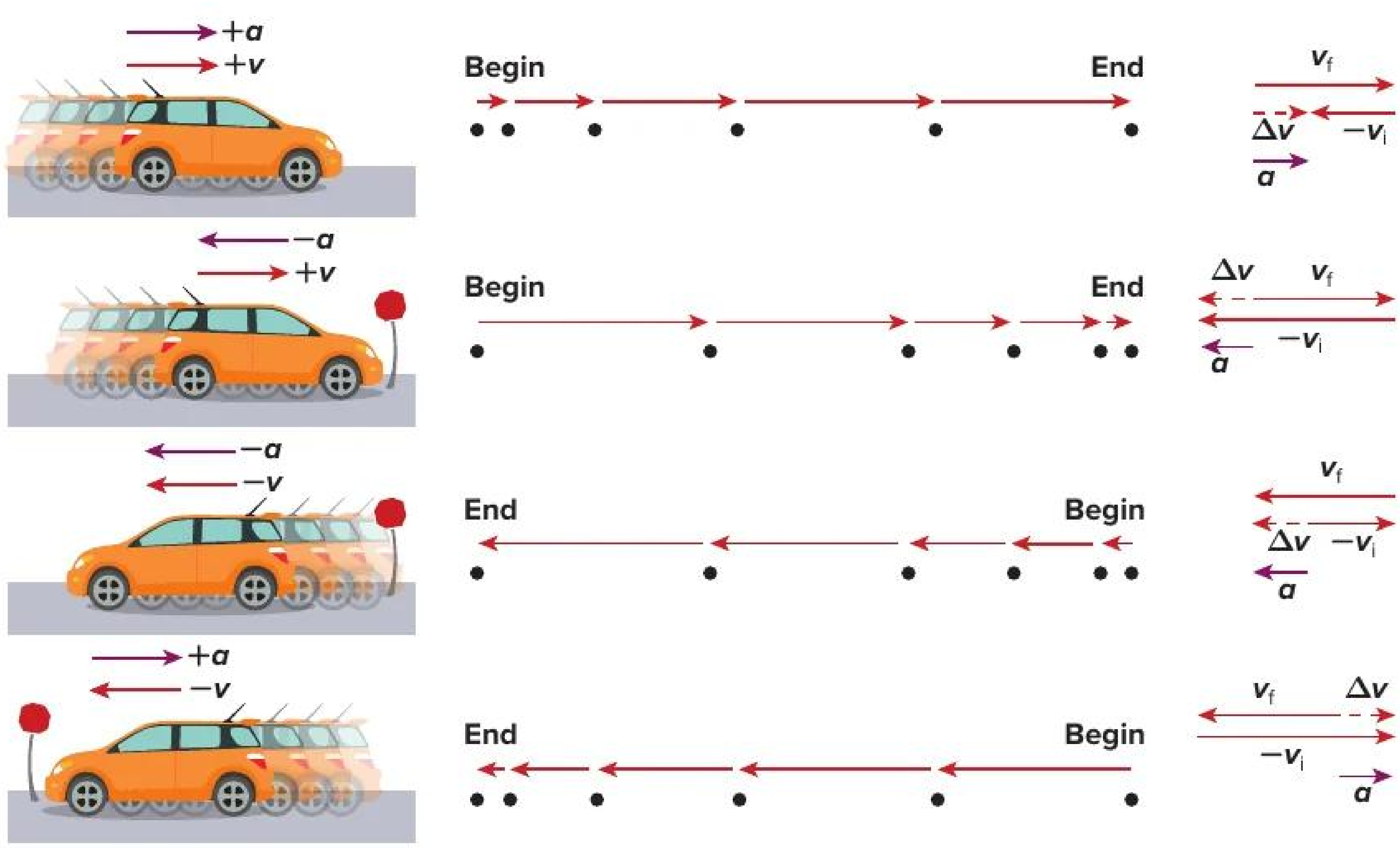


Figure 4 You need to know the direction of both the velocity and acceleration vectors in order to determine whether an object is speeding up or slowing down.

Velocity-Time Graphs

Just as it was useful to plot position versus time, it also is useful to plot velocity versus time to analyze an object's motion. On a **velocity-time graph,** or *v-t* graph, velocity is plotted on the vertical axis and time is plotted on the horizontal axis.

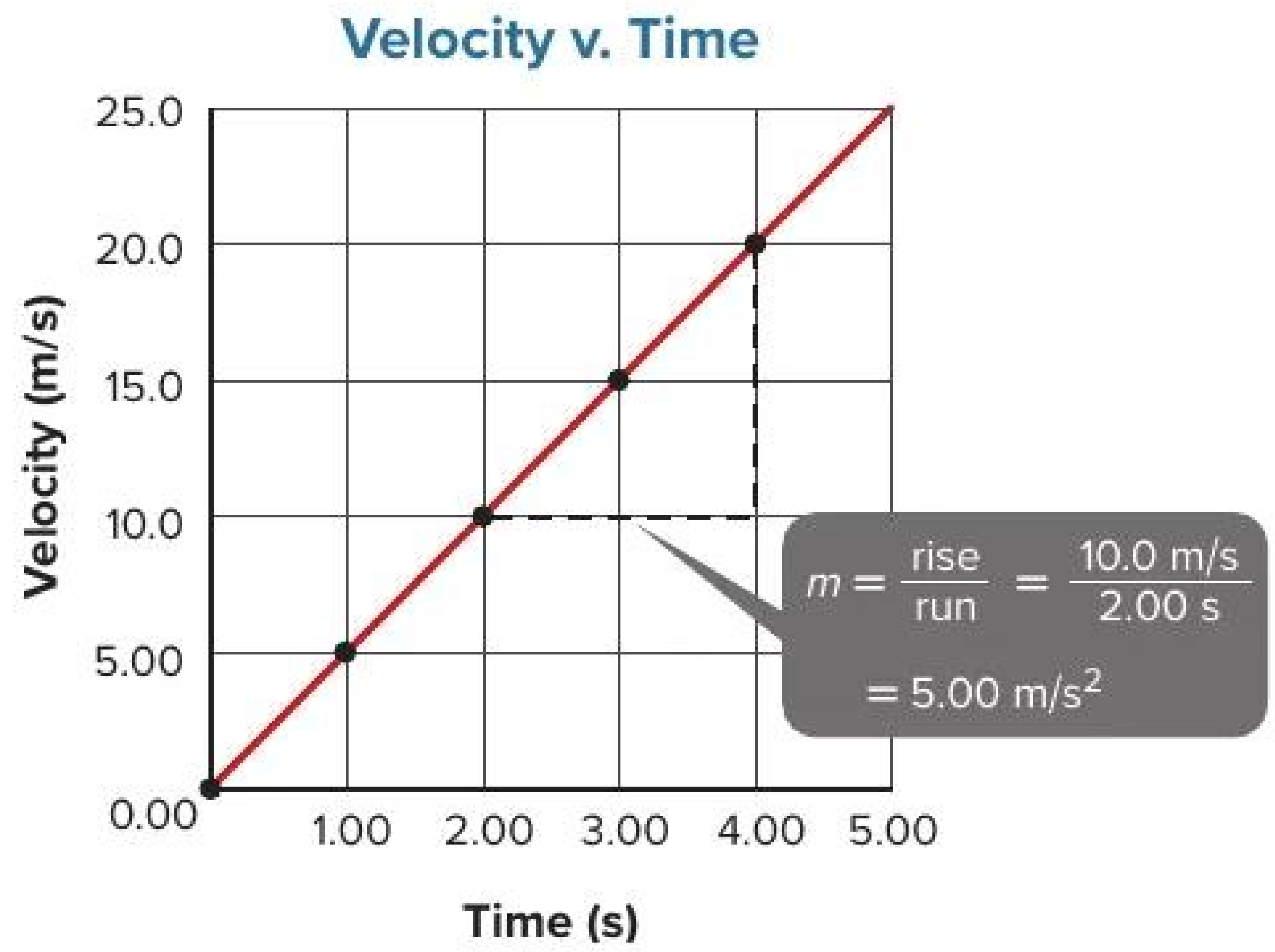


Figure 5 You can determine acceleration from a velocity-time graph by calculating the slope of the data. The slope is the rise divided by the run using any two points on the line.

Slope

The velocity-time graph for a car that started at rest and sped up along a straight stretch of road is shown in **Figure 5.** The positive direction has been chosen to be the same as that of the car's motion. Notice that the graph is a straight line. This means the car sped up at a constant rate. The rate at which the car's velocity changed can be found by calculating the slope of the velocity-time graph

> **Get It?**
> **Identify** What can you conclude about the acceleration of an object if the graph of its motion is a straight line on a velocity-time graph?

The graph shows that the slope is 5.00 (m/s)/s, which is often written as 5.00 m/s^2. Consider the time interval between 4.00 s and 5.00 s. At 4.00 s, the car's velocity was 20.0 m/s in the positive direction. At 5.00 s, the car was traveling at 25.0 m/s in the same direction. Thus, in 1.00 s, the car's velocity increased by 5.0 m/s in the positive direction. When the velocity of an object changes at a constant rate, it has a constant acceleration.

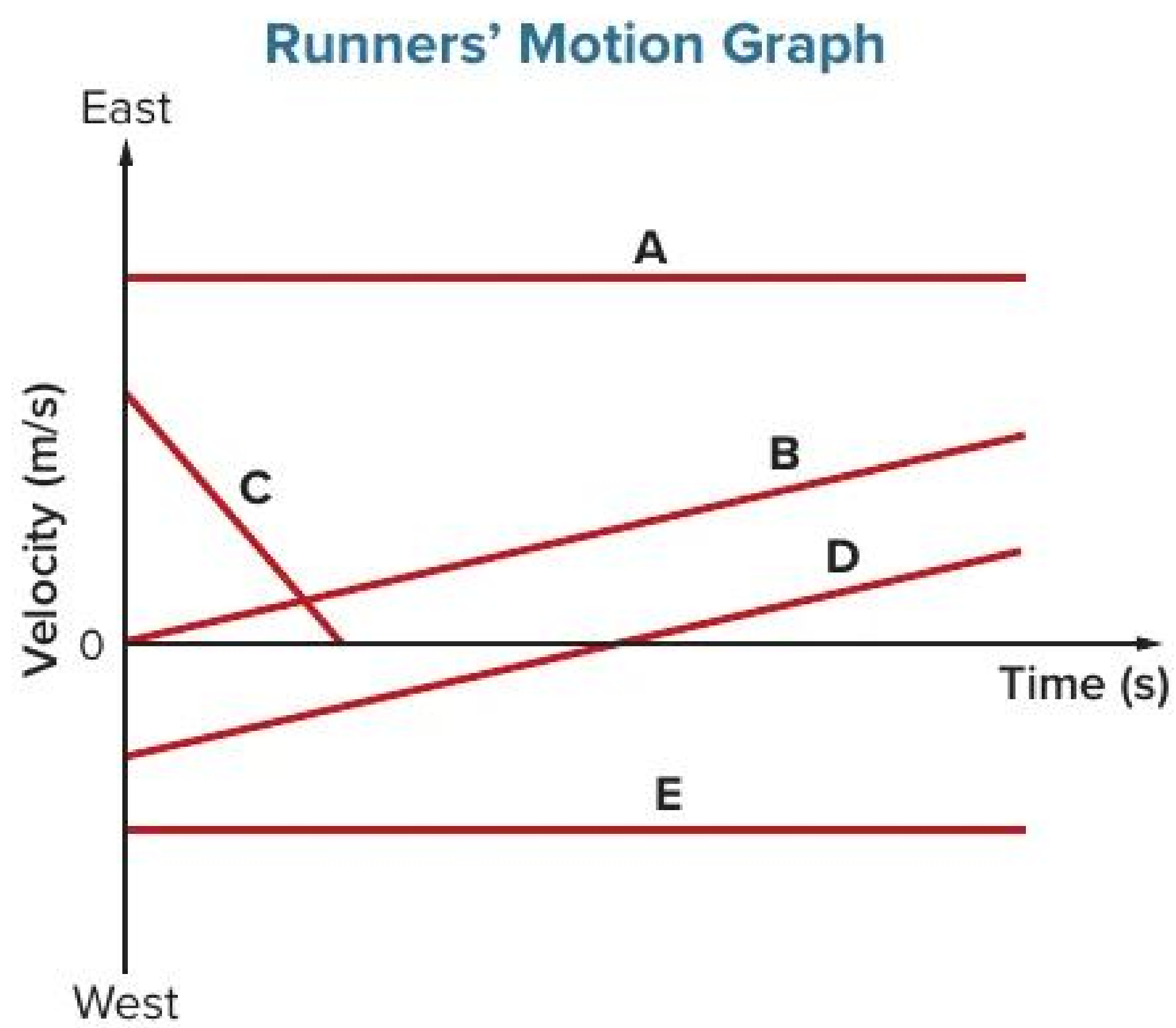


Figure 6 Because east is chosen as the positive direction on the graph, velocity is positive if the line is above the horizontal axis and negative if the line is below it. Acceleration is positive if the line is slanted upward on the graph. Acceleration is negative if the line is slanted downward on the graph. A horizontal line indicates constant velocity and zero acceleration.

Reading velocity-time graphs

The motions of five runners are shown in **Figure 6.** Assume that the positive direction is east. The slopes of Graphs A and E are zero. Thus, the accelerations are zero. Both graphs show motion at a constant velocity—Graph A to the east and Graph E to the west. Graph B shows motion with a positive velocity eastward. Its slope indicates a constant, positive acceleration. You can infer that the speed increases because velocity and acceleration are positive. Graph C has a negative slope. It shows motion that begins with a positive velocity, slows down, and then stops. This means the acceleration and the velocity are in opposite directions. The point at which Graphs C and B cross shows that the runners' velocities are equal at that time. It does not, however, identify their positions.

Graph D indicates motion that starts out toward the west, slows down, for an instant has zero velocity, and then moves east with increasing speed. The slope of Graph D is positive. Because velocity and acceleration are initially in opposite directions, the speed decreases to zero at the time the graph crosses the *x*-axis. After that time, velocity and acceleration are in the same direction, and the speed increases.

Get It?

Describe the meaning of a line crossing the *x*-axis in a velocity-time graph.

Average and Instantaneous Acceleration

How does it feel differently if the car you ride in accelerates a little or a lot? As with velocity, the acceleration of most moving objects continually changes. If you want to describe an object's acceleration, it is often more convenient to describe the overall change in velocity during a certain time interval rather than describing the continual change.

The **average acceleration** of an object is its change in velocity during some measurable time interval divided by that time interval. Average acceleration is measured in meters per second per second (m/s/s), or simply meters per second squared (m/s^2). A car might accelerate quickly at times and more slowly at times. Just as average velocity depends only on the starting and ending displacement, average acceleration depends only on the starting and ending velocity during a time interval.

Figure 7 shows a graph of motion in which the acceleration is changing. The average acceleration during a certain time interval is determined just as it is in **Figure 5** for constant acceleration. Notice, however, that because the line is curved, the average acceleration in this graph varies depending on the time interval that you choose.

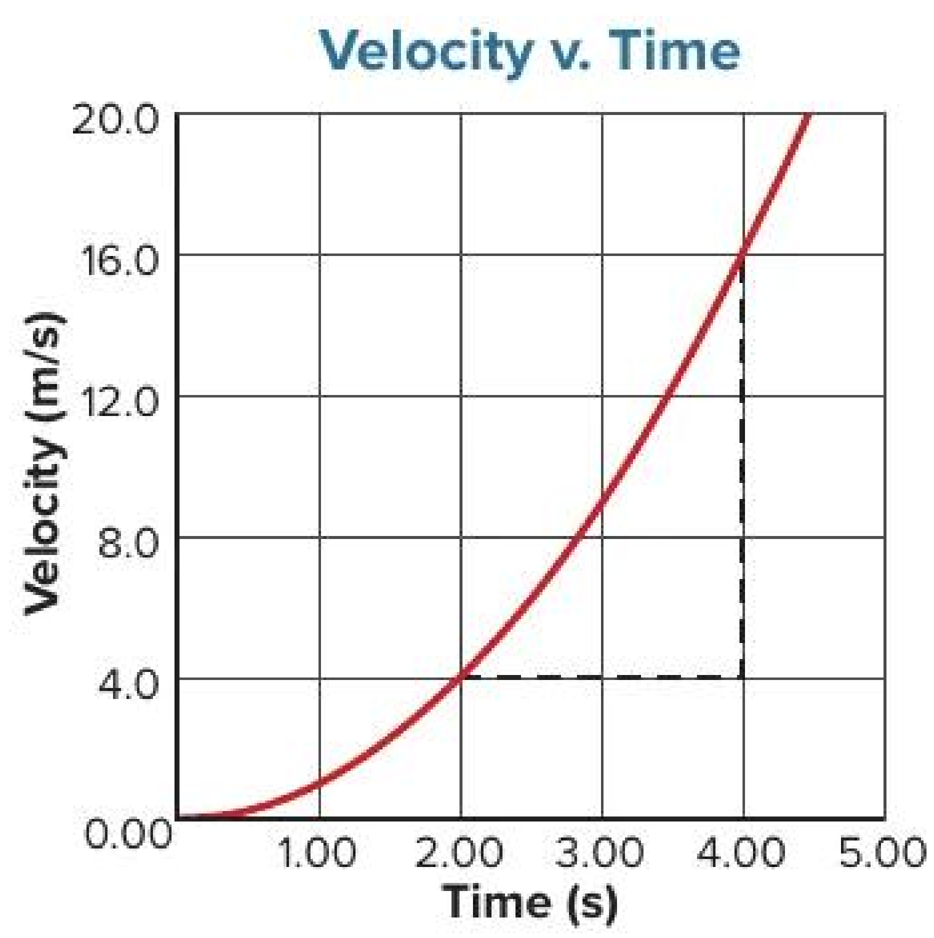


Figure 7 A curved line on a velocity-time graph shows that the acceleration is changing. The slope indicates the average acceleration during a time interval that you choose.

Calculate *How large is the average acceleration between 0.00 s and 2.00 s?*

The change in an object's velocity at an instant of time is called **instantaneous acceleration.** You can determine the instantaneous acceleration of an object by drawing a tangent line on the velocity-time graph at the point of time in which you are interested. A tangent line is a line that intersects the graph at one and only one point. The slope of this line is equal to the instantaneous acceleration. Most of the situations considered in this textbook assume an ideal case of constant acceleration. When the acceleration is the same at all points during a time interval, the average acceleration and the instantaneous accelerations are equal.

Get It?

Contrast How is instantaneous acceleration different from average acceleration?

Calculating Acceleration

How can you describe the acceleration of an object mathematically? Recall that the acceleration of an object is the slope of that object's velocity v. time graph. On a velocity v. time graph, slope equals $\frac{\Delta v}{\Delta t}$.

Average Acceleration

Average acceleration is defined as the change in velocity divided by the time it takes to make that change.

$$\bar{a} \equiv \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}$$

Suppose you run wind sprints back and forth across the gym. You run toward one wall, turn, then run toward the opposite wall. You first run at a speed of 4.0 m/s toward the wall. Then, 10.0 s later, your speed is 4.0 m/s as you run away from the wall. What is your average acceleration if the positive direction is toward the wall?

$$\bar{a} \equiv \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}$$

$$= \frac{-4.0\ \text{m/s} - 4.0\ \text{m/s}}{10.0\ \text{s}} = -0.80\ \text{m/s}^2$$

Get It?

Explain why the final velocity used in the equation is −4.0 m/s.

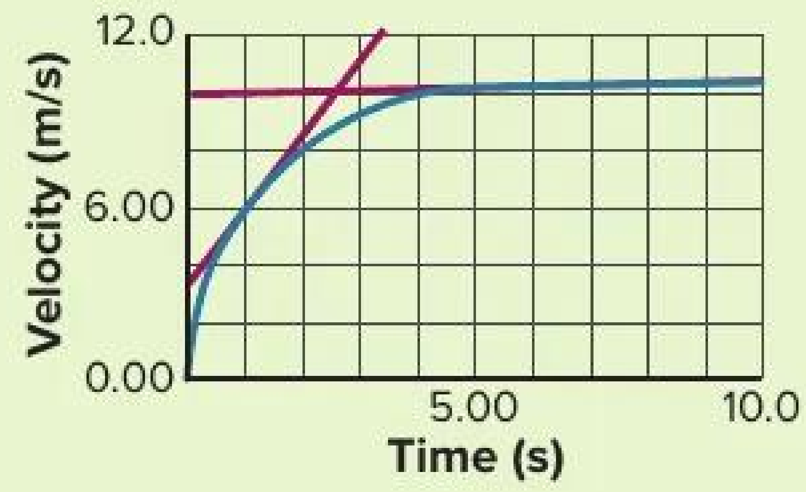
STEM CAREER Connection

Delivery Truck Driver

With more and more online sales, companies must have a way to get the products to your door. Delivery truck drivers pick up products at a distribution center and drive them to businesses and homes for delivery. Acceleration, velocity, and time are important for delivery truck drivers as they try to make their deliveries on a tight schedule.

EXAMPLE Problem 1

VELOCITY AND ACCELERATION How would you describe the sprinter's velocity and acceleration as shown on the graph?



1 ANALYZE AND SKETCH THE PROBLEM

From the graph, note that the magnitude of the sprinter's velocity starts at zero, increases rapidly for the first few seconds, and then, after reaching about 10.0 m/s, remains almost constant.

KNOWN	**UNKNOWN**
v = varies	a = ?

2 SOLVE FOR THE UNKNOWN

Draw tangents to the curve at two points. Choose t = 1.00 s and t = 5.00 s. Solve for the magnitude of the instantaneous acceleration at 1.00 s:

$$a = \frac{\text{rise}}{\text{run}}$$ The slope of the line at 1.00 s is equal to the acceleration at that time.

$$= \frac{10.0\ \text{m/s} - 6.00\ \text{m/s}}{2.4\ \text{s} - 1.00\ \text{s}}$$

$$= 2.9\ \text{m/s/s} = 2.9\ \text{m/s}^2$$

Solve for the magnitude of the instantaneous acceleration at 5.00 s:

$$a = \frac{\text{rise}}{\text{run}}$$ The slope of the line at 5.00 s is equal to the acceleration at that time.

$$= \frac{10.3\ \text{m/s} - 10.0\ \text{m/s}}{10.0\ \text{s} - 0.00\ \text{s}}$$

$$= 0.030\ \text{m/s/s} = 0.030\ \text{m/s}^2$$

The acceleration is not constant because its magnitude changes from 2.9 m/s^2 at 1.00 s to 0.030 m/s^2 at 5.00 s.

The acceleration is in the direction chosen to be positive because both values are positive.

3 EVALUATE THE ANSWER

- **Are the units correct?** Acceleration is measured in m/s^2.

PRACTICE Problems

ADDITIONAL PRACTICE

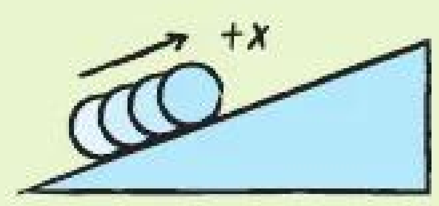
1. The velocity-time graph in **Figure 8** describes Steven's motion as he walks along the midway at the state fair. Sketch the corresponding motion diagram. Include velocity vectors in your diagram.
2. Use the *v-t* graph of the toy train in **Figure 9** to answer these questions.
   a. When is the train's speed constant?
   b. During which time interval is the train's acceleration positive?
   c. When is the train's acceleration most negative?
3. Refer to **Figure 9** to find the average acceleration of the train during the following time intervals.
   a. 0.0 s to 5.0 s **b.** 15.0 s to 20.0 s **c.** 0.0 s to 40.0 s
4. **CHALLENGE** Plot a *v-t* graph representing the following motion: An elevator starts at rest from the ground floor of a three-story shopping mall. It accelerates upward for 2.0 s at a rate of 0.5 m/s^2, continues up at a constant velocity of 1.0 m/s for 12.0 s, and then slows down with a constant downward acceleration of 0.25 m/s^2 for 4.0 s as it reaches the third floor.

Figure 8

Figure 9

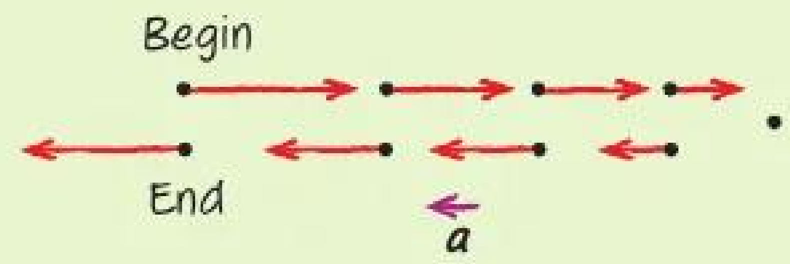
EXAMPLE Problem 2

ACCELERATION Describe a ball's motion as it rolls up a slanted driveway. It starts at 2.50 m/s, slows down for 5.00 s, stops for an instant, and then rolls back down. The positive direction is chosen to be up the driveway. The origin is where the motion begins. What are the sign and the magnitude of the ball's acceleration as it rolls up the driveway?

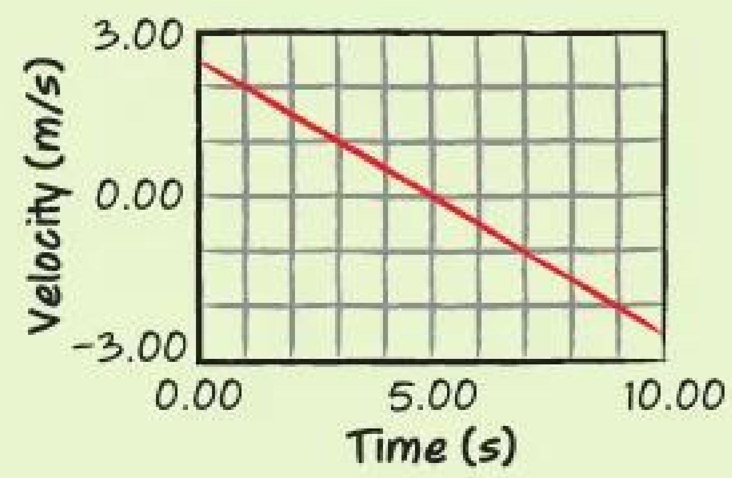


1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Draw the coordinate system based on the motion diagram.



KNOWN	UNKNOWN
$\boldsymbol{v}_i = +2.50$ m/s	$\boldsymbol{a} = ?$
$\boldsymbol{v}_f = 0.00$ m/s at $t = 5.00$ s	



2 SOLVE FOR THE UNKNOWN

Find the acceleration from the slope of the graph.

Solve for the change in velocity and the time taken to make that change.

$\Delta \boldsymbol{v} = \boldsymbol{v}_f - \boldsymbol{v}_i$

$= 0.00 \text{ m/s} - 2.50 \text{ m/s} = -2.50 \text{ m/s}$ Substitute $\boldsymbol{v}_f = 0.00$ m/s at $t_f = 5.00$ s, $\boldsymbol{v}_i = 2.50$ m/s at $t_i = 0.00$ s.

$\Delta t = t_f - t_i$

$= 5.00 \text{ s} - 0.00 \text{ s} = 5.00 \text{ s}$ Substitute $t_f = 5.00$ s, $t_i = 0.00$ s.

Solve for the acceleration.

$\bar{\boldsymbol{a}} \equiv \frac{\Delta \boldsymbol{v}}{\Delta t} = (-2.50 \text{ m/s}) / 5.00 \text{ s}$ Substitute $\Delta \boldsymbol{v} = -2.50$ m/s, $\Delta t = 5.00$ s.

$= -0.500 \text{ m/s}^2$ or 0.500 m/s^2 down the driveway

3 EVALUATE THE ANSWER

- **Are the units correct?** Acceleration is measured in m/s^2.
- **Do the directions make sense?** As the ball slows down, the direction of acceleration is opposite that of velocity.

PRACTICE Problems — ADDITIONAL PRACTICE

5. A race car's forward velocity increases from 4.0 m/s to 36 m/s over a 4.0-s time interval. What is its average acceleration?

6. The race car in the previous problem slows from 36 m/s to 15 m/s over 3.0 s. What is its average acceleration?

7. A bus is moving west at 25 m/s when the driver steps on the brakes and brings the bus to a stop in 3.0 s.

  a. What is the average acceleration of the bus while braking?

  b. If the bus took twice as long to stop, how would the acceleration compare with what you found in part **a?**

8. A car is coasting backward downhill at a speed of 3.0 m/s when the driver gets the engine started. After 2.5 s, the car is moving uphill at 4.5 m/s. If uphill is chosen as the positive direction, what is the car's average acceleration?

9. Rohith has been jogging east toward the bus stop at 3.5 m/s when he looks at his watch and sees that he has plenty of time before the bus arrives. Over the next 10.0 s, he slows his pace to a leisurely 0.75 m/s. What was his average acceleration during this 10.0 s?

10. **CHALLENGE** If the rate of continental drift were to abruptly slow from 1.0 cm/y to 0.5 cm/y over the time interval of a year, what would be the average acceleration?

Acceleration with Constant Speed

Think again about running wind sprints across the gym. You first run at a speed of 4.0 m/s toward the wall. Then, 10.0 s later, you are running away from the wall and your speed is 4.0 m/s. Notice that your speed is the same as you move toward the wall of the gym and as you move away from it. In both cases, you are running at a speed of 4.0 m/s. How is it possible for you to be accelerating?

Acceleration can occur even when speed is constant. The average acceleration for the entire trip you make toward the wall of the gym and back again is $-0.80\ m/s^2$. The negative sign indicates that the direction of your acceleration is away from the wall because the positive direction was chosen as toward the wall. The velocity changes from positive to negative when the direction of motion changes. A change in velocity results in acceleration. Thus, acceleration can also be associated with a change in the direction of motion.

Get It?

Describe the evidence that the planes at the beginning of this module are accelerating even if they are traveling at a constant speed.

Check Your Progress

11. **Describing Motion** What are three ways an object can accelerate?
12. **Position-Time and Velocity-Time Graphs** Two joggers run at a constant velocity of 7.5 m/s east. **Figure 10** shows the positions of both joggers at time $t = 0$.
    a. What would be the difference(s) in the position-time graphs of their motion?
    b. What would be the difference(s) in their velocity-time graphs?

Figure 10

13. **Velocity-Time Graph** Sketch a velocity-time graph for a car that goes east at 25 m/s for 100 s, then west at 25 m/s for another 100 s.
14. **Average Velocity and Average Acceleration** A canoeist paddles upstream at a velocity of 2.0 m/s for 4.0 s and then floats downstream at 4.0 m/s for 4.0 s.
    a. What is the average velocity of the canoe during the 8.0-s time interval?
    b. What is the average acceleration of the canoe during the 8.0-s time interval?
15. **Critical Thinking** A police officer clocked a driver going 32 km/h over the speed limit just as the driver passed a slower car. When the officer stopped the car, the driver argued that the other driver should get a ticket as well. The driver said that the cars must have been going the same speed because they were observed next to each other. Is the driver correct? Explain with a sketch and a motion diagram.

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LESSON 2

MOTION WITH CONSTANT ACCELERATION

FOCUS QUESTION

How are position, velocity, acceleration, and time related?

Position with Constant Acceleration

If an object experiences constant acceleration, its velocity changes at a constant rate. How does its position change? The positions at different times of a car with constant acceleration are graphed in **Figure 11.** The graph shows that the car's motion is not uniform. The displacements for equal time intervals on the graph get larger and larger. As a result, the slope of the line in **Figure 11** gets steeper as time goes on. For an object with constant acceleration, the position-time graph is a parabola.

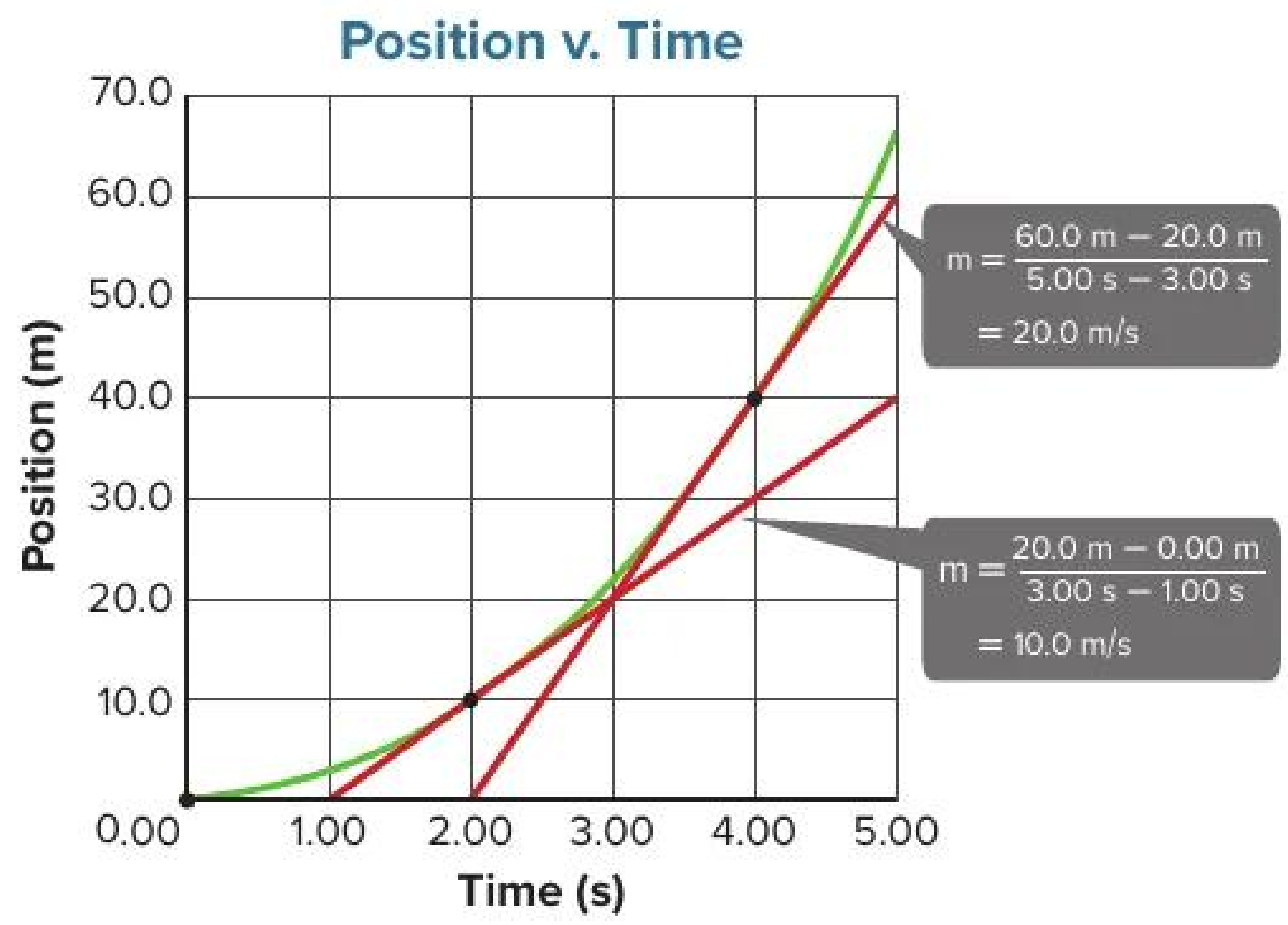


Figure 11 The slope of a position-time graph changes with time for an object with constant acceleration.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

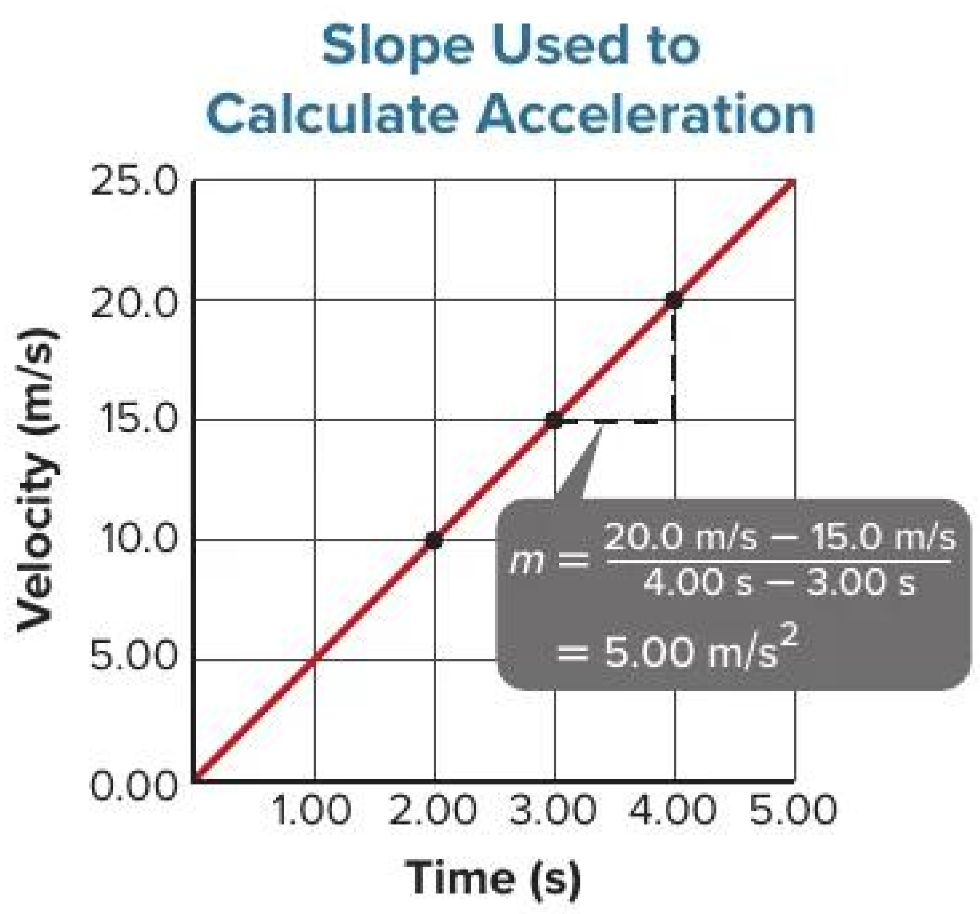
GO ONLINE to find these activities and more resources.

Probeware Lab: Measuring Acceleration

Analyze data to determine how the displacement, velocity, and acceleration of an object change over time.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.



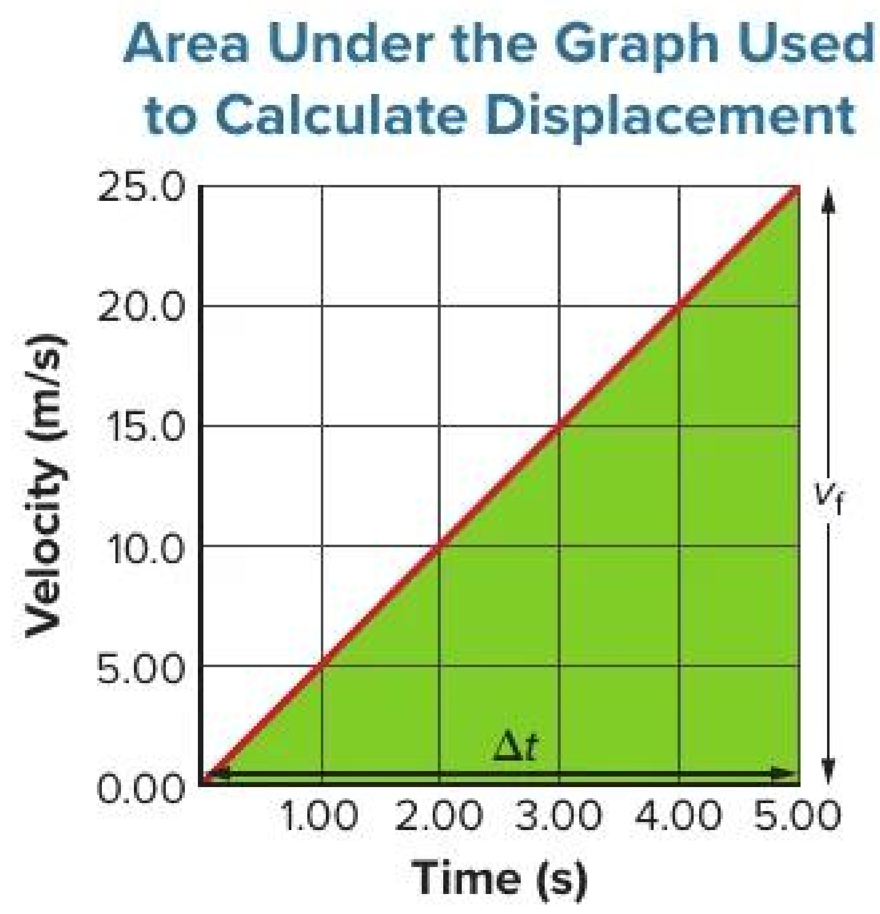


Figure 12 The slopes of the position-time graph in **Figure 11** are shown in these velocity-time graphs. The rise divided by the run gives the acceleration on the left. The area under the curve gives the displacement on the right.

Calculate *What is the slope of the velocity-time graph on the left between t = 2.00 s and t = 5.00 s?*

The slopes from the position-time graph in **Figure 11** have been used to create the velocity-time graph on the left in **Figure 12.** For an object with constant acceleration, the velocity-time graph is a straight line.

Get It?

Identify What is the shape of a position-time graph of an object traveling with constant acceleration?

A unique position-time graph cannot be created using a velocity-time graph because it does not contain information about position. It does, however, contain information about displacement. Recall that for an object moving at a constant velocity, the velocity is the displacement divided by the time interval. The displacement is then the product of the velocity and the time interval. On the right graph in **Figure 12**, v is the height of the plotted line above the horizontal axis, and Δt is the width of the shaded triangle. The area is $\left(\frac{1}{2}\right)v\Delta t$, or Δx. Thus, the area under the v-t graph equals the displacement.

Get It?

Identify What is the shape of a velocity-time graph of an object traveling with constant acceleration?

Velocity with Average Acceleration

You have read that the equation for average velocity can be algebraically rearranged to show the new position after a period of time, given the initial position and the average velocity. The definition of average acceleration can be manipulated similarly to show the new velocity after a period of time, given the initial velocity and the average acceleration.

If you know an object's average acceleration during a time interval, you can use it to determine how much the velocity changed during that time.

You can rewrite the definition of average acceleration $\left(\bar{a} \equiv \frac{\Delta v}{\Delta t}\right)$ as follows:

$$\Delta v = \bar{a}\Delta t$$

$$v_f - v_i = \bar{a}\Delta t$$

The equation for final velocity with average acceleration can be written:

Final Velocity with Average Acceleration

The final velocity is equal to the initial velocity plus the product of the average acceleration and the time interval.

$$v_f = v_i + \bar{a}\Delta t$$

In cases when the acceleration is constant, the average acceleration ($\bar{a}$) is the same as the instantaneous acceleration (a) at any point within the time interval. This equation can be rearranged to find the time at which an object with constant acceleration has a given velocity. You can also use it to calculate the initial velocity of an object when both a velocity and the time at which it occurred are given.

Real-World Physics

DRAG RACING A dragster driver tries to obtain maximum acceleration over a course. The fastest U.S. National Hot Rod Association time on record for the 402-m course is 3.771 s. The highest final speed on record is 145.3 m/s (324.98 mph).

PRACTICE Problems ADDITIONAL PRACTICE

16. A golf ball rolls up a hill toward a miniature-golf hole. Assume the direction toward the hole is positive.

a. If the golf ball starts with a speed of 2.0 m/s and slows at a constant rate of 0.50 m/s², what is its velocity after 2.0 s?

b. What is the golf ball's velocity if the constant acceleration continues for 6.0 s?

c. Describe the motion of the golf ball in words and with a motion diagram.

17. A bus traveling 30.0 km/h east has a constant increase in speed of 1.5 m/s². What is its velocity 6.8 s later?

18. If a car accelerates from rest at a constant rate of 5.5 m/s² north, how long will it take for the car to reach a velocity of 28 m/s north?

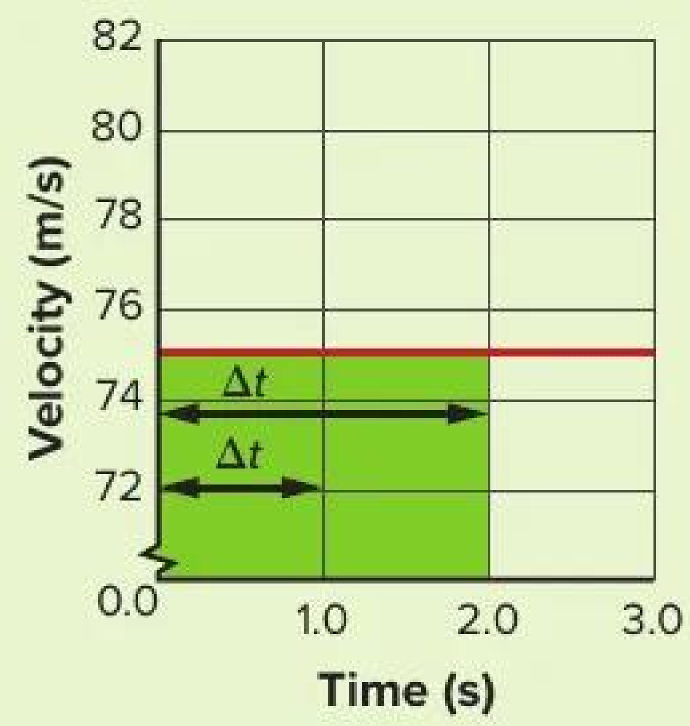
19. CHALLENGE A car slows from 22 m/s to 3.0 m/s at a constant rate of 2.1 m/s². How many seconds are required before the car is traveling at a forward velocity of 3.0 m/s?

CCC CROSSCUTTING CONCEPTS

Scale, Proportion, and Quantity Using algebraic thinking, draw a conclusion about how changes in the initial velocity of an object affects the final position of the object. Make a table that provides evidence to support your conclusions.

EXAMPLE Problem 3

FINDING DISPLACEMENT FROM A VELOCITY-TIME GRAPH The velocity-time graph at the right shows the motion of an airplane. Find the displacement of the airplane for $\Delta t = 1.0$ s and for $\Delta t = 2.0$ s. Let the positive direction be forward.



1 ANALYZE AND SKETCH THE PROBLEM

- The displacement is the area under the *v-t* graph.
- The time intervals begin at $t = 0.0$ s.

KNOWN	UNKNOWN
$\boldsymbol{v} = +75$ m/s	$\Delta \boldsymbol{x} = ?$
$\Delta t = 1.0$ s	
$\Delta t = 2.0$ s	

2 SOLVE FOR THE UNKNOWN

Use the relationship among displacement, velocity, and time interval to find $\Delta \boldsymbol{x}$ during $\Delta t = 1.0$ s.

$$\Delta x = v\Delta t$$
$$= (+75 \text{ m/s})(1.0 \text{ s}) \quad \text{Substitute } \boldsymbol{v} = +75 \text{ m/s}, \Delta t = 1.0 \text{ s.}$$
$$= +75 \text{ m}$$

Use the same relationship to find $\Delta \boldsymbol{x}$ during $\Delta t = 2.0$ s.

$$\Delta x = v\Delta t$$
$$= (+75 \text{ m/s})(2.0 \text{ s}) \quad \text{Substitute } \boldsymbol{v} = +75 \text{ m/s}, \Delta t = 2.0 \text{ s.}$$
$$= +150 \text{ m}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Displacement is measured in meters.
- **Do the signs make sense?** The positive sign agrees with the graph.
- **Is the magnitude realistic?** Moving a distance of about one football field per second is reasonable for an airplane.

PRACTICE Problems

ADDITIONAL PRACTICE

20. The graph in **Figure 13** describes the motion of two bicyclists, Akiko and Brian, who start from rest and travel north, increasing their speed with a constant acceleration. What was the total displacement of each bicyclist during the time shown for each?

Hint: Use the area of a triangle: area = $\left(\frac{1}{2}\right)$*(base)(height).*

21. The motion of two people, Carlos and Diana, moving south along a straight path is described by the graph in **Figure 14.** What is the total displacement of each person during the first 4.0-s interval shown on the graph?

22. CHALLENGE A car, just pulling onto a straight stretch of highway, has a constant acceleration from 0 m/s to 25 m/s west in 12 s.

a. Draw a *v-t* graph of the car's motion.

b. Use the graph to determine the car's displacement during the 12.0-s time interval.

c. Another car is traveling along the same stretch of highway. It travels the same distance in the same time as the first car, but its velocity is constant. Draw a *v-t* graph for this car's motion.

d. Explain how you knew this car's velocity.

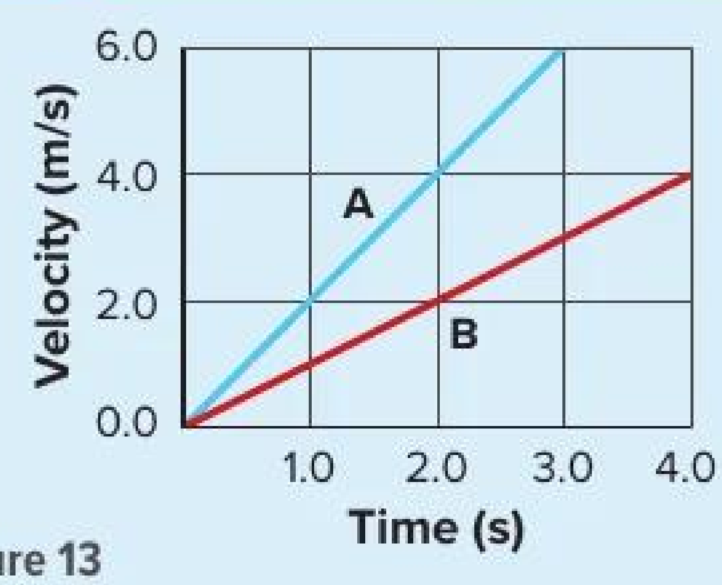


Figure 13

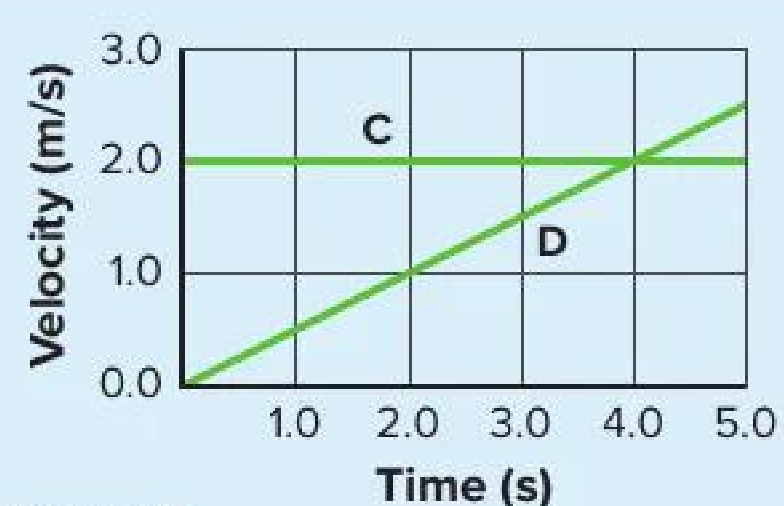


Figure 14

Motion with an initial nonzero velocity The graph in **Figure 15** describes constant acceleration that started with an initial velocity of v_i. To determine the displacement, you can divide the area under the graph into a rectangle and a triangle. The total area is then:

$$\Delta x = \Delta x_{\text{rectangle}} + \Delta x_{\text{triangle}} = v_i(\Delta t) + \left(\frac{1}{2}\right)\Delta v \Delta t$$

Substituting $a\Delta t$ for the change in velocity in the equation yields:

$$\Delta x = \Delta x_{\text{rectangle}} + \Delta x_{\text{triangle}} = v_i(\Delta t) + \left(\frac{1}{2}\right)a(\Delta t)^2$$

When the initial or final position of the object is known, the equation can be written as follows:

$$x_f - x_i = v_i(\Delta t) + \left(\frac{1}{2}\right)a(\Delta t)^2 \text{ or } x_f = x_i + v_i(\Delta t) + \left(\frac{1}{2}\right)a(\Delta t)^2$$

If the initial time is $t_i = 0$, the equation then becomes the following.

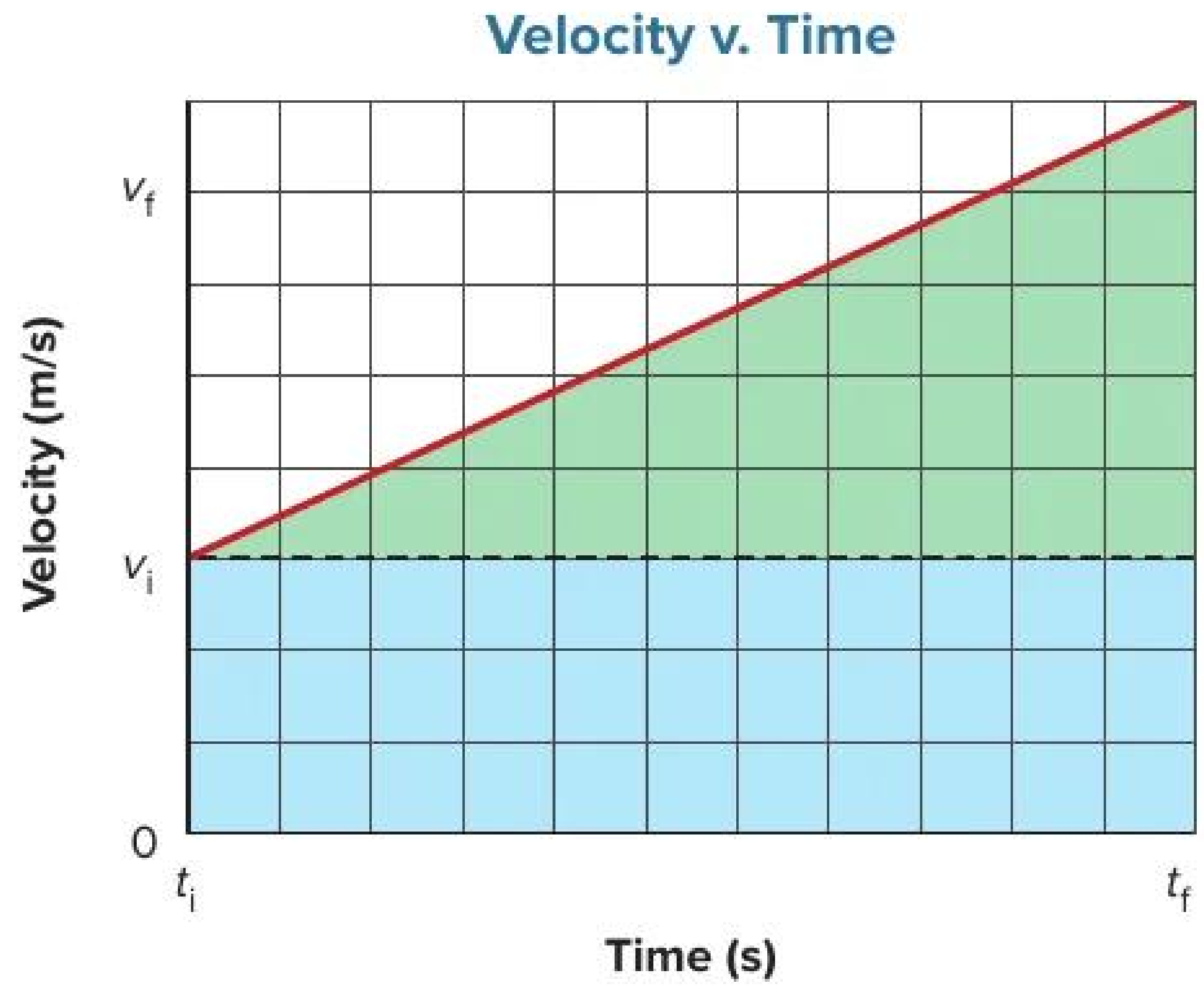


Figure 15 For motion with constant acceleration, if the initial velocity on a velocity-time graph is not zero, the area under the graph is the sum of a rectangular area and a triangular area.

Position with Average Acceleration

An object's final position is equal to the sum of its initial position, the product of the initial velocity and the final time, and half the product of the acceleration and the square of the final time.

$$x_f = x_i + v_i t_f + \left(\frac{1}{2}\right)a t_f^2$$

An Alternative Equation

Often, it is useful to relate position, velocity, and constant acceleration without including time.

Rearrange the equation $v_f = v_i + at_f$ to solve for time: $t_f = \frac{v_f - v_i}{a}$.

You can then rewrite the position with average acceleration equation by substituting t_f to obtain the following:

$$x_f = x_i + v_i\left(\frac{v_f - v_i}{a}\right) + \left(\frac{1}{2}\right)a\left(\frac{v_f - v_i}{a}\right)^2$$

This equation can be solved for the velocity (v_f) at any position (x_f).

Velocity with Constant Acceleration

The square of the final velocity equals the sum of the square of the initial velocity and twice the product of the acceleration and the displacement since the initial time.

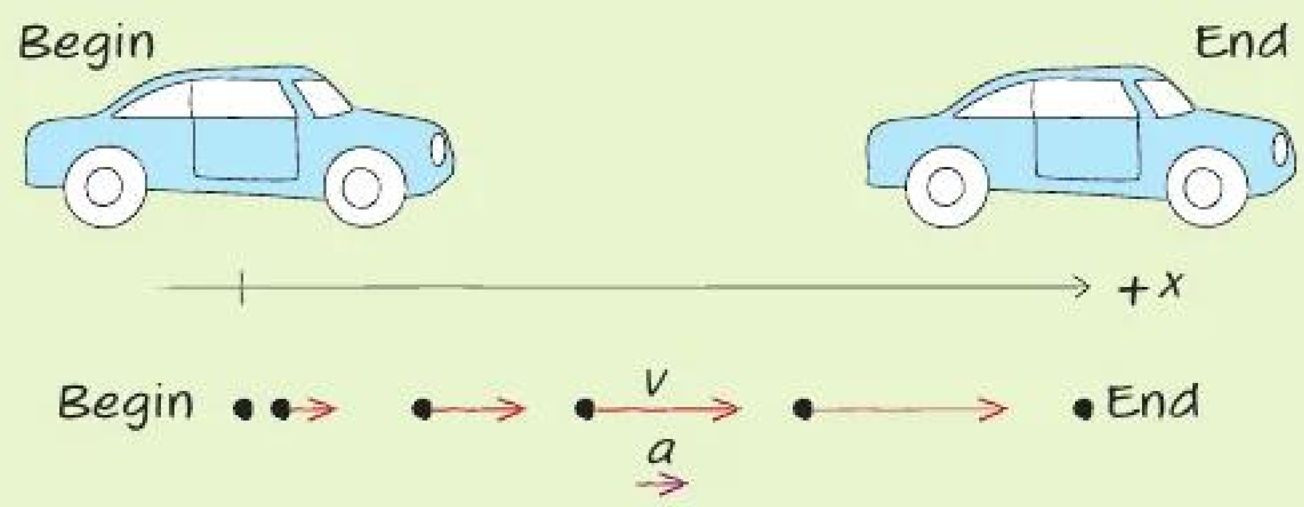
$$v_f^2 = v_i^2 + 2a(x_f - x_i)$$

EXAMPLE Problem 4

DISPLACEMENT An automobile starts at rest and accelerates at 3.5 m/s² after a traffic light turns green. How far will it have gone when it is traveling at 25 m/s?

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Establish coordinate axes. Let the positive direction be to the right.
- Draw a motion diagram.



KNOWN	UNKNOWN
$x_i = 0.00$ m	$x_f = ?$
$v_i = 0.00$ m/s	
$v_f = +25$ m/s	
$\bar{a} = a = +3.5$ m/s²	

2 SOLVE FOR THE UNKNOWN

Use the relationship among velocity, acceleration, and displacement to find x_f.

$$v_f^2 = v_i^2 + 2a(x_f - x_i)$$

$$x_f = x_i + \frac{v_f^2 - v_i^2}{2a}$$

$$= 0.00\text{ m} + \frac{(+25\text{ m/s})^2 - (0.00\text{ m/s})^2}{2(+3.5\text{ m/s}^2)}$$

Substitute $x_i = 0.00$ m, $v_f = +25$ m/s, $v_i = 0.00$ m/s, $a = +3.5$ m/s².

$$= +89\text{ m}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Position is measured in meters.
- **Do the signs make sense?** The positive sign agrees with both the pictorial and physical models.
- **Is the magnitude realistic?** The displacement is almost the length of a football field. The result is reasonable because 25 m/s (about 55 mph) is fast.

PRACTICE Problems

ADDITIONAL PRACTICE

23. A skateboarder is moving at a constant speed of 1.75 m/s when she starts up an incline that causes her to slow down with a constant acceleration of –0.20 m/s². How much time passes from when she begins to slow down until she begins to move back down the incline?

24. A race car travels on a straight racetrack with a forward velocity of 44 m/s and slows at a constant rate to a velocity of 22 m/s over 11 s. How far does it move during this time?

25. A car accelerates at a constant rate from 15 m/s to 25 m/s while it travels a distance of 125 m. How long does it take to achieve the final speed?

26. A bike rider pedals with constant acceleration to reach a velocity of 7.5 m/s north over a time of 4.5 s. During the period of acceleration, the bike's displacement is 19 m north. What was the initial velocity of the bike?

27. CHALLENGE The car in **Figure 16** travels west with a forward acceleration of 0.22 m/s². What was the car's velocity ($\boldsymbol{v}_i$) at point $\boldsymbol{x}_i$ if it travels a distance of 350 m in 18.4 s?

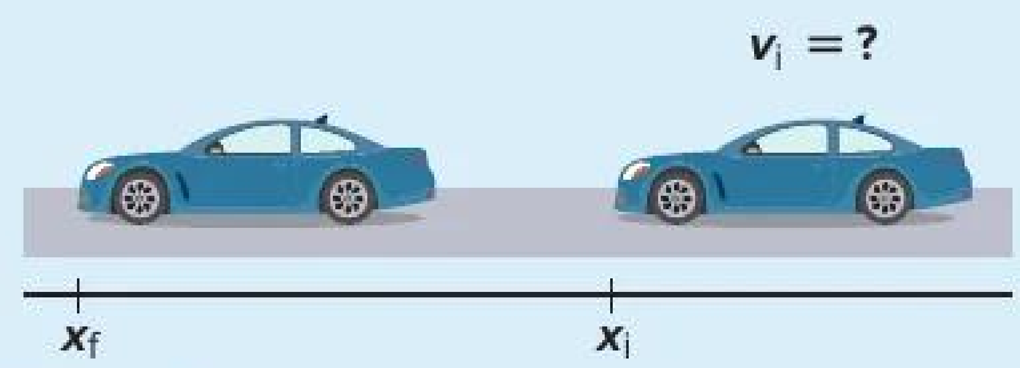


Figure 16

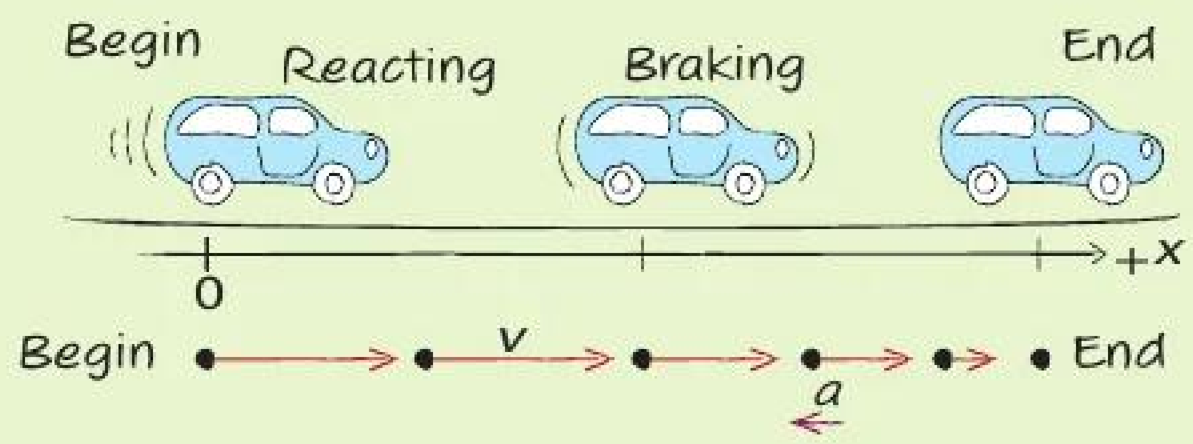
EXAMPLE Problem 5

TWO-PART MOTION You are driving a car, traveling at a constant velocity of 25 m/s along a straight road, when you see a child suddenly run onto the road. It takes 0.45 s for you to react and apply the brakes. As a result, the car slows with a steady acceleration of 8.5 m/s² in the direction opposite your motion and comes to a stop. What is the total displacement of the car before it stops?

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Choose a coordinate system with the motion of the car in the positive direction.
- Draw the motion diagram, and label $\boldsymbol{v}$ and $\boldsymbol{a}$.

KNOWN	UNKNOWN
$\boldsymbol{v}_{\text{reacting}} = +25$ m/s	$\boldsymbol{x}_{\text{reacting}} = ?$
$t_{\text{reacting}} = 0.45$ s	$\boldsymbol{x}_{\text{braking}} = ?$
$\boldsymbol{a}_{\text{braking}} = -8.5$ m/s²	$\boldsymbol{x}_{\text{total}} = ?$
$\boldsymbol{v}_{\text{i, braking}} = +25$ m/s	
$\boldsymbol{v}_{\text{f, braking}} = 0.00$ m/s	



2 SOLVE FOR THE UNKNOWN

Reacting:

Use the relationship among displacement, velocity, and time interval to find the displacement of the car as it travels at a constant speed.

$\boldsymbol{x}_{\text{reacting}} = \boldsymbol{v}_{\text{reacting}}\, t_{\text{reacting}}$

$\boldsymbol{x}_{\text{reacting}} = (+25 \text{ m/s})(0.45 \text{ s})$ Substitute $\boldsymbol{v}_{\text{reacting}} = +25$ m/s, $t_{\text{reacting}} = 0.45$ s.

$= +11$ m

Braking:

Use the relationship among velocity, acceleration, and displacement to find the displacement of the car while it is braking.

$v_{\text{f, braking}}{}^2 = v_{\text{reacting}}{}^2 + 2a_{\text{braking}}(x_{\text{braking}})$

Solve for x_{braking}.

$$x_{\text{braking}} = \frac{v_{\text{f, braking}}{}^2 - v_{\text{reacting}}{}^2}{2a_{\text{braking}}}$$

$$= \frac{(0.00 \text{ m/s})^2 - (+25 \text{ m/s})^2}{2(-8.5 \text{ m/s}^2)}$$ Substitute $v_{\text{f, braking}} = 0.00$ m/s, $v_{\text{reacting}} = +25$ m/s, $a_{\text{braking}} = -8.5$ m/s².

$= +37$ m

The total displacement is the sum of the reacting displacement and the braking displacement.

Solve for $\boldsymbol{x}_{\text{total}}$.

$\boldsymbol{x}_{\text{total}} = \boldsymbol{x}_{\text{reacting}} + \boldsymbol{x}_{\text{braking}}$

$= +11 \text{ m} + 37 \text{ m}$ Substitute $\boldsymbol{x}_{\text{reacting}} = +11$ m, $\boldsymbol{x}_{\text{braking}} = +37$ m.

$= +48$ m

3 EVALUATE THE ANSWER

- **Are the units correct?** Displacement is measured in meters.
- **Do the signs make sense?** Both xreacting and xbraking are positive, as they should be.
- **Is the magnitude realistic?** The braking displacement is small because the magnitude of the acceleration is large.

PRACTICE Problems

ADDITIONAL PRACTICE

28. A car with an initial velocity of 24.5 m/s east has an acceleration of 4.2 m/s^2 west. What is its displacement at the moment that its velocity is 18.3 m/s east?

29. A man runs along the path shown in **Figure 17.** From point A to point B, he runs at a forward velocity of 4.5 m/s for 15.0 min. From point B to point C, he runs up a hill. He slows down at a constant rate of 0.050 m/s^2 for 90.0 s and comes to a stop at point C. What was the total distance the man ran?

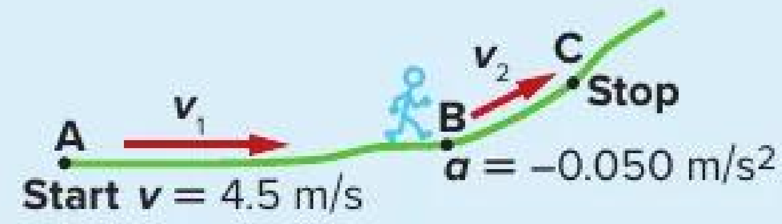


Figure 17

30. You start your bicycle ride at the top of a hill. You coast down the hill at a constant acceleration of 2.00 m/s^2. When you get to the bottom of the hill, you are moving at 18.0 m/s, and you pedal to maintain that speed. If you continue at this speed for 1.00 min, how far will you have gone from the time you left the hilltop?

31. Sunee is training for a 5.0-km race. She starts out her training run by moving at a constant pace of 4.3 m/s for 19 min. Then she accelerates at a constant rate until she crosses the finish line 19.4 s later. What is her acceleration during the last portion of the training run?

32. CHALLENGE Sekazi is learning to ride a bike without training wheels. His father pushes him with a constant acceleration of 0.50 m/s^2 east for 6.0 s. Sekazi then travels at 3.0 m/s east for another 6.0 s before falling. What is Sekazi's displacement? Solve this problem by constructing a velocity-time graph for Sekazi's motion and computing the area underneath the graphed line.

Check Your Progress

33. **Displacement** Given initial and final velocities and the constant acceleration of an object, what mathematical relationship would you use to find the displacement?

34. **Acceleration** A woman driving west along a straight road at a speed of 23 m/s sees a deer on the road ahead. She applies the brakes when she is 210 m from the deer. If the deer does not move and the car stops right before it hits the deer, what is the acceleration provided by the car's brakes?

35. **Distance** The airplane in **Figure 18** starts from rest and accelerates east at a constant 3.00 m/s^2 for 30.0 s before leaving the ground.
    a. What was the plane's displacement (Δx)?
    b. How fast was the airplane going when it took off?

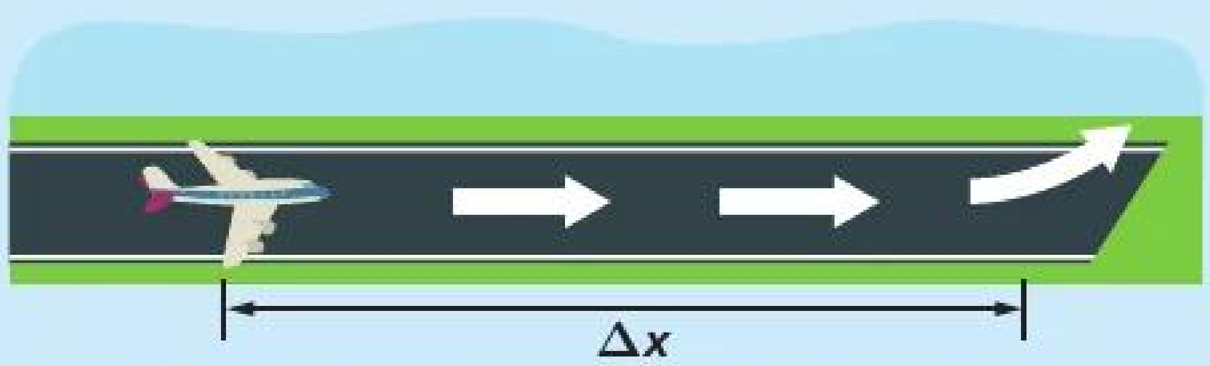


Figure 18

36. **Distance** An in-line skater accelerates from 0.0 m/s to 5.0 m/s in 4.5 s, then continues at this constant speed for another 4.5 s. What is the total distance traveled by the in-line skater?

37. **Final Velocity** A plane travels 5.0×10^2 m north while accelerating uniformly from rest at 5.0 m/s^2. What final velocity does it attain?

38. **Final Velocity** An airplane accelerated uniformly from rest at the rate of 5.0 m/s^2 south for 14 s. What final velocity did it attain?

39. **Graphs** A sprinter walks to the starting blocks at a constant speed, then waits. When the starting pistol sounds, she accelerates rapidly until she attains a constant velocity. She maintains this velocity until she crosses the finish line, and then she slows to a walk, taking more time to slow down than she did to speed up at the beginning of the race. Sketch a velocity-time and a position-time graph to represent her motion. Draw them one above the other using the same time scale. Indicate on your position-time graph where the starting blocks and finish line are.

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LESSON 3

FREE FALL

FOCUS QUESTION

How does an object's speed change as it falls?

Galileo's Discovery

Do heavier objects accelerate more as they fall? If you release a paper and a book, the book hits the ground first. But if you put the paper flat on the book, they fall together. Collisions with particles of air have a greater effect on the paper. To understand falling objects, first consider the case in which air does not have an appreciable effect on motion. Recall that gravity is an attraction between objects. **Free fall** is the motion of an object when gravity is the only significant force acting on it.

About 400 years ago, Galileo Galilei discovered that, neglecting the effect of the air, all objects in free fall have the same acceleration. It doesn't matter what they are made of or how much they weigh. The acceleration of an object due only to the effect of gravity is known as **free-fall acceleration.** **Figure 19** depicts the results of a 1971 free-fall experiment on the Moon in which astronauts verified Galileo's results.

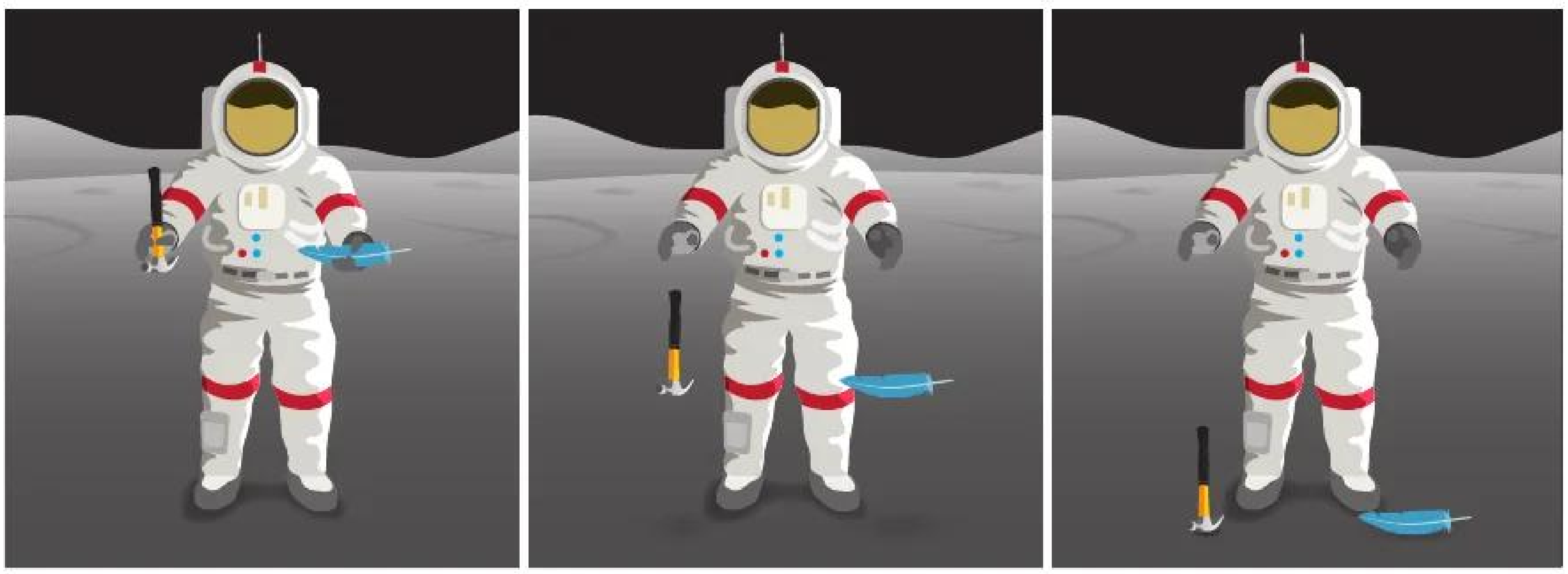

Figure 19 In 1971, astronaut David Scott dropped a hammer and a feather at the same time from the same height above the Moon's surface. The hammer's mass was greater, but both objects hit the ground at the same time because the Moon has gravity but no air.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Free-Fall Acceleration

Calculate the acceleration due to gravity for a system in free-fall.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the Unit and Module questions?

Near Earth's surface, free-fall acceleration is about 9.8 m/s^2 downward (which is equal to about 22 mph/s downward). Think about skydivers. Each second skydivers fall, their downward velocity increases by 9.8 m/s. When analyzing free fall, whether you treat the acceleration as positive or negative depends on the coordinate system you use. If you define upward as the positive direction, then the free-fall acceleration is negative. If you decide that downward is the positive direction, then free-fall acceleration is positive.

Get It?
Identify Why is it important to clearly define the coordinate system you want to use when analyzing objects in free fall?

Free-Fall Acceleration

Galileo's discovery explains why parachutists can form a ring in midair. Regardless of their masses, they fall with the same acceleration. To understand the acceleration that occurs during free fall, look at the multiflash photo of a dropped ball in **Figure 20.**

When the photograph was taken, the time interval between flashes was set to 0.06 s. So, the same amount of time passes between one image of the ball and the next. Look at the distance that the ball travels during each time interval. The distance between each pair of images increases as the ball falls. So, the speed of the ball is increasing. If the upward direction is positive, then the velocity is becoming more and more negative.

Figure 20 Because of free-fall acceleration, the speed of this falling ball increases 9.8 m/s each second.

Ball thrown upward
Instead of a dropped ball, could this photo also illustrate a ball thrown upward? Suppose you throw a ball upward with a speed of 20.0 m/s. If you choose upward to be positive, then the ball starts at the bottom of the photo with a positive velocity. The acceleration is $a = -9.8$ m/s^2. Because velocity and acceleration are in opposite directions, the speed of the ball decreases. If you think of the bottom of the photo as the start, this agrees with the multiflash photo.

Rising and falling motion
After 1 s, the ball's velocity is reduced by 9.8 m/s, so it now is traveling at +10.2 m/s. After 2 s, the velocity is +0.4 m/s, and the ball still is moving upward. What happens during the next second? The ball's velocity is reduced by another 9.8 m/s and equals −9.4 m/s. The ball now is moving downward. After 4 s, the velocity is −19.2 m/s, meaning the ball is falling even faster.

Get It?
Analyze During which second does the rising ball stop and reverse direction? How can you tell?

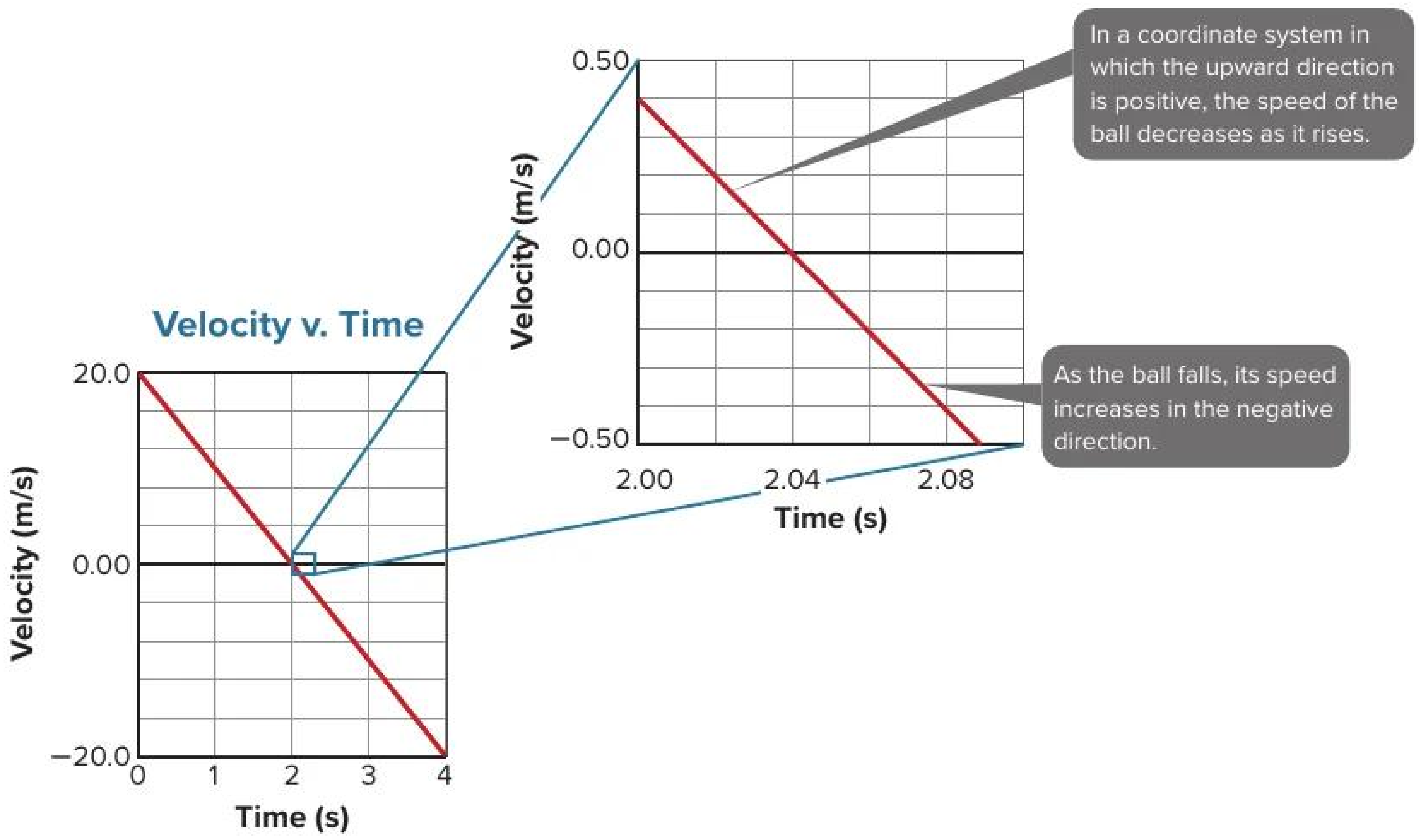

Figure 21 The velocity-time graph describes the change in the ball's speed as it rises and falls. The graph on the right gives a close-up view of the change in velocity at the top of the ball's trajectory.

Analyze *What would the graph look like if downward were chosen as the positive direction?*

Velocity-time graph The *v*-*t* graph for the ball as it goes up and down is shown in **Figure 21.** The straight line sloping downward does not mean that the speed is always decreasing. The speed decreases as the ball rises and increases as it falls. At around 2 s, the velocity changes smoothly from positive to negative. As the ball falls, its speed increases in the negative direction. The figure also shows a closer view of the *v*-*t* graph. At an instant of time, near 2.04 s, the velocity is zero.

Position-time graph Look at the position-time graphs in **Figure 22** on the next page. These graphs show how the ball's height changes as it rises and falls. If an object is moving with constant acceleration, its position-time graph forms a parabola. Because the ball is rising and falling, its graph is an inverted parabola. The shape of the graph shows the progression of time. It does not mean that the ball's path was in the shape of a parabola. The close-up graph on the right shows that at about 2.04 s, the ball reaches its maximum height.

Get It?

Describe If you throw a ball straight up, what would the shape of its position-time graph look like?

Maximum height Compare the close-up graphs in **Figure 21** and **Figure 22.** Just before the ball reaches its maximum height, its velocity is decreasing in the negative direction. At the instant of time when its height is maximum, its velocity is zero. Just after it reaches its maximum height, the ball's velocity is increasing in the negative direction.

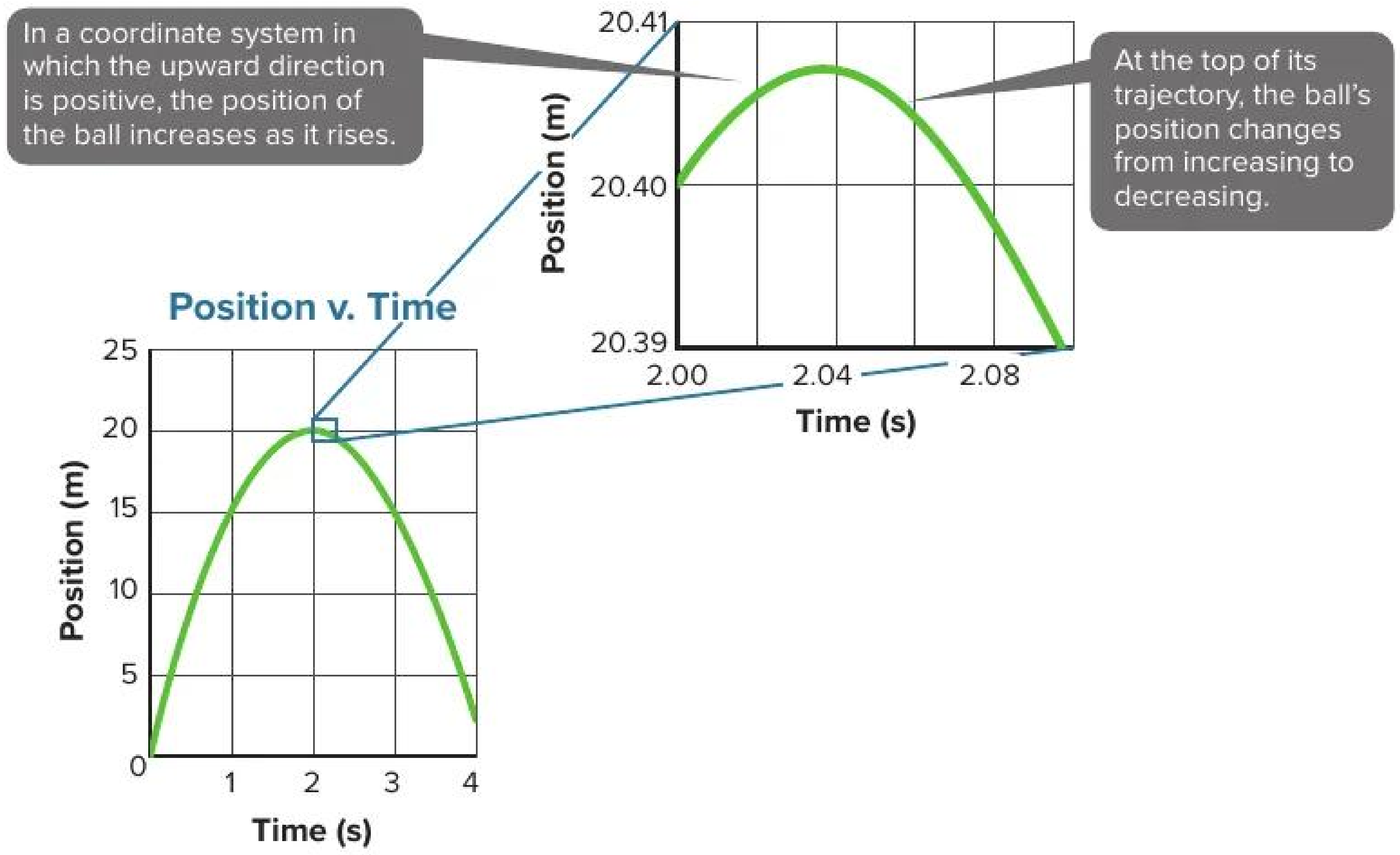

Figure 22 A position-time graph shows how the ball's position changes as it rises and falls. The graph at the right shows a close-up view of how the position changes at the top of the ball's trajectory.

Acceleration The slope of the line on the velocity-time graph in **Figure 21** is constant at $-9.8\ m/s^2$. This shows that the ball's free-fall acceleration is $9.8\ m/s^2$ in the downward direction the entire time the ball is rising and falling.

It may seem that the acceleration should be zero at the top of the trajectory, but this is not the case. At the top of the flight, the ball's velocity is 0 m/s. If its acceleration were also zero, the ball's velocity would not change and would remain at 0 m/s. The ball would not gain any downward velocity and would simply hover in the air. Have you ever seen that happen? Objects tossed in the air on Earth always fall, so you know the acceleration of an object at the top of its flight must not be zero. Further, because the object falls down, you know the acceleration must be downward.

Get It?

Analyze If you throw a ball straight up, what are its velocity and acceleration at the uppermost point of its path?

SCIENCE USAGE v. COMMON USAGE

Free fall

Science usage: motion of a body when air resistance is negligible and the acceleration can be considered due to gravity alone.
Acceleration during free fall is $9.8\ m/s^2$ downward.

Common usage: a rapid and continuing drop or decline
The stock market's free fall in 1929 marked the beginning of the Great Depression.

Figure 23 The people on this amusement-park ride experience free-fall acceleration.

Free-fall rides Amusement parks use the concept of acceleration to design rides that give the riders the sensation of free fall. These types of rides usually consist of three parts: the ride to the top, momentary suspension, and the fall downward. Motors provide the force needed to move the cars to the top of the ride. When the cars are in free fall, the most massive rider and the least massive rider will have the same acceleration.

Suppose the free-fall ride shown in **Figure 23** starts from the top at rest and is in free fall for 1.5 s. What would be its velocity at the end of 1.5 s? Choose a coordinate system with a positive axis upward and the origin at the initial position of the car. Because the car starts at rest, v_i would be equal to 0.0 m/s. To calculate the final velocity, use the equation for velocity with constant acceleration.

$$\begin{aligned} v_f &= v_i + \bar{a}t_f \\ &= 0.0\text{ m/s} + (-9.8\text{ m/s}^2)(1.5\text{ s}) \\ &= -15\text{ m/s} \end{aligned}$$

How far do people on the ride fall during this time? Use the equation for displacement when time and constant acceleration are known.

$$\begin{aligned} x_f &= x_i + v_i t_f + \left(\tfrac{1}{2}\right)\bar{a}t_f^2 \\ &= 0.0\text{ m} + (0.0\text{ m/s})(1.5\text{s}) + \left(\tfrac{1}{2}\right)(-9.8\text{ m/s}^2)(1.5\text{ s})^2 \\ &= -11\text{ m} \end{aligned}$$

PRACTICE Problems ADDITIONAL PRACTICE

40. A construction worker accidentally drops a brick from a high scaffold.
- **a.** What is the velocity of the brick after 4.0 s?
- **b.** How far does the brick fall during this time?

41. Suppose for the previous problem you choose your coordinate system so that the opposite direction is positive.
- **a.** What is the brick's velocity after 4.0 s?
- **b.** How far does the brick fall during this time?

42. A student drops a ball from a window 3.5 m above the sidewalk. How fast is it moving when it hits the sidewalk?

43. A tennis ball is thrown straight up with an initial speed of 22.5 m/s. It is caught at the same distance above the ground.
- **a.** How high does the ball rise?
- **b.** How long does the ball remain in the air?

Hint: The time it takes the ball to rise equals the time it takes to fall.

44. You decide to flip a coin to determine whether to do your physics or English homework first. The coin is flipped straight up.
- **a.** What are the velocity and acceleration of the coin at the top of its trajectory?
- **b.** If the coin reaches a high point of 0.25 m above where you released it, what was its initial speed?
- **c.** If you catch it at the same height as you released it, how much time was it in the air?

45. CHALLENGE A basketball player is holding a ball in her hands at a height of 1.5 m above the ground. She drops the ball, and it bounces several times. After the first bounce, the ball only returns to a height of 0.75 m. After the second bounce, the ball only returns to a height of 0.25 m.
- **a.** Suppose downward is the positive direction. What would the shape of a velocity-time graph look like for the first two bounces?
- **b.** What would be the shape of a position-time graph for the first two bounces?

Variations in Free Fall

When astronaut David Scott performed his free-fall experiment on the Moon, the hammer and the feather did not fall with an acceleration of magnitude 9.8 m/s^2. The value 9.8 m/s^2 is free-fall acceleration only near Earth's surface. The magnitude of free-fall acceleration on the Moon is approximately 1.6 m/s^2, which is about one-sixth its value on Earth.

When you study force and motion, you will learn about factors that affect the value of free-fall acceleration. One factor is the mass of the object, such as Earth or the Moon, that is responsible for the acceleration. Free-fall acceleration is not as great near the Moon as near Earth because the Moon has much less mass.

Free-fall acceleration also depends on the distance from the object responsible for it. The rings drawn around Earth in **Figure 24** show how free-fall acceleration decreases with distance from Earth. It is important to understand, however, that variations in free-fall acceleration at different locations on Earth's surface are very small, even with great variations in elevation. In New York City, for example, the magnitude of free-fall acceleration is about 9.81 m/s^2. In Denver, Colorado, it is about 9.79 m/s^2, despite a change in elevation of almost 1600 m greater. For calculations in this book, a value of 9.8 m/s^2 will be used for free-fall acceleration.

Figure 24 As the distance from Earth increases, the effect of free-fall acceleration decreases.

Analyze *According to the diagram, what is the magnitude of free-fall acceleration a distance above Earth's surface equal to Earth's radius?*

Check Your Progress

46. **Free Fall** Suppose you hold a book in one hand and a flat sheet of paper in your other hand. You drop them both, and they fall to the ground. Explain why the falling book is a good example of free fall, but the paper is not.

47. **Final Velocity** Your sister drops your house keys down to you from the second-floor window, as shown in **Figure 25.** What is the velocity of the keys when you catch them?

48. **Free-Fall Ride** Suppose a free-fall ride at an amusement park starts at rest and is in free fall. What is the velocity of the ride after 2.3 s? How far do people on the ride fall during the 2.3-s time period?

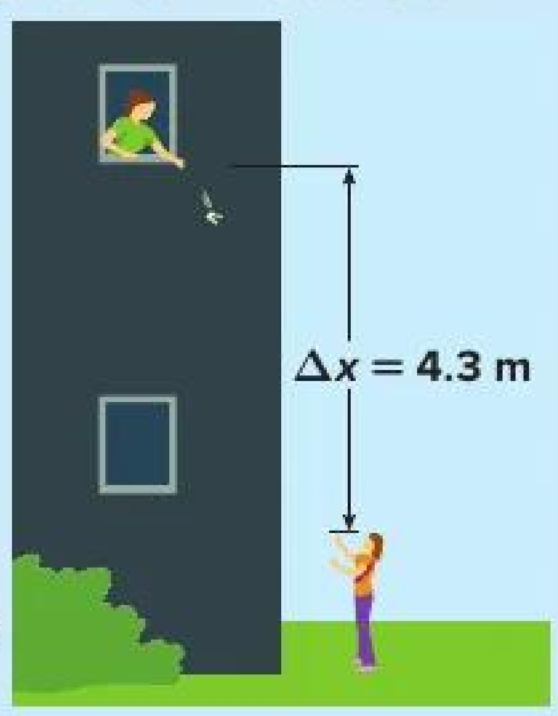

Figure 25

49. **Maximum Height and Flight Time** The free-fall acceleration on Mars is about one-third that on Earth. Suppose you throw a ball upward with the same velocity on Mars as on Earth.
    a. How would the ball's maximum height compare to that on Earth?
    b. How would its flight time compare?

50. **Velocity and Acceleration** Suppose you throw a ball straight up into the air. Describe the changes in the velocity of the ball. Describe the changes in the acceleration of the ball.

51. **Critical Thinking** A ball thrown vertically upward continues upward until it reaches a certain position, and then falls downward. The ball's velocity is instantaneously zero at that highest point. Is the ball accelerating at that point? Devise an experiment to prove or disprove your answer.

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STEM AT WORK

Designing Fun

Think about the last amusement park attraction that made your pulse quicken. Perhaps it was a heart-pounding roller coaster or a chilling haunted house. Did you ever wonder how theme park rides are created? The people who design the attractions at theme parks have many different titles—theme park designer, creative design engineer, industrial designer, building information modeling manager, and many others. No matter their title, they all concentrate on creating exciting attractions that draw visitors to the parks.

Roller coasters are just one of many types of attractions created by theme park designers.

Tools of the Trade

Most theme park designers have a background in physics, engineering, and mathematics. Some are also graphic designers or writers. They use a variety of tools to create the attractions that delight park visitors.

CAD (computer-aided design) drafting software, for example, allows designers to create 2D and 3D blueprints for attractions. Increasingly, designers are also employing BIM (building information modeling) systems, used to create 3D models that can be viewed at different levels of complexity. There are other modeling software programs that allow designers to work in 3D as well. Theme park designers also use computer graphics software to create graphics and animations, and they use computer programs to alter images.

Forces and Safety

Theme park designers work with acceleration and gravitational forces to produce thrills for riders. Roller coasters, for example, offer both changes in speed (such as slowly grinding up a hill and then barreling down it) and in direction (such as suddenly banking to the left or right). Attractions that drop riders from great heights and then slow their descent before they reach the ground make use of free-fall acceleration.

Designers must consider the attractions' effects on the human inner ear, heart, and other body systems. They want riders to be exhilarated, but they must also ensure that riders are safe. They must be mindful, for instance, that gravitational forces do not exceed the amount an average person can tolerate without suffering ill effects. Designers create elaborate systems of seatbelts and other restraints, headrests, and padding to protect riders from injury. They design improved braking systems to maximize safety.

DEVELOP AND USE MODELS TO ILLUSTRATE

With a partner, brainstorm, design, and build a model of a theme park ride that uses acceleration and gravitational forces. Use modeling software, if available.

MODULE 3
STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 ACCELERATION

- acceleration
- velocity-time graph
- average acceleration
- instantaneous acceleration

- Acceleration is the rate at which an object's velocity changes.
- Velocity and acceleration are not the same thing. An object moving with constant velocity has zero acceleration. When the velocity and the acceleration of an object are in the same direction, the object speeds up; when they are in opposite directions, the object slows down.
- You can use a velocity-time graph to find the velocity and the acceleration of an object. The average acceleration of an object is the slope of its velocity-time graph.

$$\bar{a} \equiv \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}$$

Lesson 2 MOTION WITH CONSTANT ACCELERATION

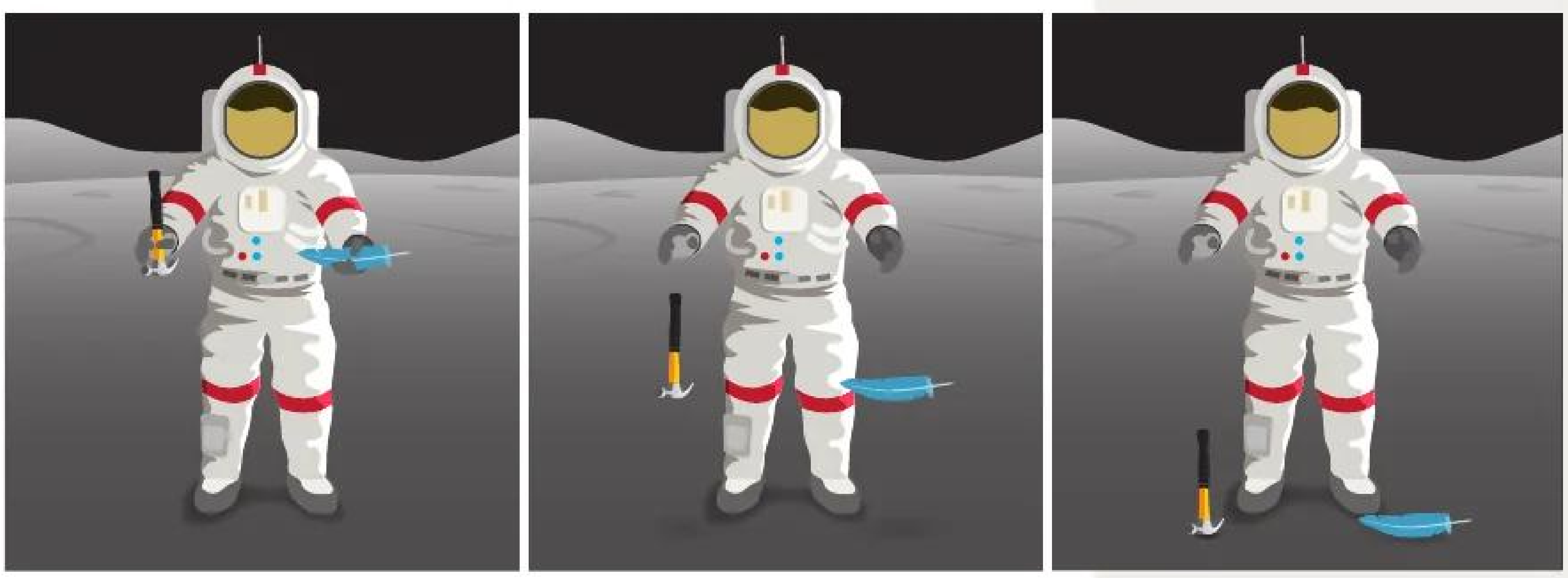
- If an object is moving with constant acceleration, its position-time graph is a parabola, and its velocity-time graph is a straight line.
- The area under an object's velocity-time graph is its displacement.
- In motion with constant acceleration, position, velocity, acceleration, and time are related:

$$v_f = v_i + \bar{a}\Delta t$$
$$x_f = x_i + v_i t_f + \frac{1}{2}\bar{a}t_f^2$$
$$v_f^2 = v_i^2 + 2\bar{a}(x_f - x_i)$$

Lesson 3 FREE FALL

- free fall
- free-fall acceleration

- Free-fall acceleration on Earth is about 9.8 m/s² downward. The sign associated with free-fall acceleration in equations depends on the choice of the coordinate system.
- When an object is in free fall, gravity is the only force acting on it. Equations for motion with constant acceleration can be used to solve problems involving objects in free fall.



THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

Why do sudden changes in the direction or speed of jet planes affect pilots?

CER Claim, Evidence, Reasoning

Explain your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

SEP Data Analysis Lab

How do free fall motion on Earth and Jupiter compare?

Suppose a ball could be thrown vertically upward with the same initial velocity on Earth and on Jupiter.

Data and Observations An object on the planet Jupiter has about three times the free-fall acceleration as on Earth. Neglect the effects of atmospheric resistance and assume gravity is the only force on the ball.

CER Analyze and Interpret Data

1. **Claim** How would the maximum height reached by the ball on Jupiter compare to the maximum height reached on Earth?
2. **Evidence and Reasoning** Use sketches and mathematics to explain your approach to this problem and your reasoning to justify your claim.
3. How would your claim change if the initial velocity of the ball on Jupiter were three times greater? Explain your reasoning.

MODULE 4

FORCES IN ONE DIMENSION

MODULE 4

FORCES IN ONE DIMENSION

ENCOUNTER THE PHENOMENON

How do wing suits help BASE jumpers control their velocity?

GO ONLINE to play a video about da Vinci's parachute.

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

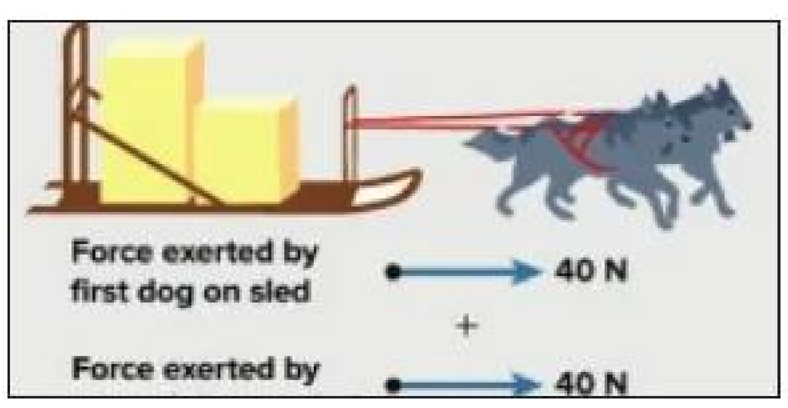
CER Claim, Evidence, Reasoning

Make Your Claim Use your CER chart to make a claim about how BASE jumpers control their velocity with wing suits. Explain your reasoning.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.



LESSON 1: Explore & Explain: Newton's Second Law

LESSON 2: Explore & Explain: Drag Force

Smithsonian

Additional Resources

(t)Video Supplied by BBC Worldwide Learning, (b)U.S. Army Photo by Sgt. Aaron Ricca, 115th Mobile Public Affairs Detachment

LESSON 1
FORCE AND MOTION

FOCUS QUESTION

What causes a change in motion?

Force

Consider a textbook resting on a table. To cause it to move, you could either push or pull on it. In physics, a push or a pull is called a **force.** If you push or pull harder on an object, you exert a greater force on the object. In other words, you increase the magnitude of the applied force. The direction in which the force is exerted also matters—if you push the resting book to the right, the book will start moving to the right. If you push the book to the left, it will start moving to the left. Because forces have both magnitude and direction, forces are vectors. The symbol $\boldsymbol{F}$ is vector notation that represents the size and direction of a force, while F represents only the magnitude. The magnitude of a force is measured in units called newtons (N).

Unbalanced forces change motion Recall that motion diagrams describe the positions of an object at equal time intervals. For example, the motion diagram for the book in **Figure 1** shows the distance between the dots increasing. This means the speed of the book is increasing. At $t = 0$, it is at rest, but after 2 seconds it is moving at 1.5 m/s. This change in speed means it is accelerating. What is the cause of this acceleration? The book was at rest until you pushed it, so the cause of the acceleration is the force exerted by your hand. In fact, all accelerations are the result of an unbalanced force acting on an object.

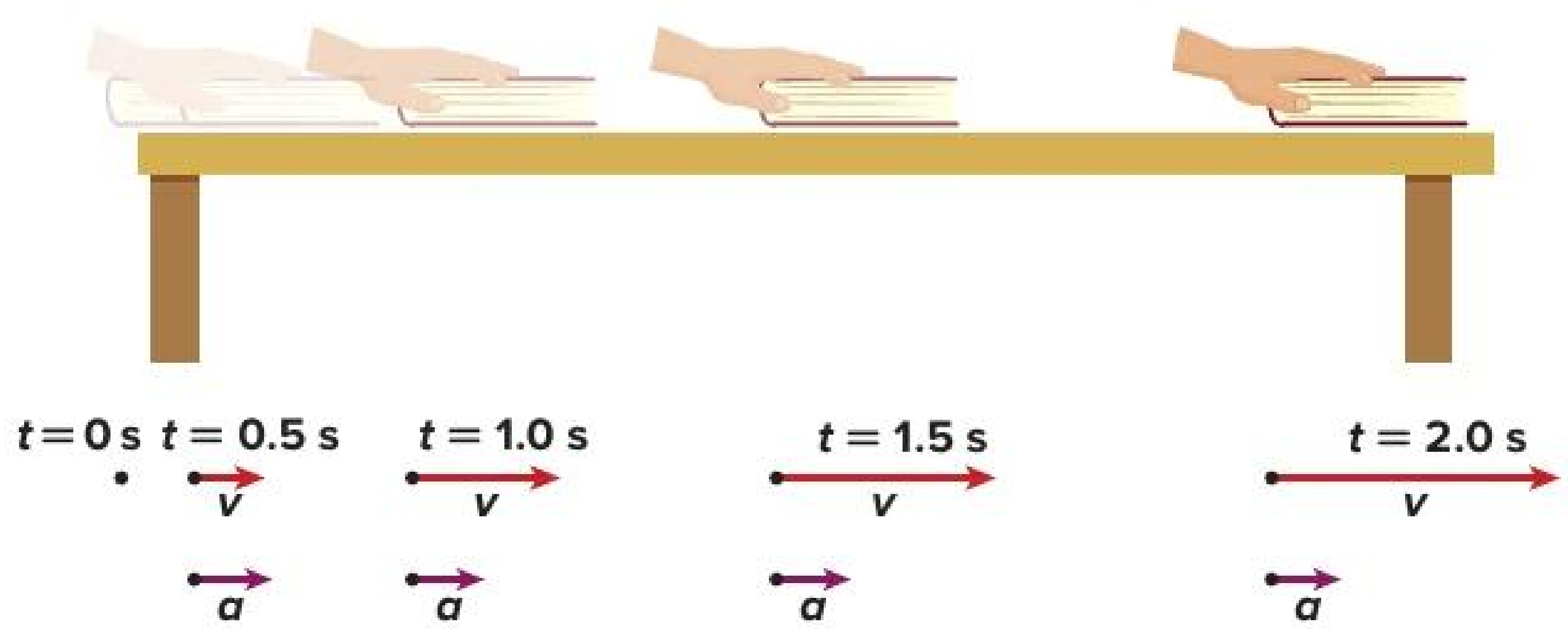


Figure 1 The hand pushing on the book exerts a force that causes the book to accelerate in the direction of the unbalanced force.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practices: Newton's Second Law

HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

Systems and external world When considering how a force affects motion, it is important to identify the object or objects of interest, called the **system.** Everything around the system with which the system can interact is called the external world. In **Figure 2**, the book is the system. Your hand, Earth, string and the table are parts of the external world that interact with the book by pushing or pulling on it.

Contact forces Again, think about the different ways in which you could move a textbook. You could push or pull it by directly touching it, or you could tie a string around it and pull on the string. These are examples of contact forces. A contact force exists when an object from the external world touches a system, exerting a force on it. If you are holding this physics textbook right now, your hands are exerting a contact force on it. If you place the book on a table, you are no longer exerting a contact force on the book. The table, however, is exerting a contact force because the table and the book are in contact.

Field forces There are other ways in which the motion of the textbook can change. You could drop it, and as you learned in a previous chapter, it would accelerate as it falls to the ground. The gravitational force of Earth acting on the book causes this acceleration. This force affects the book whether or not Earth is actually touching it. Gravitational force is an example of a field force. Field forces are exerted without contact. Can you think of other kinds of field forces? If you have ever investigated magnets, you know that they exert forces without touching. You will investigate magnetism and other field forces in future chapters. For now, the only field force you need to consider is the gravitational force.

Agents Forces result from interactions; every contact and field force has a specific and identifiable cause, called the agent. You should be able to name the agent exerting each force as well as the system upon which the force is exerted. For example, when you push your textbook, your hand (the agent) exerts a force on the textbook (the system). If there are not both an agent and a system, a force does not exist. What about the gravitational force? The agent is the mass of Earth exerting a field force on the book. The labels on the forces in **Figure 2** are good examples of how to identify a force's agent and the system upon which the force acts.

Get It?
Explain how contact forces are different from field forces.

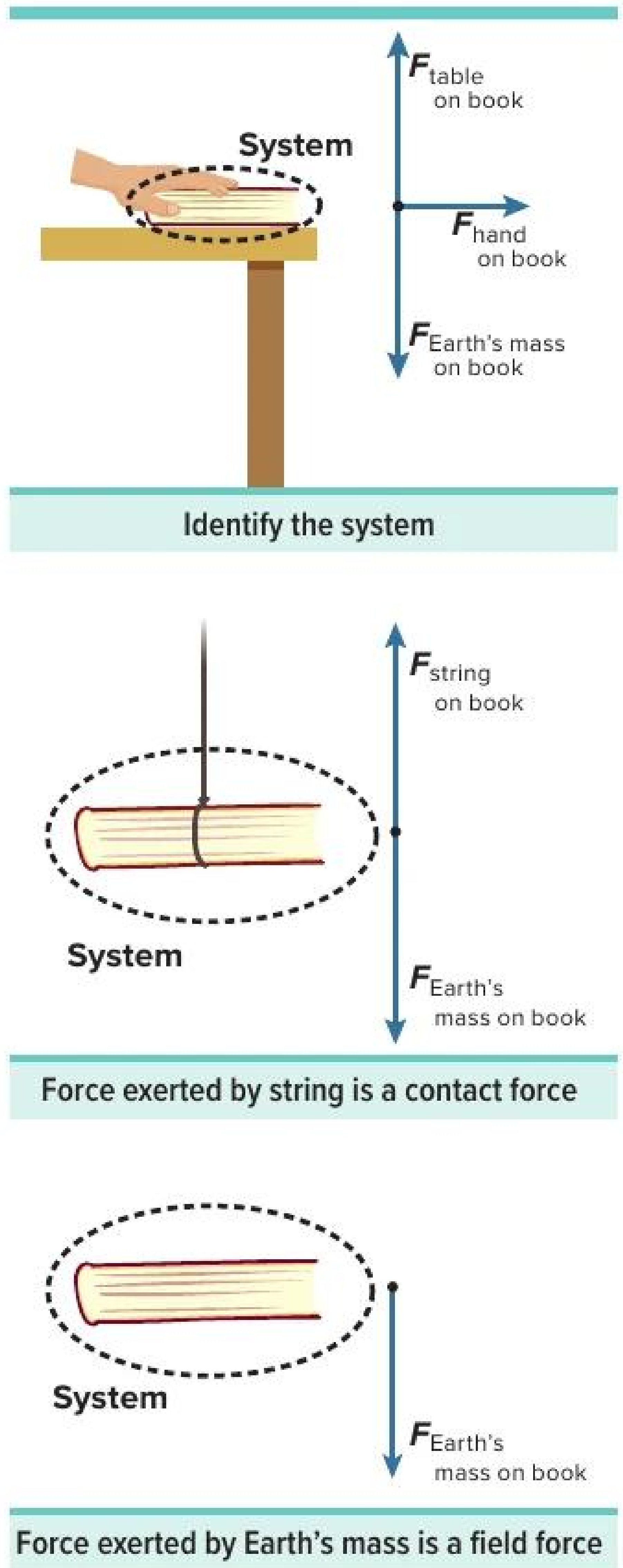


Figure 2 The book is the system in each of these situations.

Classify *each force in the first panel as either a contact force or a field force.*

SCIENCE USAGE V. COMMON USAGE

Force

Science usage: a push or pull exerted on an object
The force of gravity exerted by the Sun on Earth pulls Earth into orbit around the Sun.

Common usage: to compel by physical, moral, or intellectual means
Emi forced her younger brother to wash the dishes.

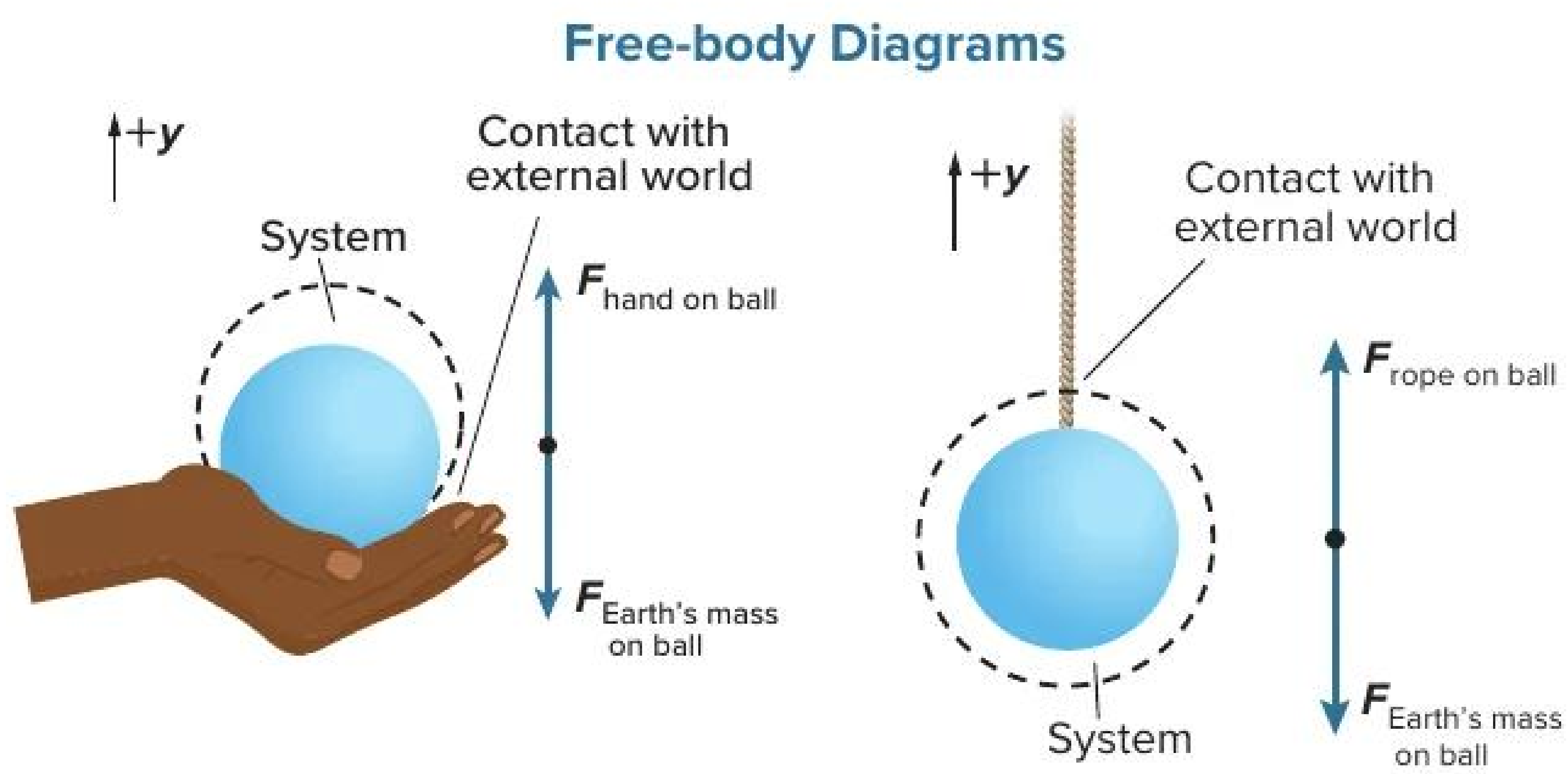
STEM CAREER Connection

Astronaut

On Earth, we are used to accounting for the force exerted by Earth's gravitational field. To prepare for missions in space, astronauts must become familiar with the effects of forces on objects in a zero-gravity environment.

Figure 3 The drawings of the ball in the hand and the ball hanging from the string are both pictorial models. The free-body diagram for each situation is shown next to each pictorial model.

COLOR CONVENTION
Force (F) ↔ blue



Free-body diagrams Just as pictorial representations and motion diagrams are useful in solving problems about motion, similar representations will help you analyze how forces affect motion. The first step is to sketch the situation, as shown in **Figure 3**. Circle the system, and identify every place where the system touches the external world. It is at these places that an agent exerts a contact force. Then identify any field forces on the system. This gives you the pictorial representation.

A **free-body diagram** is a physical representation that shows the forces acting on a system. Follow these guidelines when drawing a free-body diagram:

- The free-body diagram is drawn separately from the sketch of the problem situation.
- Apply the particle model, and represent the object with a dot.
- Represent each force with an arrow that points in the direction the force is applied. Always draw the force vectors pointing away from the particle, even when the force is a push.
- Make the length of each arrow proportional to the size of the force. Often you will draw these diagrams before you know the magnitudes of all the forces. In such cases, make your best estimate.
- Label each force. Use the symbol F with a subscript label to identify both the agent and the object on which the force is exerted.
- Choose a direction to be positive, and indicate this on the diagram.

Using free-body diagrams and motion diagrams Recall that all accelerations are the result of unbalanced forces. If a motion diagram shows that an object is accelerating, a free-body diagram of that object should have an unbalanced force in the same direction as the acceleration. Notice that the falling ball in **Figure 3** shows an unbalanced force downward, in the direction of the acceleration of the ball.

Get It?

Compare the direction of an object's acceleration with the direction of the unbalanced force exerted on the object.

CCC CROSSCUTTING CONCEPTS

Cause and Effect Study **Figure 3**. With a partner, plan a demonstration to show the specific cause and effect relationship between the motion of an object and the magnitudes of two forces acting on it in opposite directions. Vary the forces to show the different effects when the forces are unbalanced. Gather empirical evidence to show that the acceleration (or lack of acceleration) is caused directly by the imbalance (or balance) of the forces and not simply correlation.

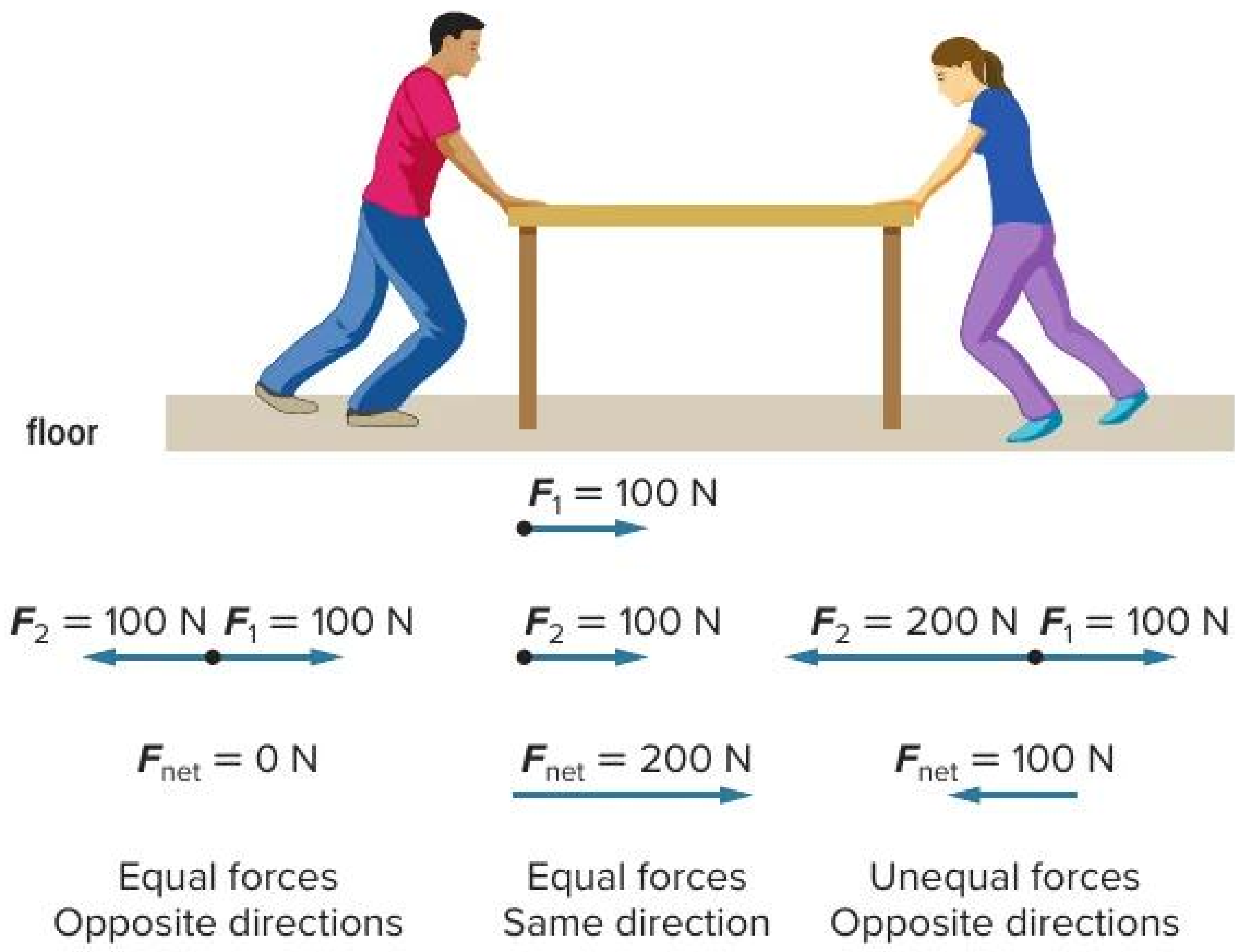


Figure 4 The net force acting on the table is the vector sum of all the forces acting on the table. This case only considers the horizontal forces acting on the table.

Combining Forces

What happens if you and a friend each push a table and exert 100 N of force on it? When you push together in the same direction, you give the table twice the acceleration that it would have if just one of you applied 100 N of force. When you push on the table in opposite directions with the same amount of force, as in **Figure 4,** there is no unbalanced force, so the table does not accelerate but remains at rest.

Net force The bottom portion of **Figure 4** shows free-body diagrams for these two situations. The third diagram in **Figure 4** shows the free-body diagram for a third situation in which your friend pushes on the table twice as hard as you in the opposite direction. Below each free-body diagram is a vector representing the resultant of the two forces. When the force vectors are in the same direction, they can be replaced by one vector with a length equal to their combined length. When the forces are in opposite directions, the resultant is the length of the difference between the two vectors. Another term for the vector sum of all the forces on an object is the **net force.**

You also can analyze the situation mathematically. Call the positive direction the direction in which you are pushing the table with a 100 N force. In the first case, your friend is pushing with a negative force of 100 N. Adding them together gives a total force of 0 N, which means there is no acceleration. In the second case, your friend's force is 100 N, so the total force is 200 N in the positive direction and the table accelerates in the positive direction. In the third case, your friend's force is −200 N, so the total force is −100 N and the table accelerates in the negative direction.

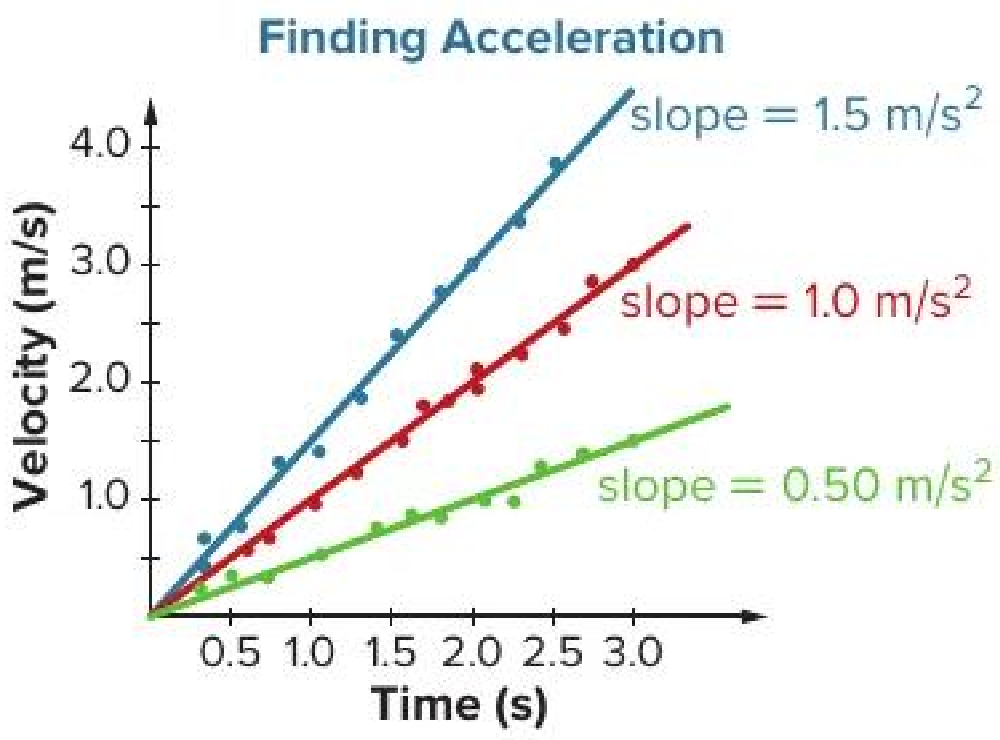
PRACTICE Problems

ADDITIONAL PRACTICE

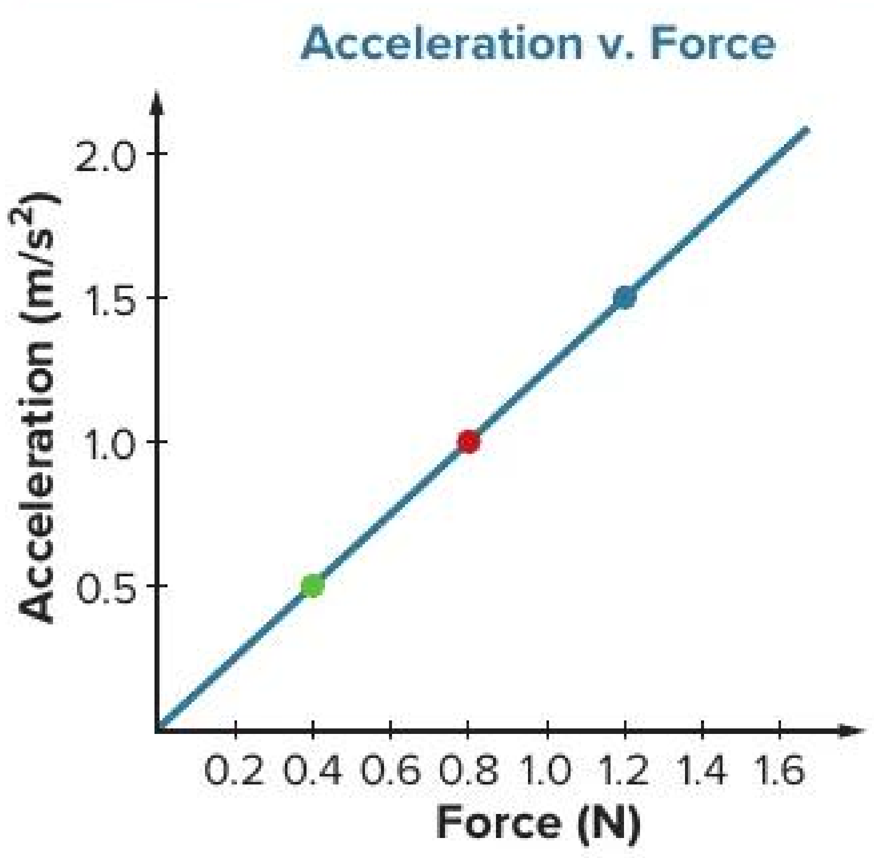
For each of the following situations, specify the system and draw a motion diagram and a free-body diagram. Label all forces with their agents, and indicate the direction of the acceleration and of the net force. Draw vectors of appropriate lengths. Ignore air resistance unless otherwise indicated.

1. A skydiver falls downward through the air at constant velocity. (The air exerts an upward force on the person.)
2. You hold a softball in the palm of your hand and toss it up. Draw the diagrams while the ball is still touching your hand.
3. After the softball leaves your hand, it rises, slowing down.
4. After the softball reaches its maximum height, it falls down, speeding up.
5. **CHALLENGE** You catch the ball in your hand and bring it to rest.

Applying a Constant Force



Velocity-Time Graphs for Constant Forces



Various Forces on the Same Mass

Figure 5 A spring scale exerts a constant unbalanced force on the cart. Repeating the investigation with different forces produces velocity-time graphs with different slopes.

Acceleration and Force

To explore how forces affect an object's motion, think about doing a series of investigations. Consider the simple situation shown in the top photo of **Figure 5** in which we exert one force horizontally on an object. Starting with the horizontal direction is helpful because gravity does not act horizontally. To reduce complications resulting from the object rubbing against the surface, the investigations should be done on a smooth surface, such as a well-polished table. We'll also use a cart with wheels that spin easily.

Apply constant force How can you exert a constant unbalanced force? One way is to use a device called a spring scale. Inside the scale is a spring that stretches proportionally to the magnitude of the applied force. The front of the scale is calibrated to read the force in newtons. If you pull on the scale so that the reading on the front stays constant, the applied force is constant. The top photo in **Figure 5** shows a spring scale pulling a low-resistance cart with a constant unbalanced force.

If you perform this investigation and measure the cart's velocity for a period of time, you could construct a graph like the green line shown in the velocity-time graphs for constant forces in the middle panel of **Figure 5**. The constant slope of the line in the velocity-time graph indicates the cart's velocity increases at a constant rate. The constant rate of change of velocity means the acceleration is constant. This constant acceleration is a result of the constant unbalanced force applied by the spring scale to the cart.

How does acceleration depend on force? Repeat the investigation with a larger constant force. Repeat it again with an even greater force. For each force, plot a velocity-time graph like the red and blue lines in the middle panel of **Figure 5.** Recall that the line's slope is the cart's acceleration. Calculate the slope of each line and plot the results for each force to make an acceleration-force graph, as shown in the bottom panel of **Figure 5**.

The graph indicates the relationship between force and acceleration is linear. Because the relationship is linear, you can apply the equation for a straight line:

$$y = kx + b$$

The y-intercept is 0, so the linear equation simplifies to $y = kx$. The y-variable is acceleration. The x-variable is force. Therefore, acceleration is equal to the slope of the line multiplied by the applied net force.

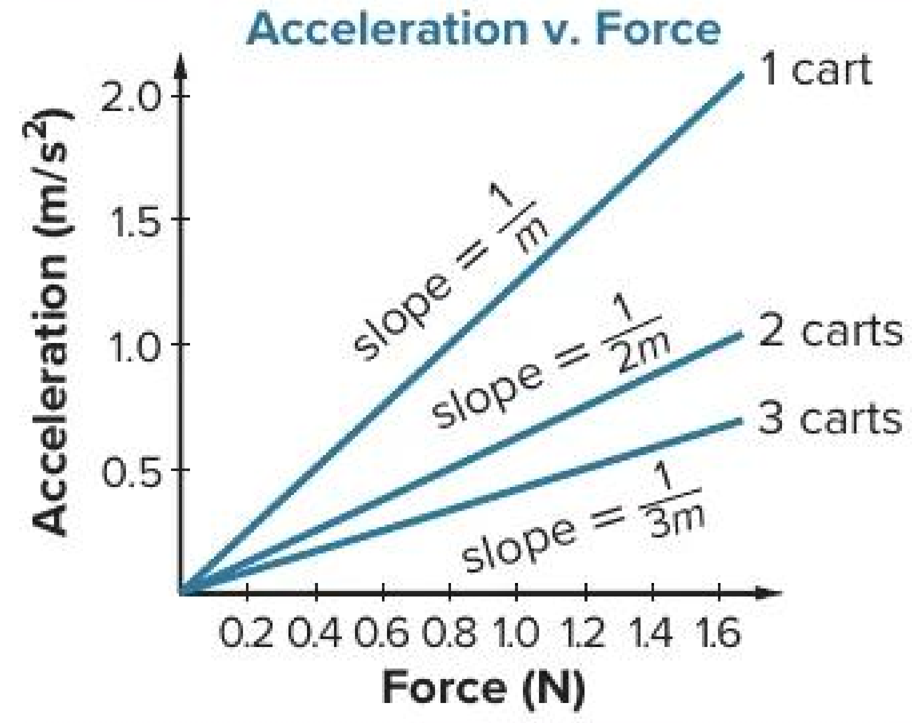
Get It?

Describe the relationship between applied net force and acceleration.

Interpreting slope What is the physical meaning of the slope of the acceleration-force graph? Does it describe something about the object that is accelerating? To see, change the object. Suppose that a second, identical cart is placed on top of the first, and then a third cart is added as in **Figure 6.** The spring scale would be pulling two carts and then three. A plot of the force versus acceleration for one, two, and three carts is shown in the graph in **Figure 6.**

The graph shows that if the same force is applied in each case, the acceleration of two carts is $\frac{1}{2}$ the acceleration of one cart, and the acceleration of three carts is $\frac{1}{3}$ the acceleration of one cart. This means that as the number of carts increases, the acceleration decreases. In other words, a greater force is needed to produce the same acceleration. The slopes of the lines in **Figure 6** depend upon the number of carts; that is, the slope depends on the total mass of the carts. In fact, the slope is the reciprocal of the mass (slope $= \frac{1}{\text{mass}}$). Using this value for slope, the mathematical equation $y = kx$ becomes the physics equation: $a = \frac{F_{net}}{m}$. What information is contained in the equation $a = \frac{F_{net}}{m}$? It tells you that a net force applied to an object causes that object to experience a change in motion—the force causes the object to accelerate. It also tells you that for the same object, if you double the force, you will double the object's acceleration. Lastly, if you apply the same force to objects with different masses, the one with the most mass will have the smallest acceleration and the one with the least mass will have the greatest acceleration.

Changing the Mass of the System



Same Force on Different Masses

Figure 6 Changing an object's mass affects that object's acceleration.

Compare *the acceleration of one cart to the acceleration of two carts for an applied force of 1 N.*

Get It?

Determine how the force exerted on an object must be changed to reduce the object's acceleration by half.

Recall that forces are measured in units called newtons. Because $F_{net} = ma$, a newton has the units of mass times the units of acceleration. So one newton is equal to one $kg{\cdot}m/s^2$. To get an approximate idea of the size of 1 N, think about the downward force you feel when you hold an apple in your hand. The force exerted by the apple on your hand is approximately one newton. **Table 1** shows the magnitudes of some other common forces.

Table 1 Common Forces

Description	*F*(N)
Force of gravity on a coin (nickel)	0.05
Force of gravity on a 0.45-kg bag of sugar	4.5
Force of gravity on a 70-kg person	686
Force exerted by road on an accelerating car	3000
Force of a rocket engine	5,000,000

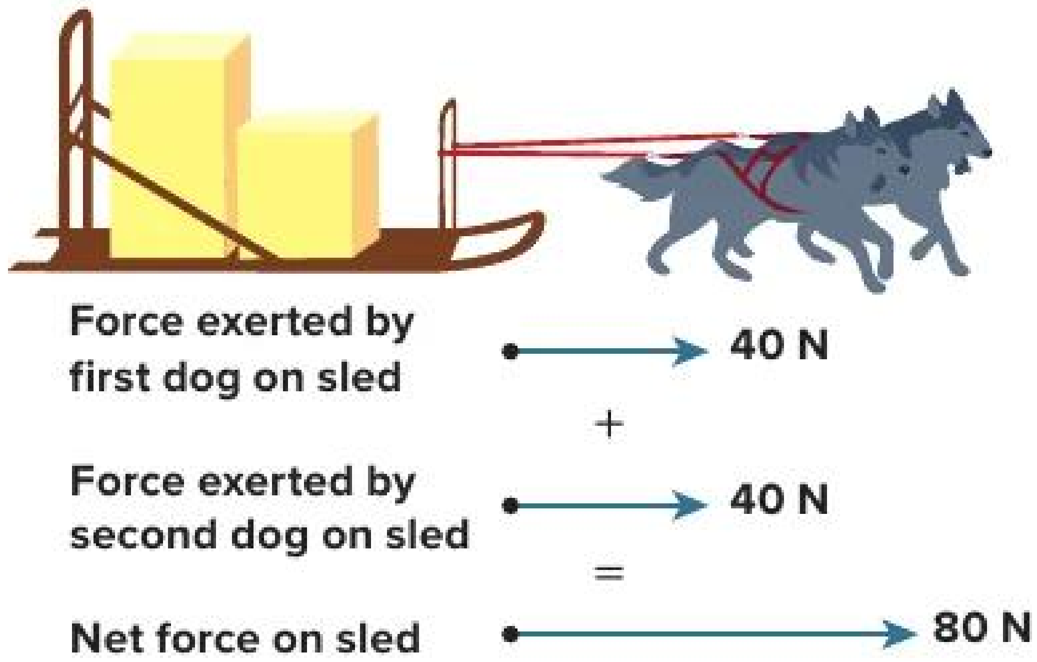


Figure 7 The net force acting on an object is the vector sum of all the forces acting on that object.

Newton's Second Law

Figure 7 shows two dogs pulling a sled. Each dog pulls with a force of 40 N. From the cart and spring-scale investigations, you know that the sled accelerates as a result of the unbalanced force acting it. Would the acceleration change if instead of two dogs each exerting a 40-N force, there was one bigger, stronger dog exerting a single 80-N force on the sled? When considering forces and acceleration, it is important to find the sum of all forces, called the net force, acting on a system.

Newton's second law states that the acceleration of an object is proportional to the net force and inversely proportional to the mass of the object being accelerated. This law is based on observations of how forces affect masses and is represented by the following equation. Newton's second law accurately predicts changes in the motion of macroscopic objects.

Newton's Second Law

The acceleration of an object is equal to the sum of the forces acting on the object divided by the mass of the object.

$$a = \frac{F_{net}}{m}$$

Solving problems using Newton's second law One of the most important steps in correctly applying Newton's second law is determining the net force acting on the object. Often, more than one force acts on an object, so you must add the force vectors to determine the net force. Draw a free-body diagram showing the direction and relative strength of each force acting on the system. Then, add the force vectors to find the net force. Next, use Newton's second law to calculate the acceleration. Finally, if necessary, you can use what you know about accelerated motion to find the velocity or position of the object.

PRACTICE Problems ADDITIONAL PRACTICE

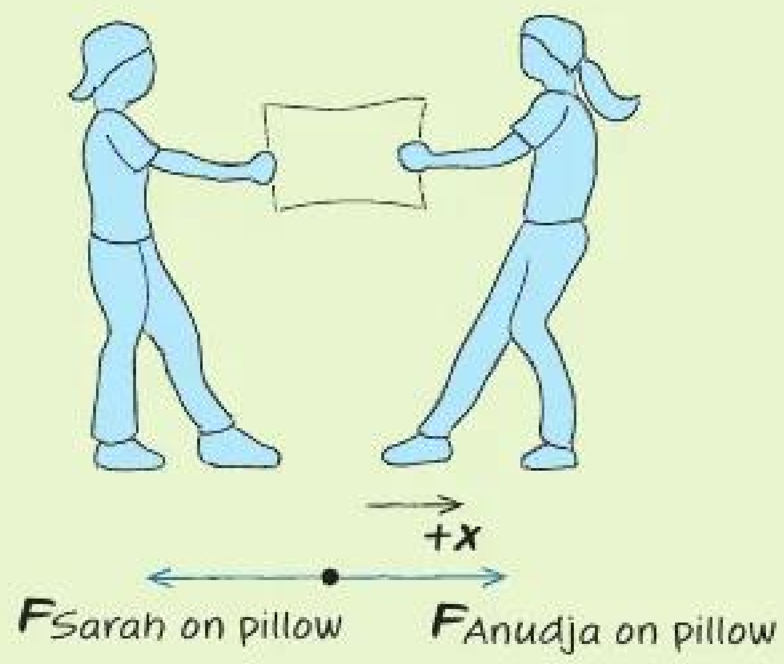
6. Two horizontal forces, 225 N and 165 N, are exerted on a canoe. If these forces are applied in the same direction, find the net horizontal force on the dance.
7. If the same two forces as in the previous problem are exerted on the canoe in opposite directions, what is the net horizontal force on the canoe? Be sure to indicate the direction of the net force.
8. **CHALLENGE** Three confused sled dogs are trying to pull a sled across the Alaskan snow. Alutia pulls east with a force of 35 N, Seward also pulls east but with a force of 42 N, and big Kodiak pulls west with a force of 53 N. What is the net force on the sled? Explain how Newton's second law accurately predicts the sled's change in motion.

EXAMPLE Problem 1

FIGHTING OVER A PILLOW Anudja is holding a pillow with a mass of 0.30 kg when Sarah decides that she wants it and tries to pull it away from Anudja. If Sarah pulls horizontally on the pillow with a force of 10.0 N and Anudja pulls with a horizontal force of 11.0 N, what is the horizontal acceleration of the pillow?

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Identify the pillow as the system, and the direction in which Anudja pulls as positive.
- Draw the free-body diagram. Label the forces.



KNOWN	UNKNOWN
$m = 0.30$ kg	$a = ?$
$F_{\text{Anudja on pillow}} = 11.0$ N	
$F_{\text{Sarah on pillow}} = 10.0$ N	

2 SOLVE FOR THE UNKNOWN

$$F_{\text{net}} = F_{\text{Anudja on pillow}} + (-F_{\text{Sarah on pillow}})$$

Use Newton's second law.

$$a = \frac{F_{\text{net}}}{m}$$

$$= \frac{F_{\text{Anudja on pillow}} + (-F_{\text{Sarah on pillow}})}{m}$$

$$= \frac{11.0\text{ N} - 10.0\text{ N}}{0.30\text{ kg}}$$ Substitute $F_{\text{Anudja on pillow}} = 11.0$ N, $F_{\text{Sarah on pillow}} = 10.0$ N, $m = 0.30$ kg.

$$= 3.3\text{ m/s}^2$$

$\boldsymbol{a} = 3.3\text{ m/s}^2$ toward Anudja

3 EVALUATE THE ANSWER

- **Are the units correct?** m/s² is the correct unit for acceleration.
- **Does the sign make sense?** The acceleration is toward Anudja because Anudja is pulling toward herself with a greater force than Sarah is pulling in the opposite direction.
- **Is the magnitude realistic?** The net force is 1 N and the mass is 0.3 kg, so the acceleration is realistic.

PRACTICE Problems

ADDITIONAL PRACTICE

9. A spring scale is used to exert a net force of 2.7 N on a cart. If the cart's mass is 0.64 kg, what is the cart's acceleration?

10. Kamaria is learning how to ice skate. She wants her mother to pull her along so that she has an acceleration of 0.80 m/s². If Kamaria's mass is 27.2 kg, with what force does her mother need to pull her? (Neglect any resistance between the ice and Kamaria's skates.)

11. CHALLENGE Two horizontal forces are exerted on a large crate. The first force is 317 N to the right. The second force is 173 N to the left.

- **a.** Draw a force diagram for the horizontal forces acting on the crate.
- **b.** What is the net force acting on the crate?
- **c.** The box is initially at rest. Five seconds later, its velocity is 6.5 m/s to the right. What is the crate's mass?

Newton's First Law

What is the motion of an object when the net force acting on it is zero? Newton's second law says that if $F_{net} = 0$, then acceleration equals zero. Recall that if acceleration equals zero, then velocity does not change. Thus a stationary object with no net force acting on it will remain at rest. What about a moving object, such as a ball rolling on a surface? How long will the ball continue to roll? The answer depends on the surface on which the ball is rolling. If the ball is rolled on a thick carpet that exerts a force on the ball, it will come to rest quickly. If it is rolled on a hard, smooth surface that exerts very little force, such as a bowling alley, the ball will roll for a long time with little change in velocity.

Galileo did many experiments and he concluded that if he could remove all forces opposing motion, horizontal motion would never stop. Galileo was the first to recognize that the general principles of motion could be found by extrapolating experimental results to an ideal case.

In the absence of a net force, the velocity of the moving ball and the lack of motion of the stationary object do not change. Newton recognized this and generalized Galileo's results into a single statement. Newton's statement, "an object that is at rest will remain at rest, and an object that is moving will continue to move in a straight line with constant speed, if and only if the net force acting on that object is zero," is called **Newton's first law.**

Inertia

Newton's first law is sometimes called the law of inertia because **inertia** is the tendency of an object to resist changes in velocity. The car and the red block in **Figure 8** demonstrate the law of inertia. In the left panel, both objects are moving to the right. In the right panel, the wooden box applies a force to the car, causing it to stop. The red block does not experience the force applied by the wooden box. It continues to move to the right with the same velocity as in the left panel.

Is inertia a force? No. Forces are results of interactions between two objects; they are not properties of single objects, so inertia cannot be a force. Remember that because velocity includes both the speed and direction of motion, a net force is required to change either the speed or the direction of motion. If the net force is zero, Newton's first law means the object will continue with the same speed and direction.

Figure 8 The car and the block approach the wooden box at the same speed. After the collision, the block continues on with the same horizontal speed.

Identify *the forces that will eventually cause the block to stop moving.*

Figure 9 An object is in equilibrium if its velocity isn't changing. In both cases pictured here, velocity isn't changing, so the net force must be zero.

Equilibrium According to Newton's first law, a net force causes the velocity of an object to change. If the net force on an object is zero, then the object is in **equilibrium.** An object is in equilibrium if it is moving at a constant velocity. Note that being at rest is simply of the state of constant velocity, $v = 0$. Newton's first law identifies a net force as something that disturbs a state of equilibrium. Thus, if there is no net force acting on the object, then the object does not experience a change in speed or direction and is in equilibrium. **Figure 9** indicates, at least in terms of net forces, there is no difference between lying on a sofa and falling at a constant velocity while skydiving—velocity isn't changing, so the net force is zero.

Keep in mind that the real world is full of forces that resist motion. Newton's ideal, friction-free world is not easy to obtain. If you analyze a situation and find that the result is different from your own experience, ask yourself if this s is because of the presence of frictional forces.

Check Your Progress

12. **Forces** Identify each of the following as either a, b, or c: mass, inertia, the push of a hand, friction, air resistance, spring force, gravity, and acceleration.
    a. contact force
    b. a field force
    c. not a force
13. **Free-Body Diagram** Draw a free-body diagram of a bag of sugar being lifted by your hand at an increasing speed. Specifically identify the system. Use subscripts to label all forces with their agents. Remember to make the arrows the correct lengths.
14. **Free-Body Diagram** Draw a free-body diagram of a water bucket being lifted by a rope at a decreasing speed. Specifically identify the system. Label all forces with their agents and make the arrows the correct lengths.
15. **Critical Thinking** A force of 1 N is the only horizontal force exerted on a block, and the horizontal acceleration of the block is measured. When the same horizontal force is the only force exerted on a second block, the horizontal acceleration is three times as large. What can you conclude about the masses of the two blocks?

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LESSON 2
WEIGHT AND DRAG FORCE

FOCUS QUESTION

How does the drag force change after a skydiver deploys their parachute?

Weight

From Newton's second law, the fact that the ball in **Figure 10** is accelerating means there must be unbalanced forces acting on the ball. The only force acting on the ball is the gravitational force due to Earth's mass. An object's **weight** is the gravitational force experienced by that object. This gravitational force is a field force whose magnitude is directly proportional to the mass of the object experiencing the force. In equation form, the gravitational force, which equals weight, can be written $F_g = mg$. The mass of the object is m, and g, called the **gravitational field,** is a vector quantity that relates an object's mass to the gravitational force it experiences at a given location.

Near Earth's surface, g is 9.8 N/kg toward Earth's center. Objects near Earth's surface experience 9.8 N of force for every kilogram of mass.

Scales When you stand on a scale as shown in the right panel of **Figure 10**, the scale exerts an upward force on you. Because you are not accelerating, the net force acting on you must be zero. Therefore the magnitude of the force exerted by the scale ($F_{\text{scale on you}}$) pushing up must equal the magnitude of F_g pulling down on you. Inside the scale, springs provide the upward force necessary to make the net force equal zero. The scale is calibrated to convert the stretch of the springs to a weight. If you were on a different planet with a different g, the scale would exert a different force to keep you in equilibrium, and consequently, the scale's reading would be different. Because weight is a force, the proper unit used to measure weight is the newton.

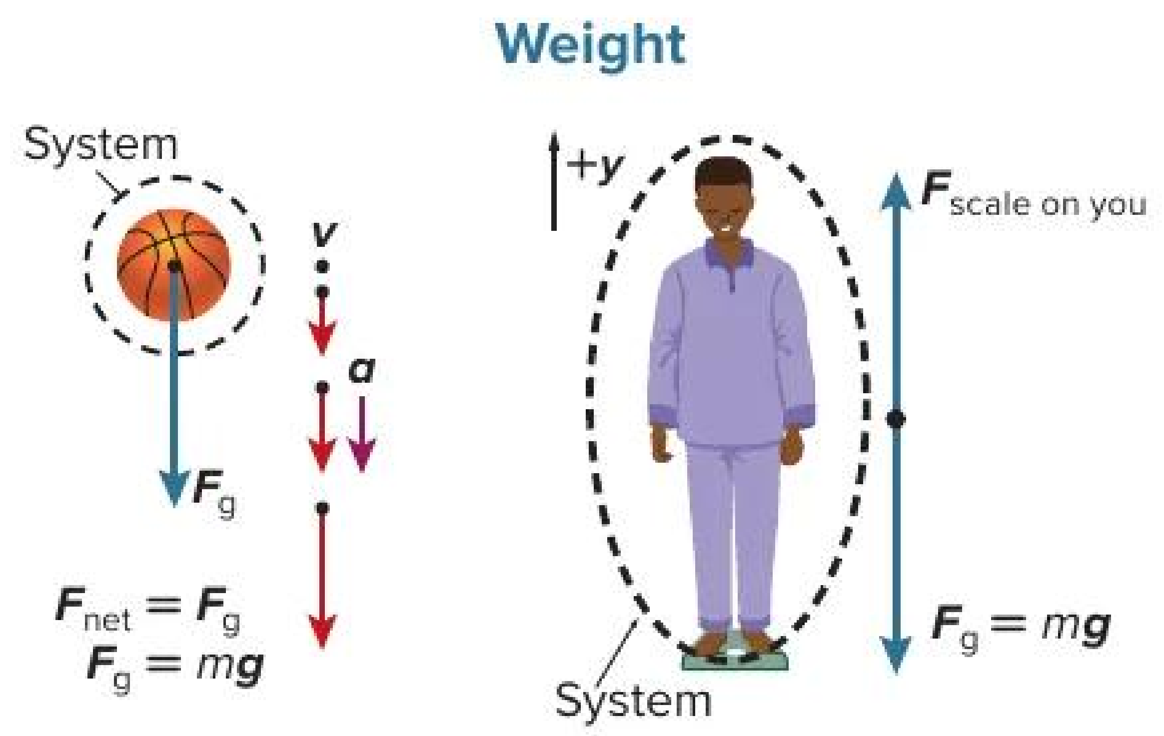


Figure 10 The gravitational force exerted by Earth's mass on an object equals the object's mass times the gravitational field, $F_g = mg$.

Identify *the forces acting on you when you are in equilibrium while standing on a scale.*

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Probeware Lab: Terminal Velocity
Analyze and interpret data to determine which factors affect the size of the drag force on a falling object.

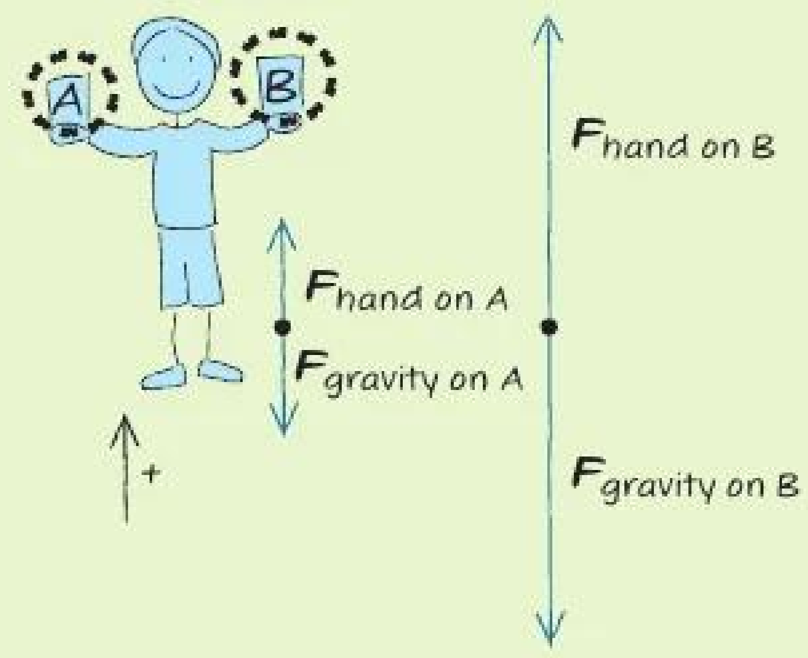
Revisit the Encounter the Phenomenon Question
What information from this lesson can help you answer the Unit and Module questions?

EXAMPLE Problem 2

COMPARING WEIGHTS Kiran holds a brass cylinder in each hand. Cylinder A has a mass of 100.0 g and cylinder B has a mass of 300.0 g. What upward forces do his two hands exert to keep the cylinders at rest? If he then drops the two, with what acceleration do they fall? (Ignore air resistance.)

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Identify the two cylinders as the systems, and choose the upward direction as positive.
- Draw the free-body diagrams. Label the forces.



KNOWN	UNKNOWNS
$m_A = 0.1000$ kg	$F_{\text{Hand on A}} = ?$
$m_B = 0.3000$ kg	$F_{\text{Hand on B}} = ?$
$g = -9.8$ N/kg	$a_A = ?$ $a_B = ?$

2 SOLVE FOR THE UNKNOWNS

For cylinder A:

$$F_{\text{Net on A}} = F_{\text{Hand on A}} + F_{\text{Gravity on A}}$$
$$0 = F_{\text{Hand on A}} + F_{\text{Gravity on A}}$$
$$F_{\text{Hand on A}} = -F_{\text{Gravity on A}}$$
$$F_{\text{Hand on A}} = -m_A g$$
$$= -(0.1000 \text{ kg})(-9.8 \text{ N/kg})$$
$$= 0.98 \text{ N up}$$

For cylinder B:

$$F_{\text{Net on B}} = F_{\text{Hand on B}} + F_{\text{Gravity on B}}$$
$$= F_{\text{Hand on B}} + F_{\text{Gravity on B}}$$
$$F_{\text{Hand on B}} = -F_{\text{Gravity on B}}$$
$$F_{\text{Hand on B}} = m_B g$$
$$= -(0.3000 \text{ kg})(-9.8 \text{ N/Kg})$$
$$= 2.9 \text{ N up}$$

After the cylinders are dropped, the only force on each is the force of gravity. Use Newton's second law.

$$a_A = \frac{F_{\text{Net on A}}}{m_A} \qquad a_B = \frac{F_{\text{Net on B}}}{m_B}$$

$$a_A = \frac{m_A g}{m_A} = g \qquad a_B = \frac{m_B g}{m_B} = g$$
Substitute $F_{\text{Net on A}} = m_A g$ and $F_{\text{Net on B}} = m_B g$

$$= -9.8 \text{ m/s}^2 \qquad = -9.8 \text{ m/s}^2$$
Substitute $g = -9.8$ N/kg $= -9.8$ m/s^2.

3 EVALUATE THE ANSWER

- **Are the units correct?** N is the correct unit for force; m/s^2 is the correct unit for acceleration.
- **Does the sign make sense?** The direction of the fall is downward, the negative direction, and the object is speeding up, so the acceleration should be negative.
- **Is the magnitude realistic?** Forces are 1–5 N, typical of that exerted by objects that have a mass of one kg or less. The accelerations are both equal to free fall acceleration.

PRACTICE Problems

ADDITIONAL PRACTICE

16. You place a 4.0-kg watermelon on a spring scale that measures in newtons. What is the scale's reading?

17. You place a 22.50-kg television on a spring scale. If the scale reads 235.2 N, what is the gravitational field?

18. A 0.50-kg guinea pig is lifted up from the ground. What is the smallest force needed to lift it? Describe the particular motion resulting from this minimum force.

19. CHALLENGE A grocery sack can withstand a maximum of 230 N before it rips. Will a bag holding 15 kg of groceries that is lifted from the checkout counter at an acceleration of 7.0 m/s^2 hold?

Apparent weight What is weight? Because the weight force is defined as $F_g = mg$, F_g changes when g varies. On or near the surface of Earth, g is approximately constant, so an object's weight does not change appreciably as it moves around near Earth's surface. If a bathroom scale provides the only upward force on you, then it reads your weight. What would it read if you stood with one foot on the scale and one foot on the floor? What if a friend pushed down on your shoulders or lifted up on your elbows? Then there would be other contact forces on you, and the scale would not read your weight.

What happens if you stand on a scale in an elevator? As long as you are not accelerating, the scale will read your weight. What would the scale read if the elevator accelerated upward? **Figure 11** shows the pictorial and physical representations for this situation. You are the system, and upward is the positive direction. Because the acceleration of the system is upward, the net force must be upward. The upward force of the scale must be greater than the downward force of your weight. Therefore, the scale reading is greater than your weight.

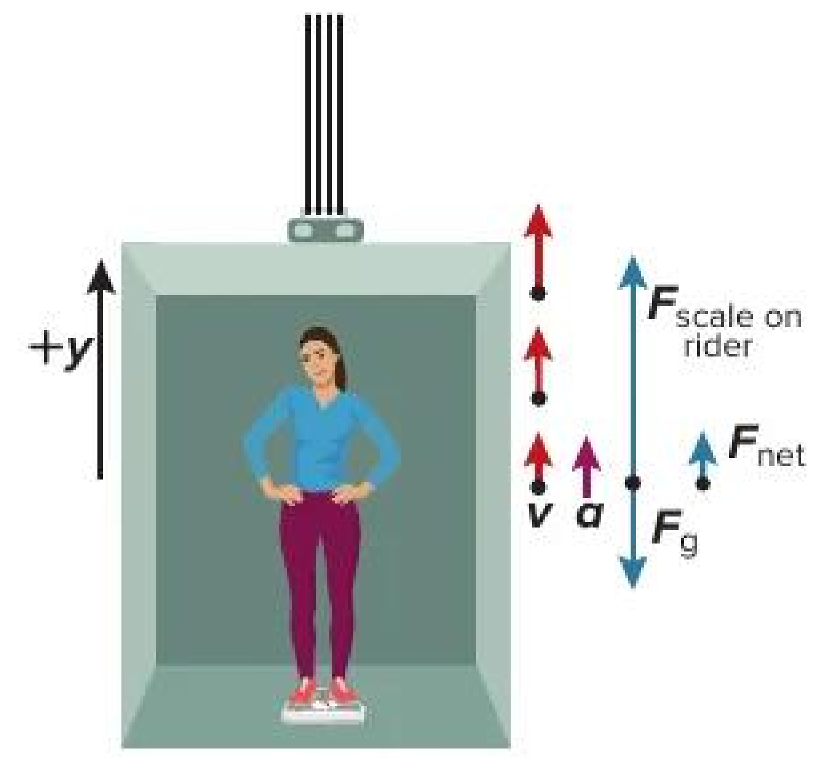


Figure 11 If you are accelerating upward, the net force acting on you must be upward. The scale must exert an upward force greater than the downward force of your weight.

Get It?

Describe the reading on the scale as the elevator accelerates upward from rest, reaches a constant speed, and then comes to a stop.

If you ride in an elevator accelerating upward, you feel as if you are heavier because the floor presses harder on your feet. On the other hand, if the acceleration is downward, then you feel lighter, and the scale reads less than your weight. The force exerted by the scale is an example of **apparent weight,** which is the support force exerted on an object.

Imagine that the cable holding the elevator breaks. What would the scale read then? The scale and you would both accelerate at $a = g$. According to this formula, the scale would read zero and your apparent weight would be zero. That is, you would be weightless. However, **weightlessness** does not mean that an object's weight is actually zero; rather, it means that there are no contact forces acting to support the object, and the object's *apparent weight* is zero. Similar to the falling elevator, astronauts experience weightlessness in orbit because they and their spacecraft are in free fall.

PROBLEM-SOLVING STRATEGY

Force and Motion

When solving force and motion problems, use the following strategies.

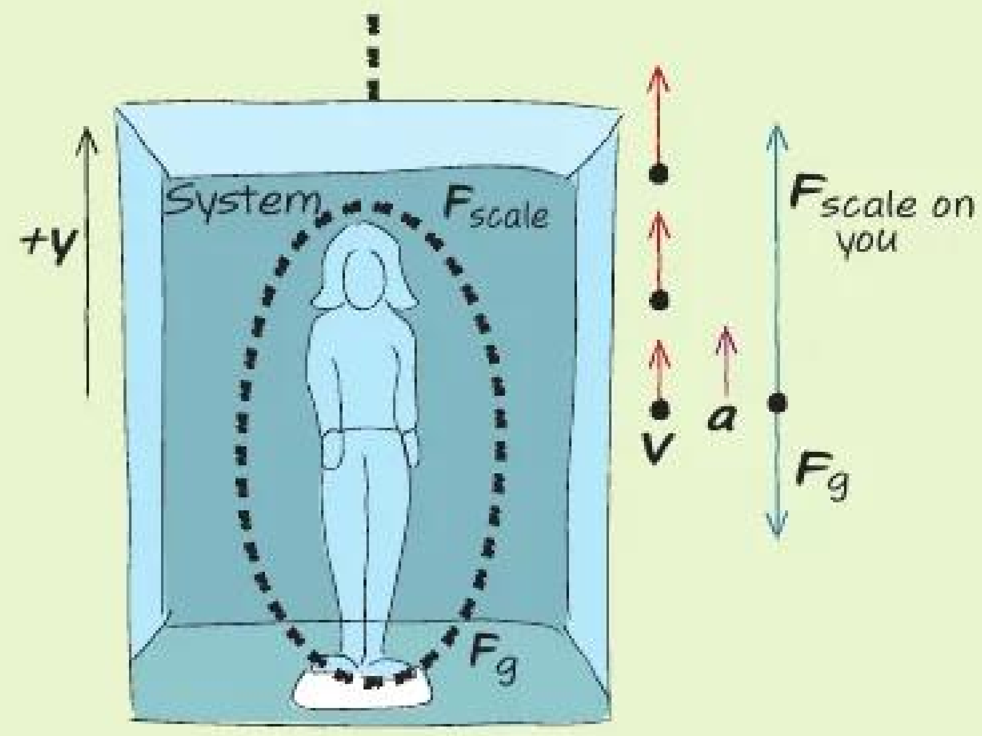
1. Read the problem carefully, and sketch a pictorial model.
2. Circle the system and choose a coordinate system.
3. Determine which quantities are known and which are unknown.
4. Create a physical model by drawing a motion diagram showing the direction of the acceleration.
5. Create a free-body diagram showing all the forces acting on the object.
6. Use Newton's laws to link acceleration and net force.
7. Rearrange the equation to solve for the unknown quantity.
8. Substitute known quantities with their units into the equation and solve.
9. Check your results to see whether they are reasonable.

EXAMPLE Problem 3

REAL AND APPARENT WEIGHT Your mass is 75.0 kg, and you are standing on a bathroom scale in an elevator. Starting from rest, the elevator accelerates upward at 2.00 m/s² for 2.00 s and then continues at a constant speed. Is the scale reading during acceleration greater than, equal to, or less than the scale reading when the elevator is at rest?

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Choose a coordinate system with the positive direction as upward.
- Draw the motion diagram. Label v and a.
- Draw the free-body diagram. The net force is in the same direction as the acceleration, so the upward force is greater than the downward force.



KNOWN	UNKNOWN
$m = 75.0$ kg	$F_{scale} = ?$
$a = 2.00$ m/s²	
$t = 2.00$ s	
$g = 9.8$ N/kg	

2 SOLVE FOR THE UNKNOWN

$F_{net} = ma$

$F_{net} = F_{scale} + (-F_g)$ — F_g is negative because it is in the negative direction defined by the coordinate system.

Solve for F_{scale}.

$F_{scale} = F_{net} + F_g$

Elevator at rest:

$F_{scale} = F_{net} + F_g$ — The elevator is not accelerating. Thus, $F_{net} = 0.00$ N.

$= F_g$ — Substitute $F_{net} = 0.00$ N.

$= mg$ — Substitute $F_g = mg$.

$= (75.0 \text{ kg})(9.8 \text{ N/kg})$ — Substitute $m = 75.0$ kg, $g = 9.8$ N/kg.

$= 735$ N

Elevator accelerating upward:

$F_{scale} = F_{net} + F_g$

$= ma + mg$ — Substitute $F_{net} = ma$, $F_g = mg$

$= (75.0 \text{ kg})(2.00 \text{ m/s}^2) + (75.0 \text{ kg})(9.8 \text{ N/kg})$ — Substitute $m = 75.0$ kg, $a = 2.00$ m/s², $g = 9.8$ N/kg

$= 885$ N

The scale reading when the elevator is accelerating (885 N) is larger than when it is at rest (735 N).

3 EVALUATE THE ANSWER

- **Are the units correct?** kg•m/s² is the force unit, N.
- **Does the sign make sense?** The positive sign agrees with the coordinate system.
- **Is the magnitude realistic?** $F_{Scale} = 885$ N is larger than it would be at rest when F_{scale} would be 735 N. The increase is 150 N, which is about 20 percent of the rest weight. The upward acceleration is about 20 percent of that due to gravity, so the magnitude is reasonable.

PRACTICE Problems ADDITIONAL PRACTICE

20. On Earth, a scale shows that you weigh 585 N.
- **a.** What is your mass?
- **b.** What would the scale read on the Moon (g = 1.60 N/kg)?

21. CHALLENGE Use the results from Example Problem 3 to answer questions about a scale in an elevator on Earth. What force would be exerted by the scale on a person in the following situations?
- **a.** The elevator moves upward at constant speed.
- **b.** It slows at 2.0 m/s^2 while moving downward.
- **c.** It speeds up at 2.0 m/s^2 while moving downward.
- **d.** It moves downward at constant speed.
- **e.** In what direction is the net force as the elevator slows to a stop as it is moving down?

Drag Force

The particles in the air around an object exert forces on that object. In fact, air exerts huge forces, but in most cases, it exerts balanced forces on all sides, and therefore has no net effect. So far, you have neglected the force of air on an object moving through the air. In actuality, when an object moves through any fluid, such as air or water, the fluid exerts a force on the moving object in the direction opposite the object's motion. A **drag force** is the force exerted by a fluid on an object opposing motion through the fluid. This force is dependent on the motion of the object, the properties of the object, and the properties of the fluid that the object is moving through. For example, as the speed of the object increases, so does the magnitude of the drag force. The size and shape of the object also affect the drag force. The fluid's properties, such as its density and viscosity, also affect the drag force.

Get It?
Describe how the wingsuits shown in the photo at the beginning of the module affect the drag force experienced by the skydivers.

PHYSICS Challenge

A 415-kg container of food and water is dropped from an airplane at an altitude of 300 m. First, consider the situation ignoring air resistance. Then calculate the more realistic situation involving a drag force provided by a parachute.

1. If you ignore air resistance, how long will it take the container to fall 300 m to the ground?
2. Again, ignoring air resistance, what is the speed of the container just before it hits the ground?
3. The container is attached to a parachute designed to produce a drag force that allows the container to reach a constant downward velocity of 6 m/s. What is the magnitude of the drag force when the container is falling at a constant 6 m/s down?

Terminal velocity If you drop a tennis ball, as in **Figure 12,** it has very little velocity at the start and thus only a small drag force. The downward force of gravity is much stronger than the upward drag force, so there is a downward acceleration. As the ball's velocity increases, so does the drag force. Soon the drag force equals the force of gravity. When this happens, there is no net force, and so there is no acceleration. The constant velocity that is reached when the drag force equals the force of gravity is called the **terminal velocity.**

When light objects with large surface areas fall, the drag force has a substantial effect on their motion, and they quickly reach terminal velocity. Heavier, more compact objects are not affected as much by the drag force. For example, the terminal velocity of a table-tennis ball in air is 9 m/s, and that of a baseball is 42 m/s. Skydivers can increase or decrease their terminal velocity by changing their body orientation and shape. A horizontal, spreadeagle shape produces the slowest terminal velocity, about 60 m/s. After the parachute opens, the skydiver becomes part of a large object with a correspondingly large drag force and a terminal velocity of about 5 m/s.

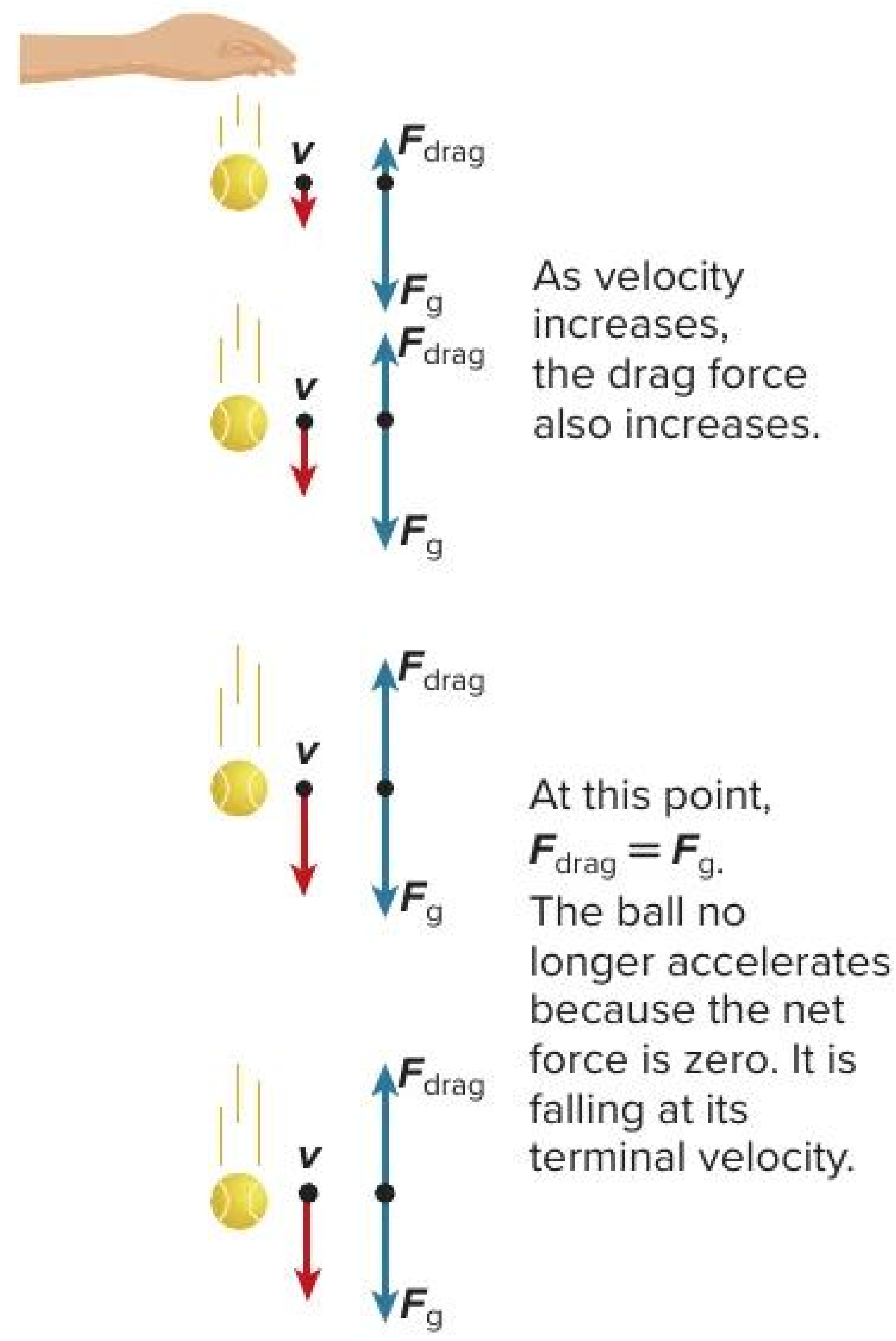


Figure 12 The drag force on an object increases as its velocity increases. When the drag force equals the gravitational force, the object is in equilibrium.

Check Your Progress

22. **Terminal Velocity** The skydiver in **Figure 13** falls at a constant speed in the spread-eagle position. Immediately after opening the parachute, is the skydiver accelerating? If so, in which direction? Explain your answer.

Figure 13

23. **Lunar Gravity** Compare the force holding a 10.0-kg rock on Earth and on the Moon. The gravitational field on the Moon is 1.6 N/kg.
24. **Motion of an Elevator** You are riding in an elevator holding a spring scale with a 1-kg mass suspended from it. You look at the scale and see that it reads 9.3 N. What does this tell you about the elevator's motion?
25. **Apparent Weight** You take a ride in a fast elevator to the top of a tall building and ride back down. Compare your apparent and real weights at each part of the journey. Sketch free-body diagrams to support your answers.
26. **Acceleration** Tecle, with a mass of 65.0 kg, is standing on an ice-skating rink. His friend applies a force of 9.0 N to him. What is Tecle's resulting acceleration?
27. **Critical Thinking** You have a job loading inventory onto trucks at a meat warehouse. Each truck has a weight limit of 10,000 N of cargo. You push each crate of meat along a low-resistance roller belt to a scale and weigh it before moving it onto the truck. One night, right after you weigh a 1000-N crate, the scale breaks. Describe a way in which you could apply Newton's laws to approximate the masses of the remaining crates.

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LESSON 3
NEWTON'S THIRD LAW

FOCUS QUESTION

If you push on a wall, what force does the wall exert on you?

Interaction Pairs

Figure 14 illustrates the idea of forces as interaction pairs. There is a force from the woman on the dog's toy, and there is a force from the dog's toy on the woman. Forces always come in pairs similar to this example. Consider the woman (A) as one system and the toy (B) as another. What forces act on each of the two systems? Looking at the force diagrams in **Figure 14**, you can see that each system exerts a force on the other. The two forces, $\boldsymbol{F}_{\text{A on B}}$ and $\boldsymbol{F}_{\text{B on A}}$, are an example of an **interaction pair,** which is a set of two forces that are in opposite directions, have equal magnitudes, and act on different objects. Sometimes, an interaction pair is called an action-reaction pair. This might suggest that one causes the other; however, this is not true. For example, the force of the woman pulling on the toy doesn't cause the toy to pull on the woman. The two forces either exist together or not at all.

Definition of Newton's third law In **Figure 14**, the force exerted by the woman on the toy is equal in magnitude and opposite in direction to the force exerted by the toy on the woman. Such an interaction pair is an example of **Newton's third law,** which states that all forces come in pairs. The two forces in a pair act on different objects and are equal in strength and opposite in direction.

FatCamera/E+/Getty Images

Figure 14 The force that the toy exerts on the woman and the force that the woman exerts on the toy are an interaction pair.

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COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Newton's Third Law
Plan and carry out a investigation that applies Newton's laws of motion to different systems.

Review the News
Obtain information from a current news story about forces and motion. Evaluate your source and communicate your findings to your class.

Newton's Third Law
The force of A on B is equal in magnitude and opposite in direction of the force of B on A.

$$F_{\text{A on B}} = -F_{\text{B on A}}$$

Using Newton's third law Consider the situation of holding a book in your hand. You can draw one free-body diagram for you and one for the book. Are there any interaction pairs? When identifying interaction pairs, keep in mind that they always occur in two different free-body diagrams, and they always will have the symmetry of subscripts noted on the previous page. In this case, the interaction pair is $F_{\text{book on hand}}$ and $F_{\text{hand on book.}}$

The ball in **Figure 15** interacts with the table and with Earth. First, analyze the forces acting on one system, the ball. The table exerts an upward force on the ball, and the mass of Earth exerts a downward gravitational force on the ball. Even though these forces are in opposite directions, they are not an interaction pair because they act on the same object. Now consider the ball and the table together. In addition to the upward force exerted by the table on the ball, the ball exerts a downward force on the table. This is an interaction pair. Notice also that the ball has a weight. If the ball experiences a force due to Earth's mass, then there must be a force on Earth's mass due to the ball. In other words, they are an interaction pair.

$$F_{\text{Earth's mass on ball}} = -F_{\text{ball on Earth's mass}}$$

An unbalanced force on Earth would cause Earth to accelerate. But acceleration is inversely proportional to mass. Because Earth's mass is so huge in comparison to the masses of other objects that we normally consider, Earth's acceleration is so small that it can be neglected. In other words, Earth can be often treated as part of the external world rather than as a second system. The problem-solving strategies below summarize how to deal with interaction pairs.

Get It?
Explain why Earth's acceleration is usually very small compared to the acceleration of the object that Earth interacts with.

PROBLEM-SOLVING STRATEGY

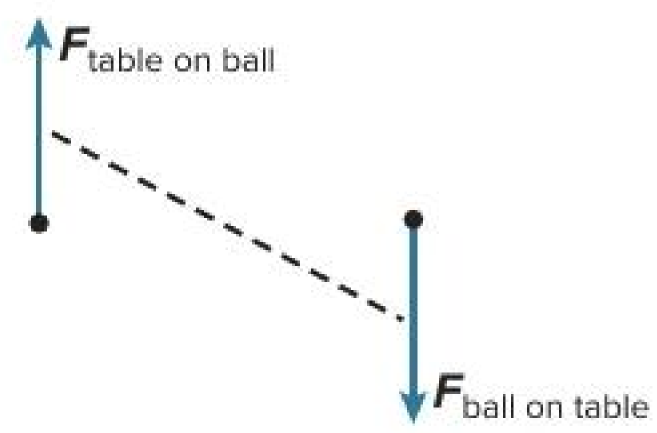
Interaction Pairs

Use these strategies to solve problems in which there is an interaction between objects in two different systems.

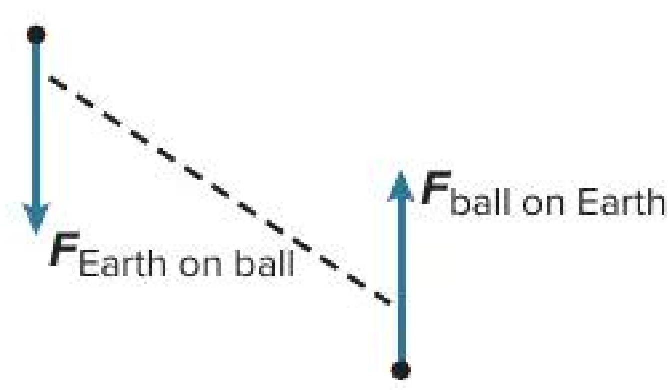
1. Separate the system or systems from the external world.
2. Draw a pictorial model with coordinate systems for each system.
3. Draw a physical model that includes free-body diagrams for each system.
4. Connect interaction pairs by dashed lines.
5. To calculate your answer, use Newton's second law to relate the net force and acceleration for each system.
6. Use Newton's third law to equate the magnitudes of the interaction pairs and give the relative direction of each force.
7. Solve the problem and check the reasonableness of the answers' units, signs, and magnitudes.

Newton's Third Law

The two forces acting on the ball are $F_{\text{table on ball}}$ and $F_{\text{Earth's mass on ball}}$. These forces are not an interaction pair.



Force interaction pair between ball and table.



Force interaction pair between ball and Earth.

Figure 15 A ball resting on a table is part of two interaction pairs.

EXAMPLE Problem 4

EARTH'S ACCELERATION A softball has a mass of 0.18 kg. What is the gravitational force on Earth due to the ball, and what is Earth's resulting acceleration? Earth's mass is 6.0×10^{24} kg.

1 ANALYZE AND SKETCH THE PROBLEM

- Draw free-body diagrams for the two systems: the ball and Earth.
- Connect the interaction pair by a dashed line.

KNOWN

$m_{ball} = 0.18$ kg

$m_{Earth} = 6.0\times10^{24}$ kg $g = 9.8$ N/kg

UNKNOWN

$F_{Earth\ on\ ball} = ?$

$a_{Earth} = ?$

2 SOLVE FOR THE UNKNOWN

Use Newton's second law to find the weight of the ball.

$F_{Earth\ on\ ball} = m_{ball}g = (0.18\ \text{kg})(-9.0\ \text{N/kg}) = -1.8\ \text{N}$ Substitute $m_{ball} = 0.18$ kg.$g = -9.8$ N/kg.

Use Newton's third law to find $F_{ball\ on\ Earth}$.

$F_{Ball\ on\ Earth} = -F_{Earth\ on\ ball} = -(-1.8\ \text{N}) = +1.8\ \text{N}$ Substitute $F_{Earth\ on\ ball} = -1.8$ N.

Use Newton's second law to find a_{Earth}.

$$a_{Earth} = \frac{F_{net}}{m_{Earth}}$$

$$= \frac{1.8\ \text{N}}{6.0\times10^{24}\ \text{kg}}$$ Substitute $F_{net} = 1.8$ N, $m_{Earth} = 6.0\times10^{24}$ kg.

$= 2.9\times10^{-25}\ \text{m/s}^2$ toward the softball

3 EVALUATE THE ANSWER

- **Are the units correct?** Force is in N and acceleration is in m/s^2.
- **Do the signs make sense?** Force and acceleration should be positive.
- **Is the magnitude realistic?** It makes sense that Earth's acceleration is small; Earth's mass is large.

PRACTICE Problems

ADDITIONAL PRACTICE

28. You lift a relatively light bowling ball with your hand, accelerating it upward. What are the forces on the ball? What forces does the ball exert? What objects are these forces exerted on?

29. A brick falls from a construction scaffold. Identify any forces acting on the brick. Also identify any forces the brick exerts and the objects on which these forces are exerted. (Air resistance may be ignored.)

30. A suitcase sits on a stationary airport luggage cart, as in **Figure 16.** Draw a free-body diagram for each object and specifically indicate any interaction pairs between the two.

31. CHALLENGE You toss a ball up in the air. Draw a free-body diagram for the ball after it has lost contact with your hand but while it is still moving upward. Identify any forces acting on the ball. Also identify any forces that the ball exerts and the objects on which these forces are exerted. Assume that air resistance is negligible.

Figure 16

Tension

Tension is simply a specific name for the force that a string or rope exerts. A simplification within this textbook is the assumption that all strings and ropes are massless. In **Figure 17**, the rope is about to break in the middle. If the rope breaks, the bucket will fall; before it breaks, there must be forces holding the rope together. The force that the top part of the rope exerts on the bottom part is $\boldsymbol{F}_{\text{top on bottom}}$. Newton's third law states that this force must be part of an interaction pair. The other member of the pair is the force that the bottom part of the rope exerts on the top, $\boldsymbol{F}_{\text{bottom on top}}$. These forces, equal in magnitude but opposite in direction, also are shown in **Figure 17**.

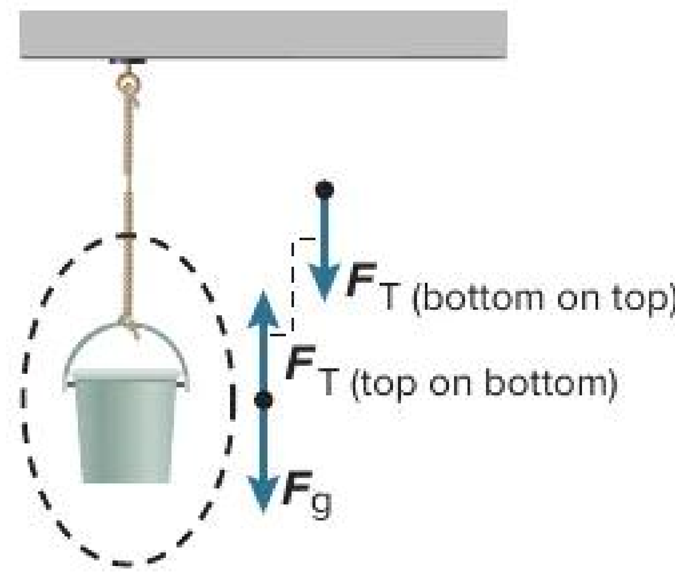


Figure 17 The tension in the rope is equal to the weight of all the objects hanging from it.

Think about this situation in another way. Before the rope breaks, the bucket is in equilibrium. This means that the force of its weight downward must be equal in magnitude but opposite in direction to the tension in the rope upward. Similarly, if you look at the point in the rope just above the bucket, it also is in equilibrium. Therefore, the tension of the rope below it pulling down must be equal to the tension of the rope above it pulling up. You can move up the rope, considering any point in the rope, and see that the tension forces at any point in the rope are pulling equally in both directions. Thus, the tension in the rope equals the weight of all objects below it.

Examine the tension forces shown in **Figure 18**. If team A is exerting a 500-N force and the rope does not accelerate, then team B also must be pulling with a force of 500 N. What is the tension in the rope? If each team pulls with 500 N of force, is the tension 1000 N? To decide, think of the rope as divided into two halves. The left side is not accelerating, so the net force on it is zero. Thus, $F_{\text{A on left side}} = F_{\text{right side on left side}} = 500\text{ N}$. Similarly, $F_{\text{B on right side}} = F_{\text{left side on right side}} = 500\text{ N}$. But the two tensions, $\boldsymbol{F}_{\text{right side on left side}}$ and $\boldsymbol{F}_{\text{left side on right side,}}$ are an interaction pair, so they are equal and opposite. Thus, the tension in the rope equals the force with which each team pulls, or 500 N. To verify this, you could cut the rope in half and tie the ends to a spring scale. The scale would read 500 N.

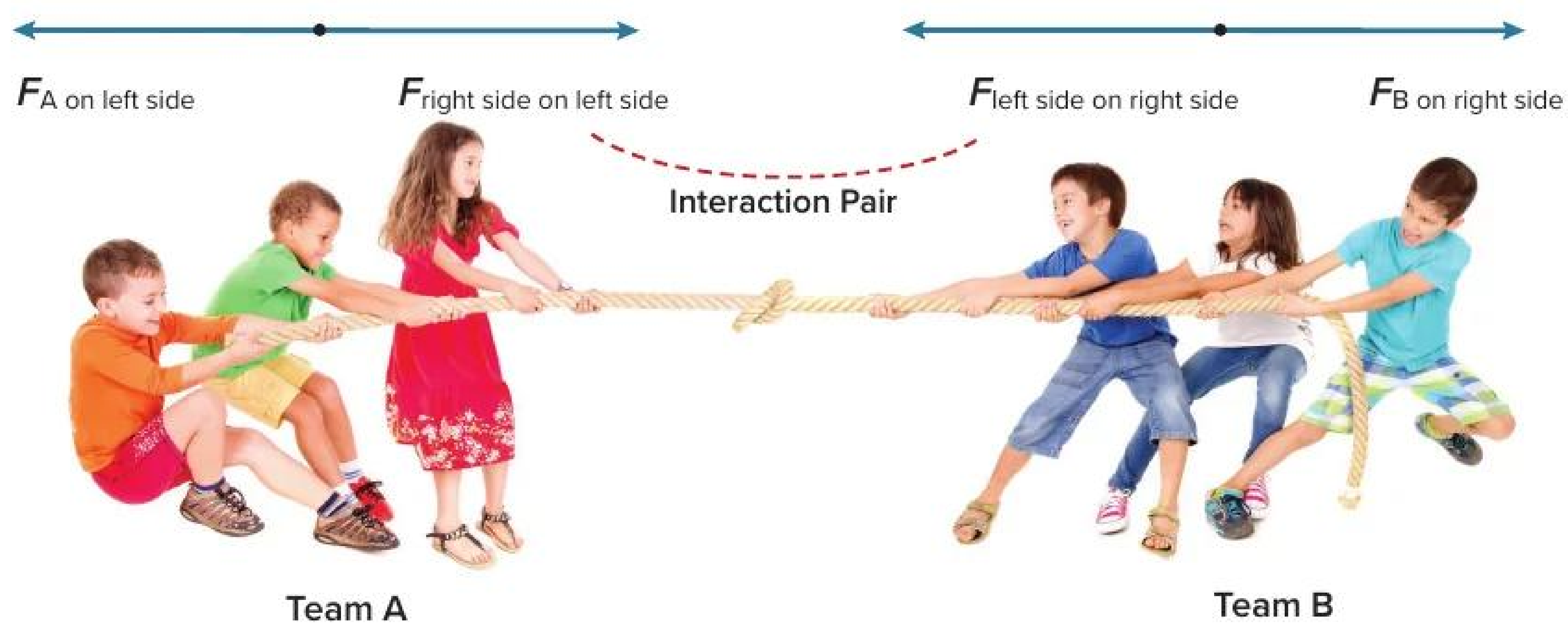


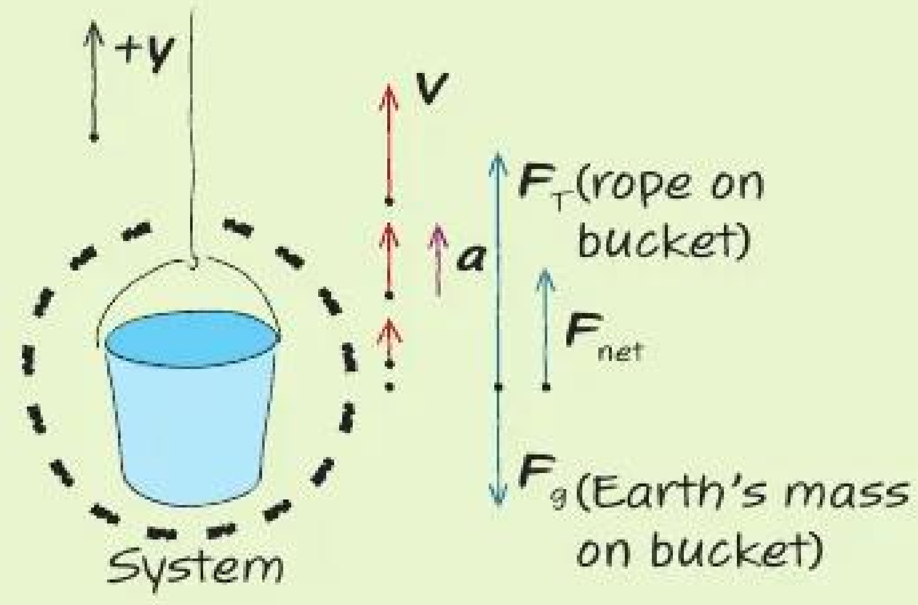
Figure 18 The rope is not accelerating, so the tension in the rope equals the force with which each team pulls.

EXAMPLE Problem 5

LIFTING A BUCKET A 50.0-kg bucket is being lifted by a rope. The rope will not break if the tension is 525 N or less. The bucket started at rest, and after being lifted 3.0 m, it moves at 3.0 m/s. If the acceleration is constant, is the rope in danger of breaking?

1 ANALYZE AND SKETCH THE PROBLEM

- Draw the situation, and identify the forces on the system.
- Establish a coordinate system with the positive axis upward.
- Draw a motion diagram; include ***v*** and ***a***.
- Draw the free-body diagram, and label for forces.



KNOWN	UNKNOWN
$m = 50.0$ kg $\quad v_t = 3.0$ m/s	$F_T = ?$
$v_i = 0.0$ m/s $\quad d = 3.0$ m	

2 SOLVE FOR THE UNKNOWN

F_{net} is the sum of the positive force of the rope pulling up (T_F) and the negative weight force ($-F_g$) pulling down as defined by the coordinate system.

$$F_{net} = F_T + (-F_g)$$

$$F_T = F_{net} + F_g = ma + mg$$ Substitue $F_{net} = ma$, $F_g = mg$

v_i, v_f, and d are known.

$$v_f^2 = v_i + 2ad$$

$$a = \frac{v_f^2 - v_i^2}{2d} = \frac{v_f^2}{2d}$$ Substitute $v_i = 0.0$ m/s

$$F_T = ma + mg$$ Substitute $a = v_f^2 / (2d)$.

$$= m\left(\frac{v_f^2}{2d}\right) + mg$$

$$= (50.0\text{ kg})\left(\frac{(3.0\text{ m/s})^2}{2(3.0\text{ m})}\right) + (50.0\text{ kg})(9.8\text{ N/kg})$$ Substitute $m = 50.0$ kg, $v_f = 3.0$ *m/s*, $d = 3.0$ *m*, g = 9.8 N/Kg.

$$= 560\text{ N}$$

The rope is in danger of breaking because the tension exceeds 525 N.

3 EVALUATE THE ANSWER

- **Are the units correct?** dimensional analysis verifies kg•m/s^2, which is N
- **Does the sign make sense?** The upward force should be positive.
- **Is the magnitude realistic?** The magnitude is a little larger than 490 N, which is the weight of the bucket. $F_g = mg = (50.0\text{ kg})(9.8\text{ N/kg}) = 490$ N

PRACTICE Problems

ADDITIONAL PRACTICE

32. Diego and Mika are trying to remove a tire from Diego's car. When they pull together in the same direction, Mika with a force of 23 N and Diego with a force of 31 N, they just barely get the tire to move off the wheel. What is the magnitude of the force between the tire and the wheel?

33. CHALLENGE You are loading equipment into a bucket that roofers will hoist to a rooftop. If the rope will not break as long as the tension does not exceed 450 N and you fill the bucket until it has a mass of 42 kg, what is the greatest acceleration the workers can give the bucket as they hoist it?

The Normal Force

Any time two objects are in contact, they exert a force on each other. Consider a box sitting on a table. There is a downward force on the box due to gravity. There also is an upward force that the table exerts on the box. This force must exist because the box is in equilibrium. The **normal force** is the perpendicular contact force that a surface exerts on another surface.

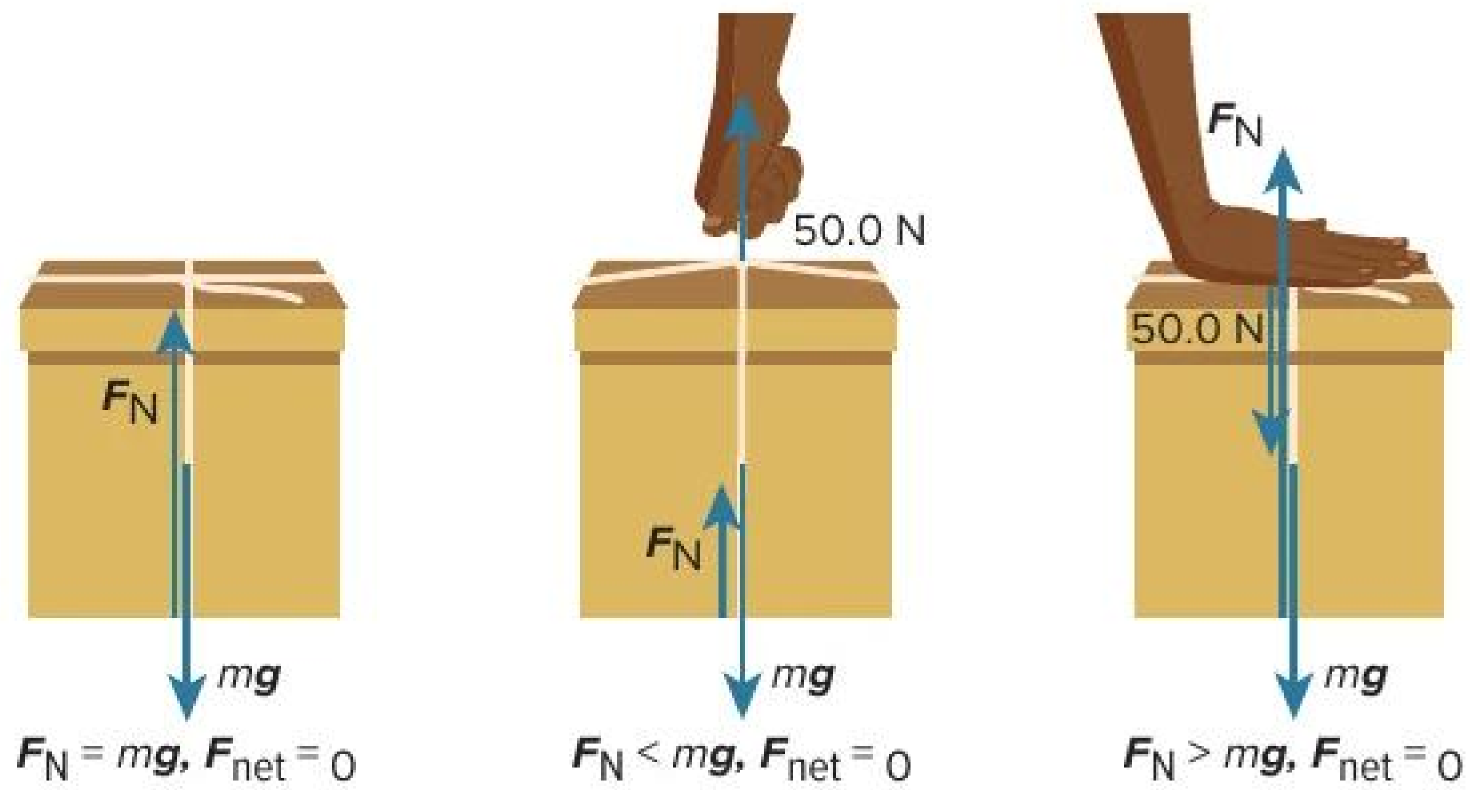


Figure 19 The normal force is not always equal to the object's weight.

The normal force always is perpendicular to the plane of contact between two objects, but is it always equal to the weight of an object? **Figure 19** shows three situations involving a box with the same weight. What if you tied a string to the box and pulled up on it a little bit, but not enough to accelerate the box, as shown in the middle panel in **Figure 19**? When you apply Newton's second law to the box and the forces acting on the box, you see $F_N + F_{\text{string on box}} - F_g = ma = 0$ N, which can be rearranged to show $F_N = F_g - F$ string on box.

You can see that in this case the normal force that the table exerts on the box is less than the box's weight (F_g). Similarly, if you pushed down on the box on the table as shown in the final panel in **Figure 19**, the normal force would be more than the box's weight. Finding the normal force will be important when you study friction in detail.

Check Your Progress

34. **Interaction Pair** Identify each force acting on the ball and its interaction pair in **Figure 20.**

Figure 20

35. **Force** Imagine lowering the ball in **Figure 20** at increasing speed. Draw separate free-body diagrams for the forces acting on the ball and for each set of interaction pairs.

36. **Tension** A block hangs from the ceiling by a massless rope. A second block is attached to the first block and hangs below it on another piece of massless rope. If each of the two blocks has a mass of 5.0 kg, what is the tension in the rope?

37. **Tension** A block hangs from the ceiling by a massless rope. A 3.0-kg block is attached to the first block and hangs below it on another piece of massless rope. The tension in the top rope is 63.0 N. Find the tension in the bottom rope and the mass of the top block.

38. **Critical Thinking** A curtain prevents two tug-of-war teams from seeing each other. One team ties its end of the rope to a tree. If the other team pulls with a 500-N force, what is the tension in the rope? Explain.

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NATURE OF SCIENCE

Finding the Source of the Force

Racetrack Playa in Death Valley, CA has a flat surface dotted with rocks and boulders of varying sizes. The rocks occasionally move, leaving trails in the mud that show their path of motion. For a long time, no one knew what caused the rocks to move. This scientific mystery was finally solved during an investigation that gathered data using advanced technology.

For many years, scientists tried to determine the source of the forces that caused these rocks to move.

Wandering Stones

The rocks on Racetrack Playa have earned many nicknames over the years. They have been called wandering stones, sliding rocks, slithering stones, and sailing stones. The rocks vary greatly in size—some of the largest have a mass of more than 300 kg. The motion of the rocks had never been observed first-hand.

Hypotheses

Many scientists developed hypotheses to explain the motion of the rocks. Some thought that the force of gravity was pulling the rocks slowly down a very slight slope. Others thought that high winds occasionally pushed the rocks with enough force to cause their motion. However, evidence did not support these hypotheses. Gravity was ruled out by data showing the rocks were moving up a slight slope, not downhill. High winds were also ruled out, because data showed that more massive rocks often moved farther than smaller rocks.

Solving the Mystery

To solve the mystery of the rocks' movement, researchers embedded GPS in fifteen rocks to track their motion. They set up a weather station to keep track of the wind speed and direction. They also set up a camera to record video of the rocks' motion.

After analyzing the data, the researchers concluded that rock movement occurred when a shallow pond formed and froze on the Playa's surface. When the ice sheet on the top of the pond started to melt, very thin floating sheets of ice were blown by light breezes. The floating ice sheets pushed against rocks, making the rocks slide, similar to the way a sail makes a boat move across the water. Data providing evidence that thin ice and light breezes could generate enough force to cause the motion of the rocks was an unexpected answer to this scientific mystery.

DEVELOP A MODEL TO ILLUSTRATE

Work with a team to draw a free-body diagram of the forces acting on a sliding rock in Racetrack Playa. Indicate the direction of the acceleration and of the net force. Next to the free-body diagram, make an illustration that uses a circle to designate the system.

MODULE 4
STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 FORCE AND MOTION

- A force is a push or a pull. Forces have both direction and magnitude. A force might be either a contact force or a field force.
- Newton's second law states that the acceleration of a system equals the net force acting on it divided by its mass.

$$a = \frac{F_{net}}{m}$$

- Newton's first law states that an object that is at rest will remain at rest and an object that is moving will continue to move in a straight line with constant speed, if and only if the net force acting on that object is zero. An object with zero net force acting on it is in equilibrium.

- force
- system
- free-body diagram
- net force
- Newton's second law
- Newton's first law
- inertia
- equilibrium

Lesson 2 WEIGHT AND DRAG FORCE

- The object's weight ($\boldsymbol{F}_g$) depends on the object's mass and the gravitational field at the object's location.

$$F_g = mg$$

- An object's apparent weight is the magnitude of the support force exerted on it. An object with no apparent weight experiences weightlessness.
- A falling object reaches a constant velocity when the drag force is equal to the object's weight. The constant velocity is called the terminal velocity. The drag force on an object is determined by the object's weight, size, and shape as well as the fluid through which it moves.

- weight
- gravitational field
- apparent weight
- weightlessness
- drag force
- terminal velocity

Lesson 3 NEWTON'S THIRD LAW

- Newton's third law states that the two forces that make up an interaction pair of forces are equal in magnitude, but opposite in direction and act on different objects. In an interaction pair, $\boldsymbol{F}_{\text{A on B}}$ does not cause $\boldsymbol{F}_{\text{B on A}}$. The two forces either exist together or not at all.

$$\boldsymbol{F}_{\text{A on B}} = -\boldsymbol{F}_{\text{B on A}}$$

- The normal force is a support force resulting from the contact between two objects. It is always perpendicular to the plane of contact between the two objects.

- interaction pair
- Newton's third law
- tension
- normal force

THREE-DIMENSIONAL THINKING
Module Wrap-Up

REVISIT THE PHENOMENON

How do wing suits help BASE jumpers control their velocity?

CER Claim, Evidence, Reasoning

Explain Your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will apply your evidence from this module and complete your project.

GO FURTHER

SEP Data Analysis Lab

How does weight change during a rocket launch?

A rocket is launched vertically. When the rocket reaches its maximum height, a parachute is deployed, and the rocket descends to the ground.

CER Analyze and Interpret Data

1. **Draw and label** a free-body diagram for the rocket during each of the following intervals:
   a. While the engine is firing
   b. After the engine shuts down but before the parachute is deployed
   c. The moment the parachute is deployed
2. **Claim** Imagine the rocket is full-sized and a person stands on a bathroom scale inside. Is the scale reading less than, equal to, or greater that the scale reading when the rocket is at rest for the following intervals?
   a. While the engine is firing
   b. After the engine shuts down but before the parachute is deployed
   c. The moment the parachute is deployed
3. **Evidence and Reasoning** Justify your answers by using your diagrams and explaining your reasoning.


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MODULE 13

VIBRATIONS AND WAVES

ENCOUNTER THE PHENOMENON

How can this pendulum save a building from earthquake damage?

GO ONLINE to play a video about how dampers are used to prevent earthquake damage.

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

CER Claim, Evidence, Reasoning

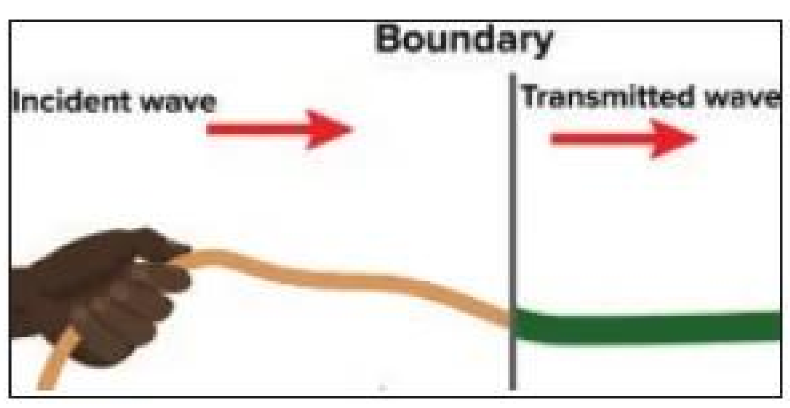
Make Your Claim Use your CER chart to make a claim about how a pendulum could save a building from earth-quake damage. Explain your reasoning.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.

LESSON 1: Explore & Explain: Pendulums



LESSON 2: Explore & Explain: Waves at Boundaries

Additional Resources

LESSON 1
PERIODIC MOTION

FOCUS QUESTION

What are some types of repetitive motion?

Mass on a Spring

The bobbing of a mass on a spring or the swaying of a pendulum are examples of **periodic motion.** In each example, at one position the net force on the object is zero and the object is in equilibrium. When the object moves away from its equilibrium position, the net force on the system becomes nonzero. This net force acts to bring the object back toward equilibrium. The **period** (T) is the time needed for one full cycle of the motion. The **amplitude** of the motion is the maximum distance the object moves from the equilibrium position.

Simple harmonic motion In **Figure 1,** the force exerted by the spring is directly proportional to the distance it is stretched. When pulled down and released, the mass bobs up and down through equilibrium. Any system where the force acting to restore an object to its equilibrium position is directly proportional to the object's displacement shows **simple harmonic motion.**

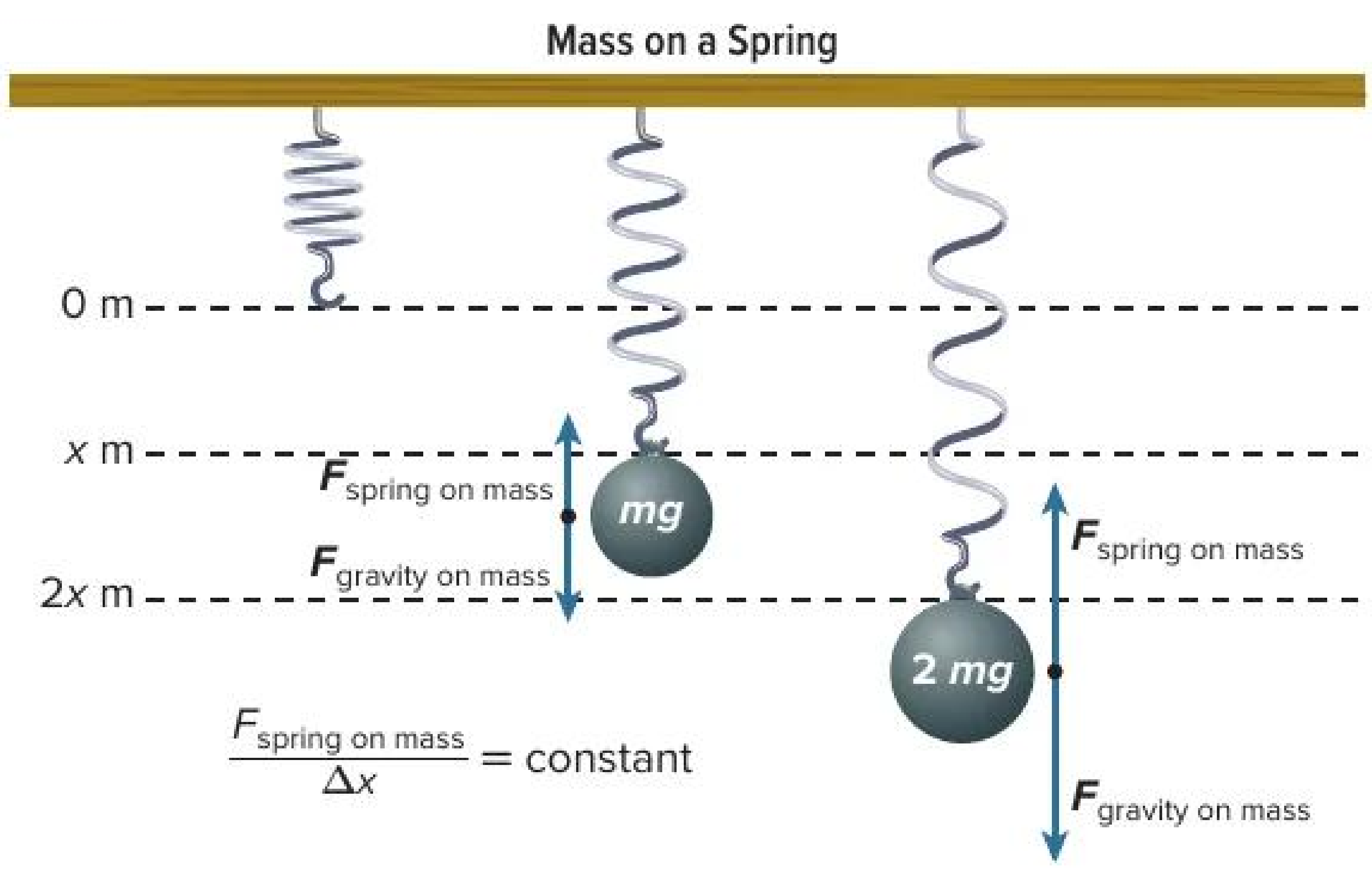


Figure 1 The force exerted on the mass by the spring is directly proportional to the mass's displacement.

Determine *the displacement if the mass is 0.5 mg.*

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Pendulum Vibrations

Plan and carry out an investigation to determine what variables affect a pendulum's period and use the resulting data to calculate the magnitude of the gravitation field.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the Unit and Module questions?

Hooke's Law

Table 1 Force Magnitude-Stretch Distance in a Spring

Stretch Distance (m)	Magnitude of Force Exerted by Spring (N)
0.0	0.0
0.030	1.9
0.060	3.7
0.090	6.3
0.12	7.8

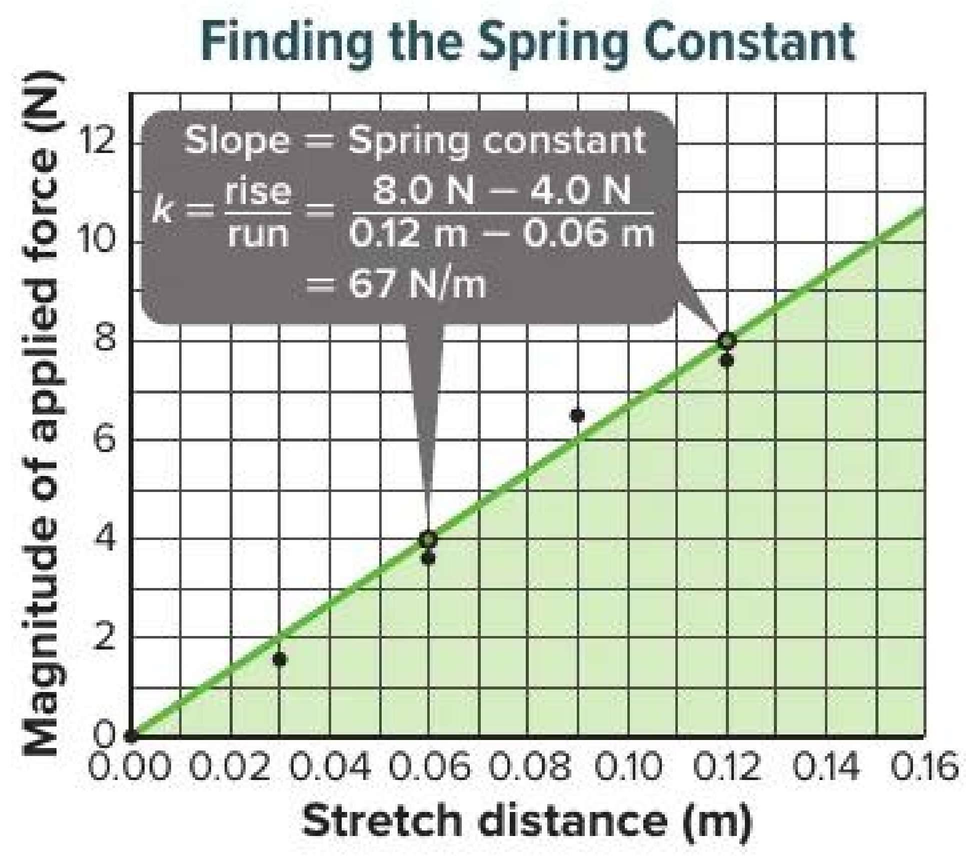


Figure 2 The spring constant can be determined from the slope of the force magnitude-stretch distance graph. The area under the curve is equal to the potential energy stored in the spring.

Hooke's Law

Table 1 shows the relationship between the magnitude of the force exerted by a spring and the distance the spring stretches. **Figure 2** is a graph of the data with the line of best fit. The linear relationship indicates that the magnitude of the force exerted by the spring is directly proportional to the amount the spring is stretched. A spring that exerts a force directly proportional to the distance stretched obeys **Hooke's law.**

Hooke's Law

The magnitude of the force exerted by a spring is equal to the spring constant times the distance the spring is stretched or compressed from its equilibrium position.

$$F = -kx$$

In this equation, k is the spring constant, which depends on the stiffness and other properties of the spring, and x is the distance the spring is stretched from its equilibrium position. Notice that k is the slope of the line in the magnitude of the force v. stretch distance graph. A steeper slope—a larger k—indicates that the spring is harder to stretch. The constant k has the same units as the slope, newtons/meter (N/m). The negative sign in Hooke's law indicates that the force is in the direction opposite the stretch or compression direction. The force exerted by the spring on the mass is always directed toward the spring's equilibrium position.

Hooke's law and real springs Not all springs obey Hooke's law. For example, rubber bands do not. Those that do obey Hooke's law are called elastic springs. Even for elastic springs, Hooke's law only applies over a limited range of distances. If a spring is stretched too far, it can become so deformed that the force is no longer proportional to the displacement.

Potential energy When you stretch a spring you transfer energy to the spring, giving it elastic potential energy. The work done by an applied force is equal to the area under a force v. distance graph like the one shown in **Figure 2.** This work is equal to the elastic potential energy stored in the spring. To calculate this stored energy, find the area of the triangle by multiplying one-half the base of the triangle, which is x, by the height of the triangle. According to Hooke's law, the height of the triangle—the magnitude of the force—is equal to kx.

Potential Energy in a Spring

The potential energy in a spring is equal to one-half times the product of the spring constant and the square of the displacement.

$$PE_{\text{spring}} = -\frac{1}{2}kx^2$$

This mathematical expression, which quantifies how the stored energy in a spring depends on its configuration, together with kinetic energy calculated from mass and speed data, allows the concept of the conservation of energy to be used to predict and describe system behavior. As shown in **Figure 3** on the next page, during horizontal simple harmonic motion the spring's elastic potential energy is converted to kinetic energy and then back to potential energy.

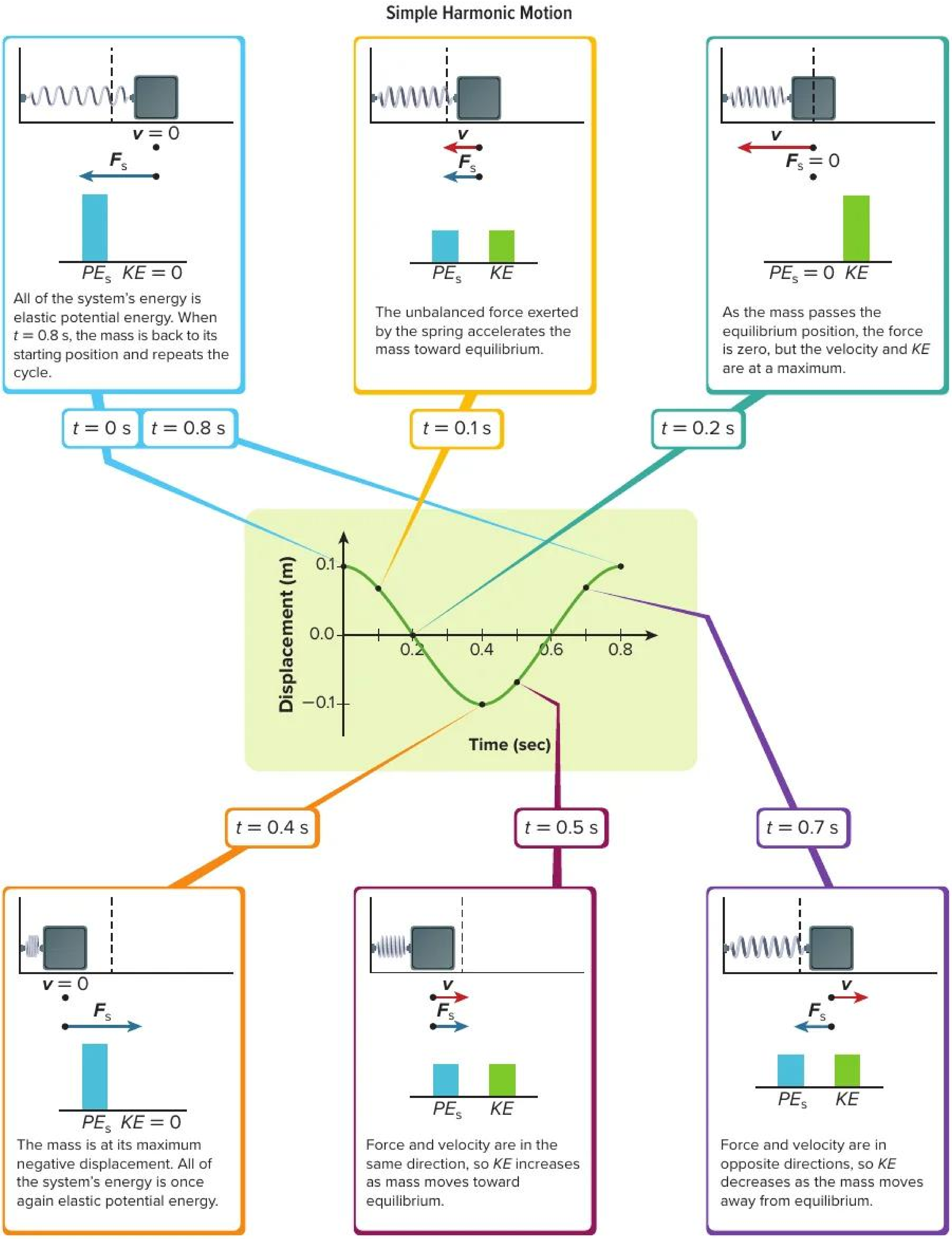


Figure 3 The total mechanical energy of the system is constant throughout the oscillation.

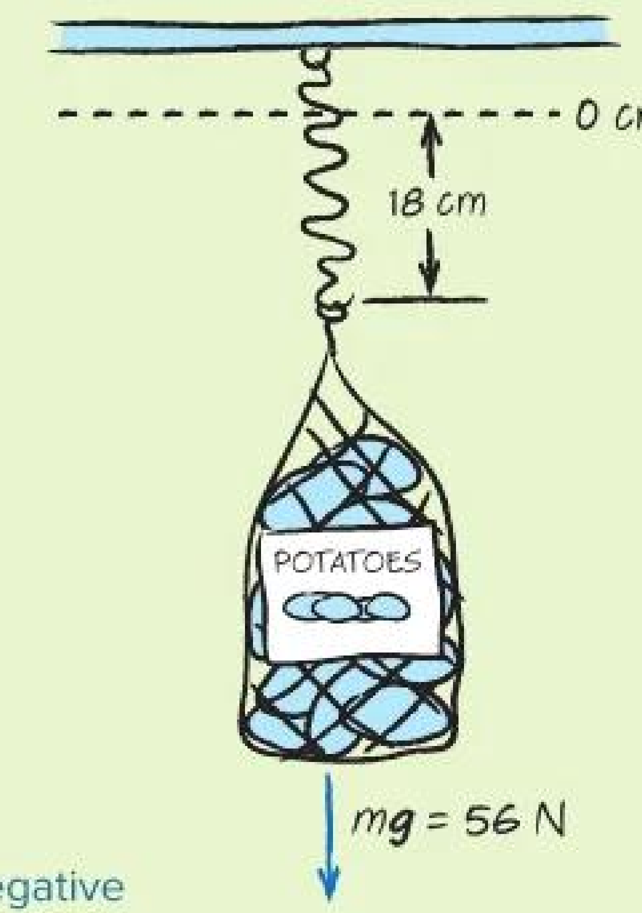
Explain *How can Hooke's law and the concept of conservation of energy be used to predict and describe the behavior of a system such as this?*

EXAMPLE Problem 1

THE SPRING CONSTANT AND THE ENERGY OF A SPRING A spring stretches by 18 cm when a bag of potatoes weighing 56 N is suspended from its end.

a. Determine the spring constant.

b. How much elastic potential energy does the stretched spring have?



1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Show and label the distance the spring has stretched and its equilibrium position.

Known	Unknown
$x = 18$ cm	$k = ?$
$F = -56$ N	$PE_s = ?$

2 SOLVE FOR THE UNKNOWN

a. Use Hooke's law and isolate k.

$$k = -\frac{F}{x}$$

$$= -\frac{-56\text{ N}}{0.18\text{ m}}$$

Substitute $F = -56$ N, $x = 0.18$ m. The force is negative because it is in the opposite direction of x.

$$= 310\text{ N/m}$$

b. $PE_s = \frac{1}{2}kx^2$

$$= \frac{1}{2}(310\text{ N/m})(0.18\text{ m})^2$$

Substitute $k = 310$ N/m, $x = 0.18$ m.

$$= 5.0\text{ J}$$

3 EVALUATE THE ANSWER

- **Are the magnitudes realistic?** N/m is the correct unit for the spring constant. (N/m)(m^2) = N•m = J, which is the correct unit for energy.
- **Is the magnitude realistic?** The average magnitude of the force the spring exerts is the average of 0 and 56 N. The work done is $W = Fx = (28\text{ N})(0.18\text{ m}) = 5.0$ J.

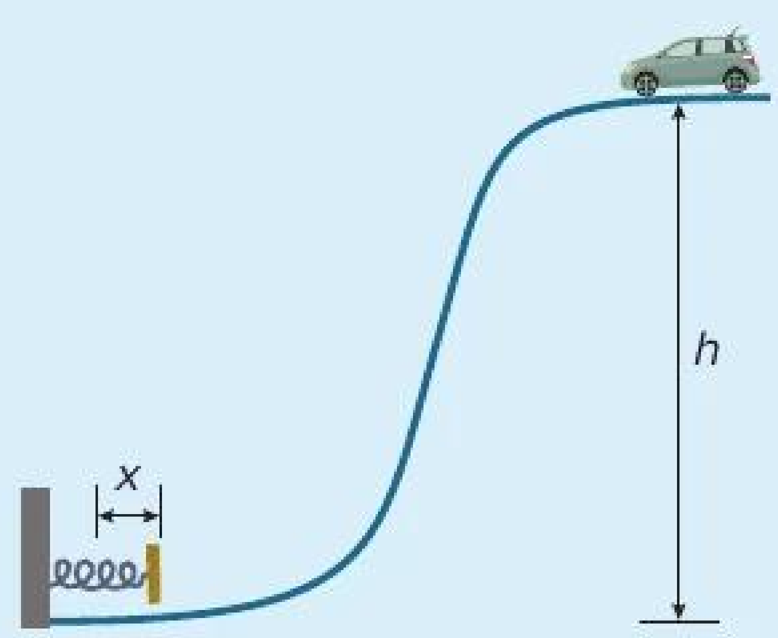
PRACTICE Problems ADDITIONAL PRACTICE

1. What is the spring constant of a spring that stretches 12 cm when an object weighing 24 N is hung from it?
2. What is the elastic potential energy of a spring with $k = 144$ N/m that is compressed by 16.5 cm?
3. A spring has a spring constant of 56 N/m. How far will a block weighing 18 N stretch it?
4. **CHALLENGE** A spring has a spring constant of 256 N/m. How far must it be stretched to give it an elastic potential energy of 48 J?

PHYSICS Challenge

A car of mass m rests at the top of a hill of height h before rolling without friction into a crash barrier located at the bottom of the hill. The crash barrier contains a spring with a spring constant k, which is designed to bring the car to rest with minimum damage.

1. Determine, in terms of m, h, k, and g, the maximum distance (x) the spring will be compressed when the car hits it.
2. If the car rolls down a hill that is twice as high, by what factor will the spring compression increase?
3. What will happen after the car has been brought to rest?



Pendulums

Simple harmonic motion also occurs in the swing of a pendulum. A **simple pendulum** consists of a massive object, called the bob, suspended by a string or a light rod of length ℓ. The bob swings back and forth, as shown in **Figure 4.** The string or rod exerts a tension force (F_T), and gravity exerts a force (F_g) on the bob. Throughout the pendulum's path, the component of the gravitational force in the direction of the pendulum's circular path is a restoring force. At the left and right positions, the restoring force is at a maximum and the velocity is zero. At the equilibrium position, the restoring force is zero and the velocity is maximum.

For small angles (less than about 15°), the restoring force is proportional to the displacement from equilibrium. Similar to the motion of the mass on a spring discussed earlier, the motion of the pendulum is simple harmonic motion. The period of a pendulum is given by the following equation.

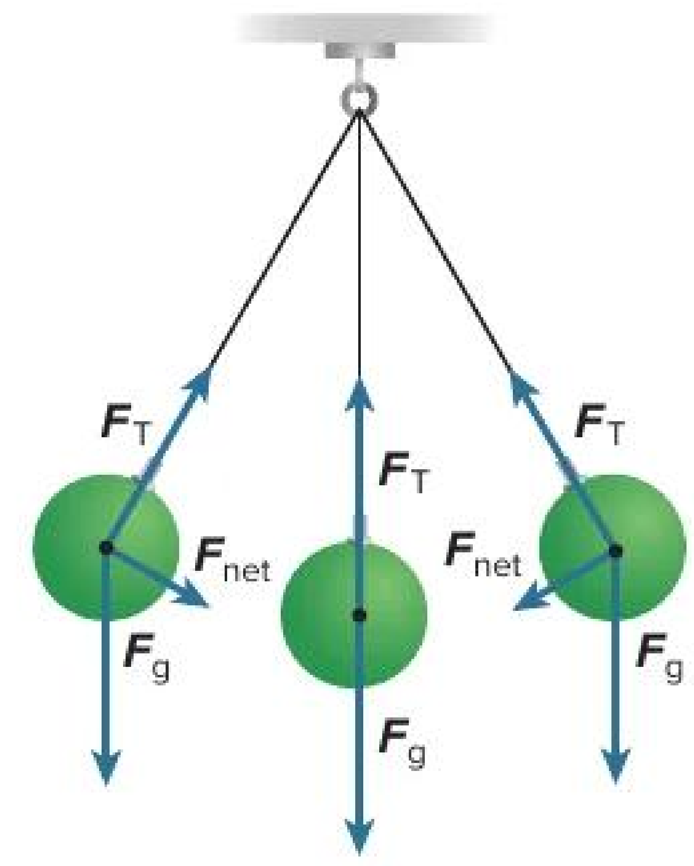


Figure 4 The pendulum's motion is an example of simple harmonic motion because the restoring force is directly proportional to the displacement from equilibrium.

Period of a Pendulum

The period of a pendulum is equal to 2π times the square root of the length of the pendulum divided by the gravitational field.

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$

Notice that the period depends only on the length of the pendulum and the gravitational field, not on the mass of the bob or the amplitude of oscillation. One practical use of the pendulum is to measure g, which can vary slightly at different locations on Earth.

Get It?

Compare the period of a very massive pendulum, like the one shown at the beginning of the module, with the period of a pendulum with the same length but a tiny mass.

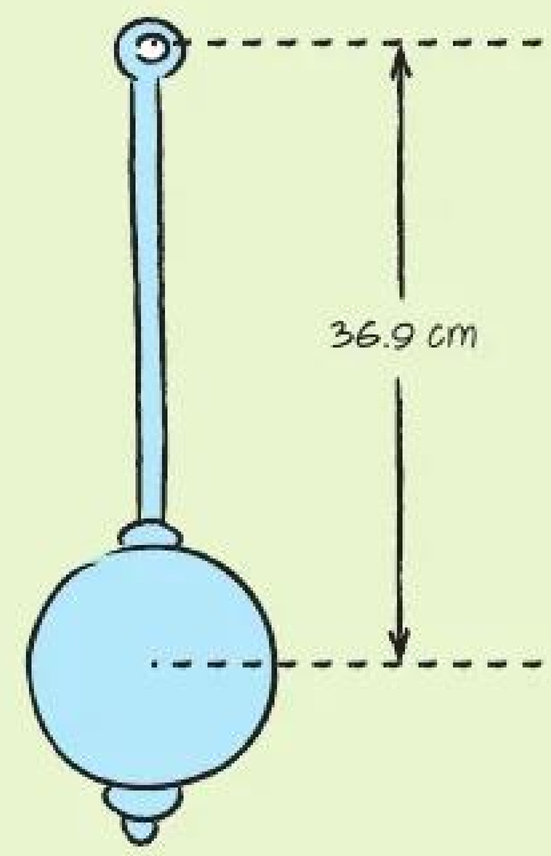
Resonance

To get a playground swing going, you can "pump" it by leaning back and pulling the chains at the same point in each swing. Another option is to have a friend give you repeated pushes at just the right times. **Resonance** occurs when forces are applied to a vibrating or oscillating object at time intervals equal to the period of oscillation. As a result, the amplitude of the vibration increases. Other familiar examples of resonance include rocking a car to free it from a snow bank and jumping rhythmically on a trampoline or a diving board to go higher.

Resonance in simple harmonic motion systems causes a larger and larger displacement as energy is added in small increments. As a child you may have been told to hold a seashell such as a conch up to your ear to "hear the sound of the ocean." The sound you hear when you hold a seashell or other similar-shaped object up to your ear actually comes from resonance. Sound waves resulting from background noise in the room interact with the seashell. Sounds with frequencies matching one of the natural frequencies at which the seashell vibrates result in resonance, and the sound becomes amplified and loud enough to hear. The large amplitude oscillations caused by resonance can also produce useful results. Resonance is used in musical instruments to amplify sounds and in clocks to increase accuracy.

EXAMPLE Problem 2

FINDING *g* USING A PENDULUM A pendulum with a length of 36.9 cm has a period of 1.22 s. What is the gravitational field at the pendulum's location?



1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Label the length of the pendulum.

Known	Unknown
$\ell = 36.9$ cm	$g = ?$
$T = 1.22$ s	

2 SOLVE FOR THE UNKNOWN

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$ Solve for g.

$$g = (2\pi)^2\frac{\ell}{T^2}$$

$$= \frac{4\pi^2(0.369\text{ m})}{(1.22\text{ s})^2}$$ Substitute $l = 0.369$ m, $T = 1.22$ s.

$$= 9.78\text{ m/s}^2 = 9.78\text{ N/kg}$$

3 EVALUATE THE ANSWER

- **Are the magnitudes realistic?** N/kg is the correct unit for gravitational field.
- **Is the magnitude realistic?** The calculated value of g is quite close to the accepted value of g, 9.8 N/kg. This pendulum could be at a higher elevation above sea level.

PRACTICE Problems — ADDITIONAL PRACTICE

5. What is the period on Earth of a pendulum with a length of 1.0 m?

6. How long must a pendulum be on the Moon, where $g = 1.6$ N/kg, to have a period of 2.0 s?

7. CHALLENGE On a certain planet, the period of a 0.75-m-long pendulum is 1.8 s. What is g for this planet?

Check Your Progress

8. **Periodic Motion** Explain why a pendulum is an example of periodic motion.

9. **Energy of a Spring** The springs shown in **Figure 5** are identical. Contrast the potential energies of the bottom two springs.

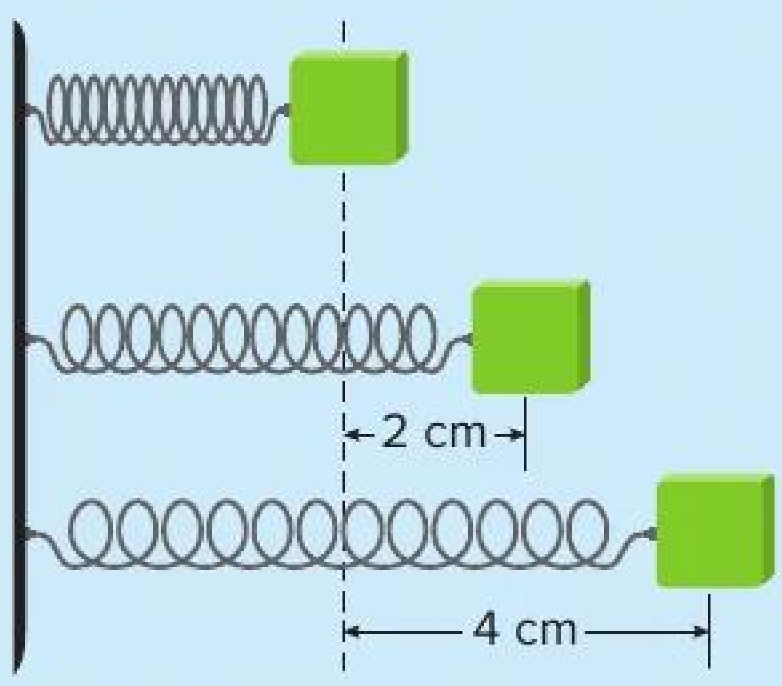


Figure 5

10. **Hooke's Law** Objects of various weights are hung from a rubber band that is suspended from a hook. The weights of the objects are plotted on a graph against the stretch of the rubber band. How can you tell from the graph whether the rubber band obeys Hooke's law?

11. **Pendulum** How must the length of a pendulum be changed to double its period? How must the length be changed to halve the period?

12. **Resonance** If a car's wheel is out of balance, the car will shake strongly at a specific speed but not at a higher or lower speed. Explain.

13. **Critical Thinking** How is uniform circular motion similar to simple harmonic motion? How are they different?

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LESSON 2
WAVE PROPERTIES

FOCUS QUESTION

What are some common types of waves?

Mechanical Waves

A **wave** is a disturbance that carries energy through matter or space without transferring matter. You have learned how Newton's laws of motion and the law of conservation of energy govern the behavior of particles. These laws also govern the behavior of waves. Water waves, sound waves, and the waves that travel along a rope or a spring are mechanical waves. Mechanical waves pass through a physical medium, such as water, air, or a rope.

Transverse waves A **wave pulse** is a single bump or disturbance that passes through a medium. In the left panel of **Figure 6,** the wave pulse disturbs the rope in the vertical direction, but the pulse travels horizontally. A wave that disturbs the particles in the medium perpendicular to the direction of the wave's travel is called a **transverse wave.** If the disturbances continue at a constant rate, a **periodic wave** is generated.

Longitudinal waves In a coiled spring toy, you can produce another type of wave. If you squeeze together several turns of the coiled spring toy and then suddenly release them, pulses will move away in both directions. The result is called a **longitudinal wave** because the disturbance is parallel to the direction of the wave's travel. Sound waves are longitudinal waves in which the molecules are alternately compressed or decompressed along the path of the wave.

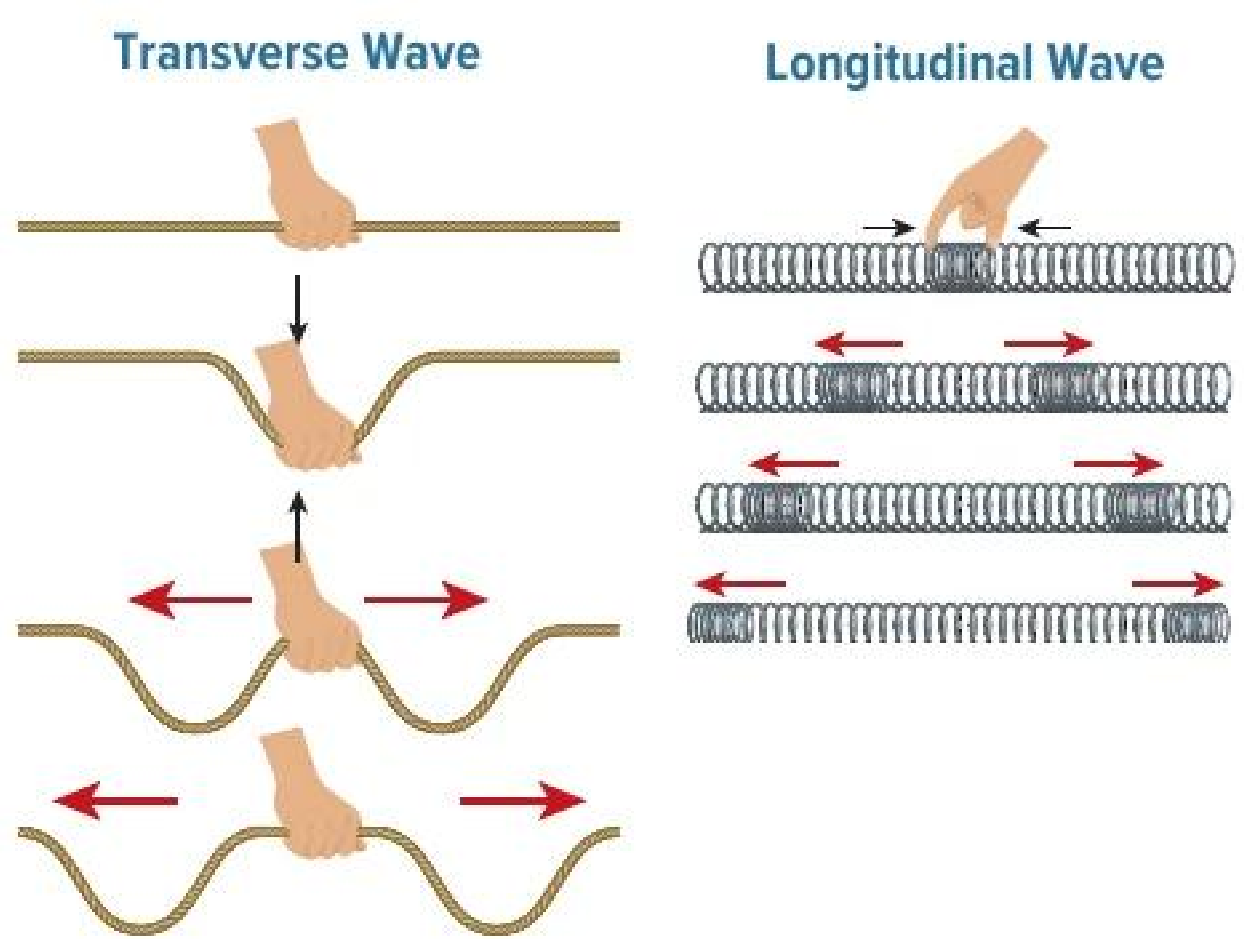

Figure 6 Shaking a rope up and down produces transverse wave pulses traveling in both directions. Squeezing and releasing the coils of a spring produces longitudinal wave pulses in both directions.
Explain *the difference between transverse and longitudinal waves.*

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COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practices: Wave Characteristics

HS-PS4-1. Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media.

CCC **Identify Crosscutting Concepts**

Create a table of the crosscutting concepts and fill in examples you find as you read.

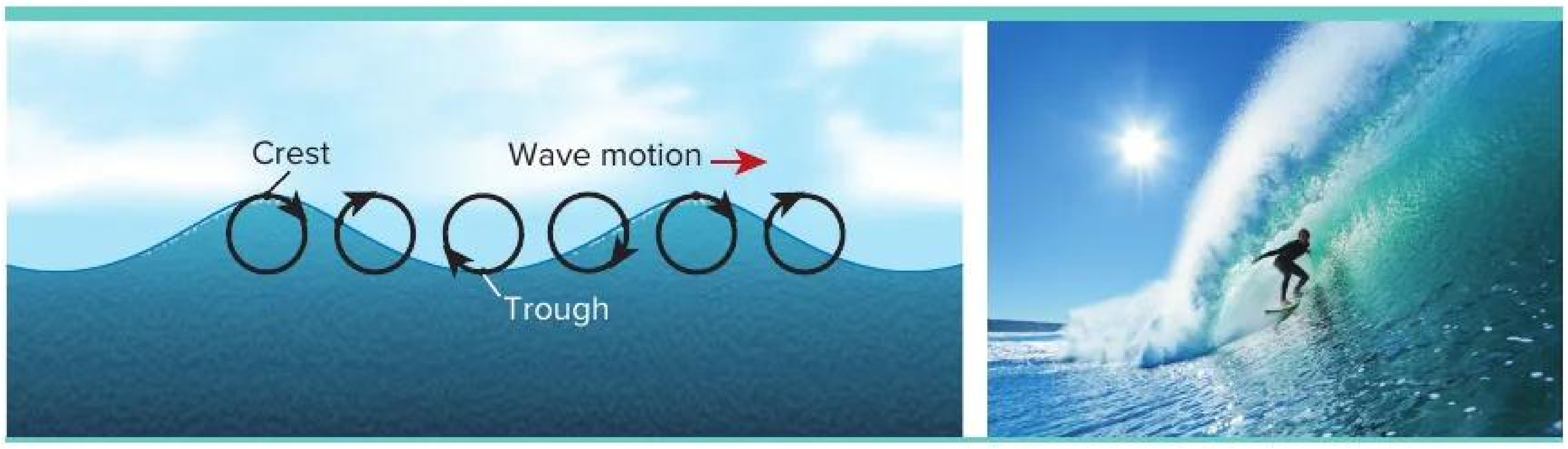


Figure 7 Surface waves in water cause movement both parallel and perpendicular to the direction of wave motion. When these waves interact with the shore, the regular, circular motion is disrupted and the waves break on the beach.

Surface waves

Waves that are deep in a lake or an ocean are longitudinal. In a **surface wave,** however, the medium's particles follow a circular path that is at times parallel to the direction of travel and at other times perpendicular to the direction of wave travel, as shown in **Figure 7.** Surface waves set particles in the medium, in this case water, moving in a circular pattern. At the top and bottom of the circular path, particles are moving parallel to the direction of the wave's travel. This is similar to a longitudinal wave. At the left and right sides of each circle, particles are moving up or down. This up-and-down motion is perpendicular to the wave's direction, similar to a transverse wave.

> Real-World Physics
>
> **Tsunamis**
>
> On March 11, 2011, a wall of water estimated to be ten meters high hit areas on the east coast of Japan—tsunami! A tsunami is a series of ocean waves that can have wavelengths over 100 km, periods of one hour, and wave speeds of 500–1000 km/h.

Wave Properties

Many types of waves share a common set of wave properties. Some wave properties depend on how the wave is produced, whereas others depend on the medium through which the wave is passing.

Amplitude

How does the pulse generated by gently shaking a rope differ from the pulse produced by a violent shake? The difference is similar to the difference between a ripple in a pond and an ocean breaker—they have different amplitudes. You read earlier that the amplitude of periodic motion is the greatest distance from equilibrium. Similarly, as shown in **Figure 8,** a transverse wave's amplitude is the maximum distance of the wave from equilibrium. Since amplitude is a distance, it is always positive. You will learn more about measuring the amplitude of longitudinal waves when you study sound.

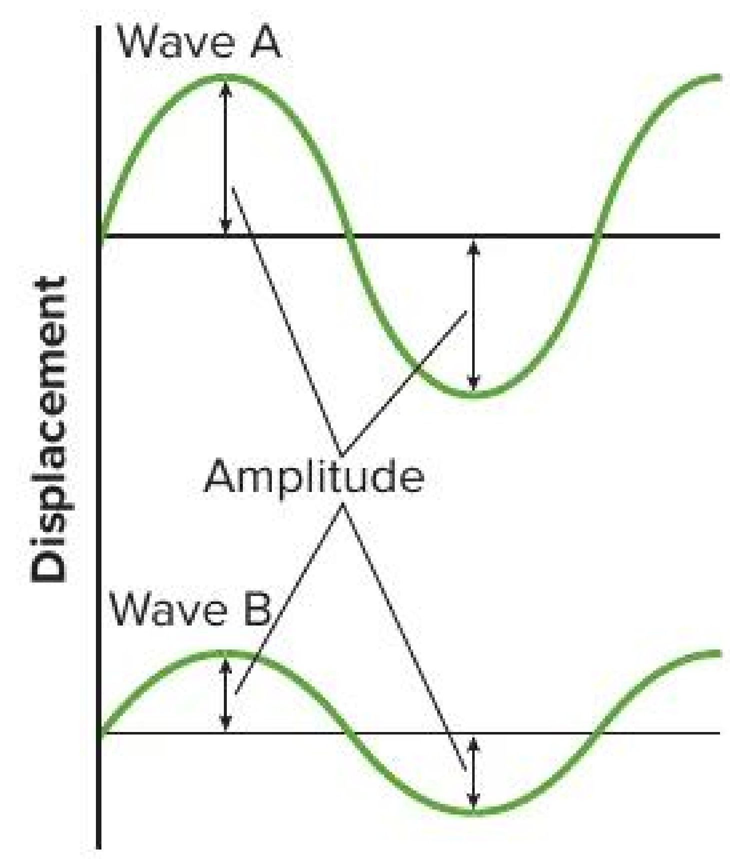


Figure 8 A wave's amplitude is measured from the equilibrium position to the highest or lowest point on the wave.

Energy of a wave

Waves, including water waves, are examples of the many ways that energy manifests at the macroscopic scale. The energy of a wave is related to its amplitude, and a wave's amplitude depends on how the wave is generated. More energy must be added to the system to generate a wave with a greater amplitude. For example, strong winds produce larger water waves than those formed by gentle breezes. Waves with greater amplitudes transfer more energy. Whereas a wave with a small amplitude might move sand on a beach a few centimeters, a giant wave can uproot and move a tree.

For waves that move at the same speed, the rate at which energy is transferred is proportional to the square of the amplitude. Thus, doubling the amplitude of a wave increases the amount of energy that wave transfers each second by a factor of four.

Wavelength Rather than focusing on one point on a wave, imagine taking a snapshot of the wave so you can see the whole wave at one instant in time. The top image in **Figure 9** shows each low point on a transverse wave, called a **trough,** and each high point on a transverse wave, called a **crest,** of a wave. The shortest distance between points where the wave pattern repeats itself is called the **wavelength.** Crests are spaced by one wavelength. Each trough also is one wavelength from the next. The Greek letter lambda (λ) represents wavelength.

Speed and velocity How fast does a wave travel? The speed of a wave pulse can be found in the same way the speed of a moving car is determined. First, measure the displacement of one of the wave's crests or compressions (Δd), then divide this by the time interval (Δt) to find the speed.

$$v = \frac{\Delta d}{\Delta t}$$

For most mechanical waves, transverse and longitudinal, except water surface waves, wave speed does not depend on amplitude, frequency, or wavelength. Speed depends only on the medium through which the waves are passing and on the type of wave. For example, sound waves have characteristic speeds in water and in air. The temperature of the medium also makes a difference. Sound waves travel faster in warm, dry air than in cool, dry air.

Get It?

Summarize how changing a wave's amplitude, frequency, or wavelength affects the wave's speed.

Phase Any two points on a wave that are one or more whole wavelengths apart are said to be in phase. Particles in the medium are in phase with one another when they have the same displacement from the equilibrium position and the same velocity. Particles with opposite displacements from the equilibrium position and opposite velocities are 180° out of phase. A crest and a trough, for example, are 180° out of phase with each other. Two particles in a wave medium can be anywhere from 0° to 360° out of phase with each other.

Period Although wave speed and amplitude can describe both wave pulses and periodic waves, period (T) applies only to periodic waves. You have learned that the period of simple harmonic motion, such as the motion of a simple pendulum, is the time it takes for the motion to complete one cycle. Such motion is usually the source, or cause, of a periodic wave. The period of a wave is equal to the period of the source. In **Figure 9** the period (T) equals 0.04 s, which is the time it takes the source to complete one cycle. The same time is taken by P, a point on the rope, to return to its initial position and velocity.

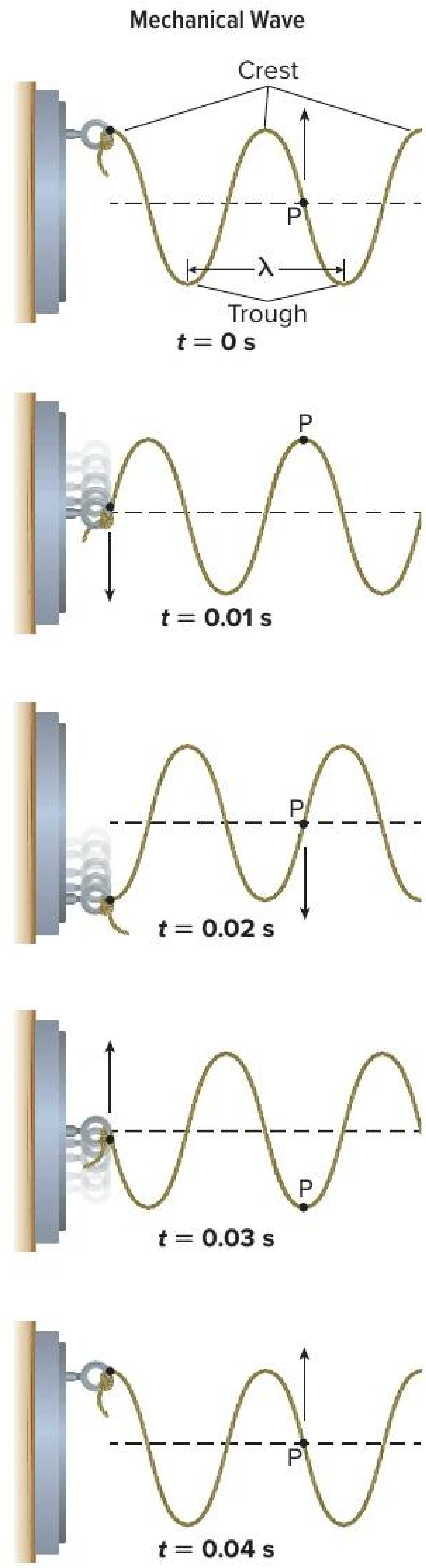


Figure 9 A mechanical oscillator moves the left end of the rope up and down, completing the cycle in 0.04 s.

Calculating frequency The **frequency** of a wave (f) is the number of complete oscillations a point on that wave makes each second. Frequency is measured in hertz (Hz). One hertz is one oscillation per second and is equal to 1/s or s^{-1}. The frequency and the period of a wave are related by the following equation.

Frequency of a Wave

The frequency of a wave is equal to the reciprocal of the period.

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

Both the period and the frequency of a wave depend only on the wave's source. They do not depend on the wave's speed or the medium.

Calculating wavelength You can directly measure a wave's wavelength by measuring the distance between adjacent crests or troughs. You can also calculate it because the wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing. In the time interval of one period, a wave moves one wavelength. Therefore, the wavelength of a wave is the speed multiplied by the period, $\lambda = vT$. Using the relation that $f = \frac{1}{T}$, the wavelength equation is very often written in the following way.

Wavelength

The wavelength of a wave is equal to the velocity divided by the frequency.

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

Graphing waves If you took a snapshot of a transverse wave on a coiled spring toy, it might look like one of the waves shown in **Figure 9.** This snapshot could be placed on a graph grid to show more information about the wave, as in the left panel of **Figure 10.** Measuring from peak to peak or trough to trough on such a snapshot provides the wavelength. Now consider recording the motion of a single particle, such as point P in **Figure 9.** That motion can be plotted on a displacement v. time graph, as in the graph on the right in **Figure 10.** Measuring from peak to peak or trough to trough in this graph provides the wave's period.

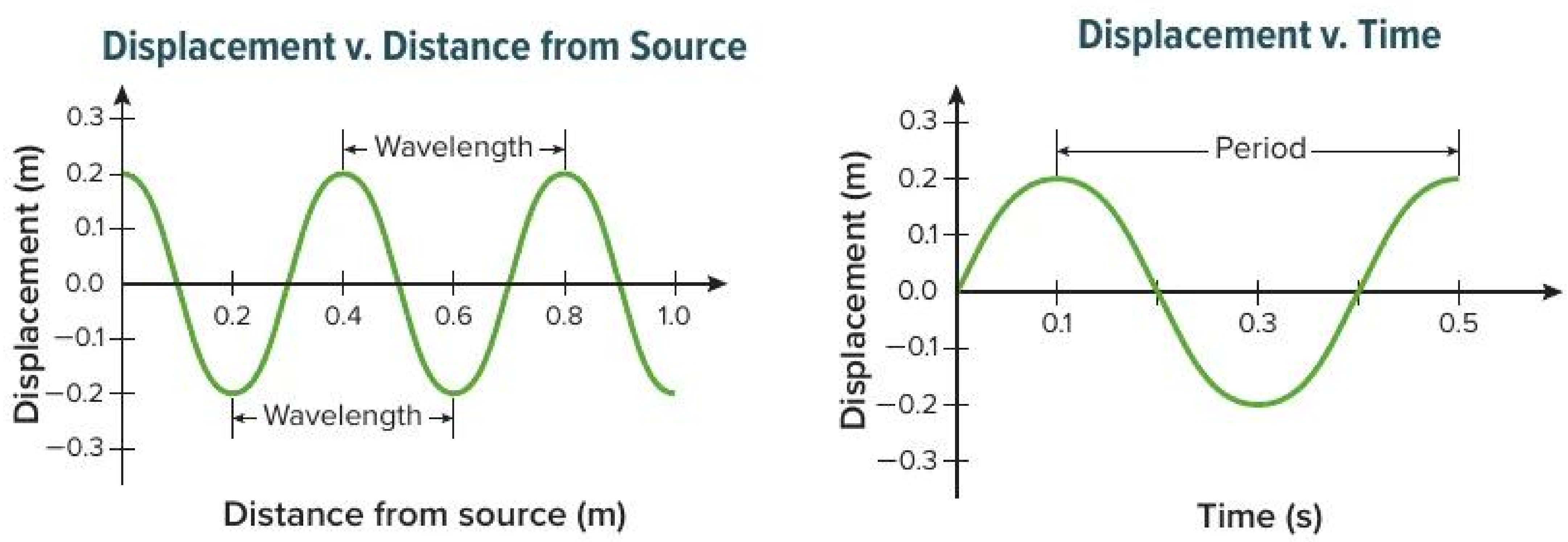


Figure 10 Graphing waves on different axes provides different kinds of information.

Determine *the period of the wave shown in the displacement v. time graph.*

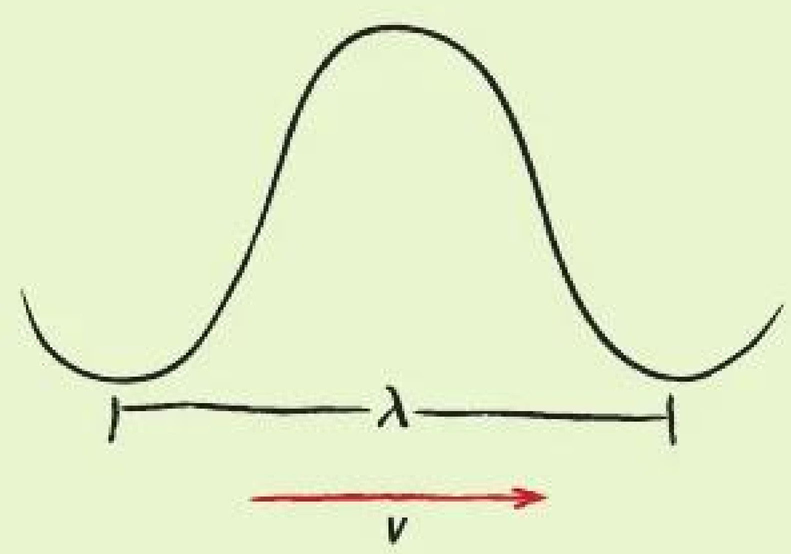
EXAMPLE Problem 3

CHARACTERISTICS OF A WAVE A sound wave has a frequency of 192 Hz and travels the length of a football field, 91.4 m, in 0.271 s.

a. What is the speed of the wave?
b. What is the wavelength of the wave?
c. What is the period of the wave?
d. If the frequency were changed to 442 Hz, what would be the new wavelength and period?

1 ANALYZE AND SKETCH THE PROBLEM

- Draw a diagram of the wave.
- Draw a velocity vector for the wave.



Known	Unknown
$f = 192$ Hz	$v = ?$
$\Delta d = 91.4$ m	$\lambda = ?$
$\Delta t = 0.271$ s	$T = ?$

2 SOLVE FOR THE UNKNOWN

a. Use the definition of velocity.

$$v = \frac{\Delta d}{\Delta t}$$
$$= \frac{91.4\text{ m}}{0.271\text{ s}}$$ Substitute $\Delta d = 91.4$ m, $\Delta t = 0.271$ s
$$= 337\text{ m/s}$$

b. Use the relationship between wave velocity, wavelength, and frequency.

$$\lambda = \frac{v}{f}$$
$$= \frac{337\text{ m/s}}{192\text{ Hz}}$$ Substitute $v = 337$ m/s, $f = 192$ Hz.
$$= 1.76\text{ m}$$

c. Use the relationship between period and frequency.

$$T = \frac{1}{f}$$
$$= \frac{1}{192\text{ Hz}}$$ Substitute $f = 192$ Hz.
$$= 0.00521\text{ s}$$

d. $\lambda = \frac{v}{f}$
$$= \frac{337\text{ m/s}}{442\text{ Hz}}$$ Substitute $v = 337$ m/s, $f = 442$ Hz.
$$= 0.762\text{ m}$$

$$T = \frac{1}{f}$$
$$= \frac{1}{442\text{ Hz}}$$ Substitute $f = 442$ Hz.
$$= 0.00226\text{ s}$$

3 EVALUATE THE ANSWER

- **Are the magnitudes realistic?** Hz has the unit s^{-1}, so $\left(\frac{m}{s}\right)/\text{Hz} = \left(\frac{m}{s}\right)\cdot s = m$, which is correct for λ.
- **Are the magnitudes realistic?** A typical sound wave travels at approximately 340 m/s in air, so 337 m/s is reasonable. The frequencies and periods are reasonable for sound waves. The frequency of 442 Hz is close to a 440-Hz A, which is A above middle-C on a piano.

PRACTICE Problems

ADDITIONAL PRACTICE

14. A sound wave produced by a clock chime is heard 515 m away 1.50 s later.
  a. Based on these measurements, what is the speed of sound in air?
  b. The sound wave has a frequency of 436 Hz. What is the period of the wave?
  c. What is its wavelength?

15. How are the wavelength, frequency, and speed of a wave related? How do they depend on the medium through which the wave is passing and the type of wave?

16. What is the speed of a periodic wave disturbance that has a frequency of 3.50 Hz and a wavelength of 0.700 m?

17. How does increasing the wavelength by 50 percent affect the frequency of a wave on a rope?

18. The speed of a transverse wave in a string is 15.0 m/s. If a source produces a disturbance that has a frequency of 6.00 Hz, what is its wavelength?

19. Five wavelengths are generated every 0.100 s in a tank of water. What is the speed of the wave if the wavelength of the surface wave is 1.20 cm?

20. A periodic longitudinal wave that has a frequency of 20.0 Hz travels along a coiled spring toy. If the distance between successive compressions is 0.600 m, what is the speed of the wave?

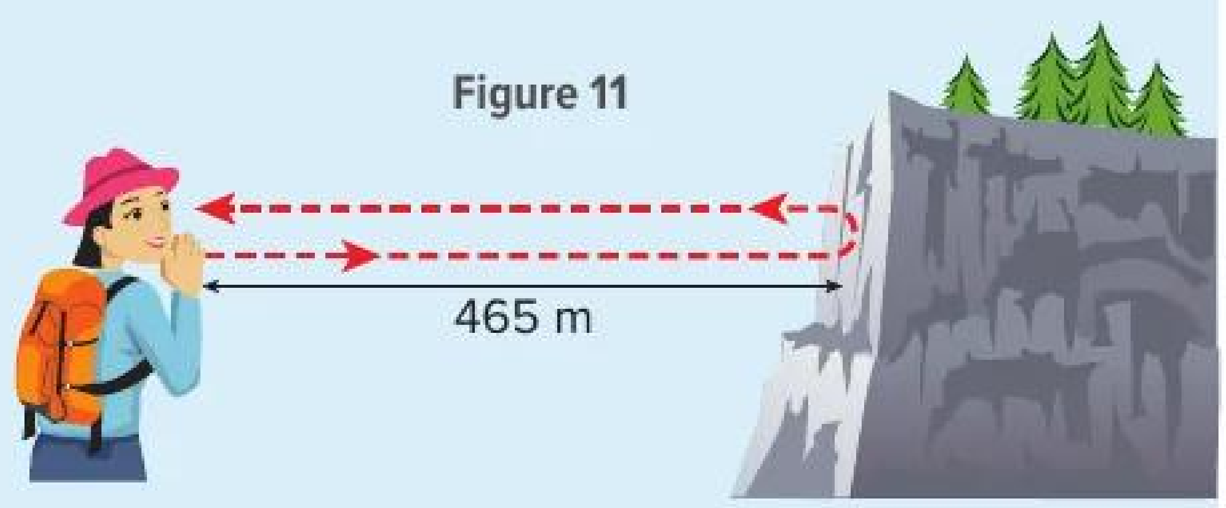
21. How does the frequency of a wave change when the period of the wave is doubled?

22. Describe the change in the wavelength of a wave when the period is reduced by one-half.

23. If the speed of a wave increases to 1.5 times its original speed while the frequency remains constant, how does the wavelength change?

24. CHALLENGE A hiker shouts toward a vertical cliff as shown in **Figure 11.** The echo is heard 2.75 s later.
  a. What is the speed of sound of the hiker's voice in air?
  b. The wavelength of the sound is 0.750 m. What is its frequency?
  c. What is the period of the wave?

Figure 11



Check Your Progress

25. **Transverse Waves** Suppose you and your lab partner are asked to demonstrate that a transverse wave transports energy without transferring matter. How could you do it?

26. **Wave Characteristics** You are creating transverse waves on a rope by shaking your hand from side to side. Without changing the distance your hand moves, you begin to shake it faster and faster. What happens to the amplitude, wavelength, frequency, period, and velocity of the wave?

27. **Longitudinal Waves** Describe longitudinal waves. What types of mediums transmit longitudinal waves?

28. **Speeds in Different Mediums** If you pull on one end of a coiled spring toy, does the pulse reach the other end instantaneously? What happens if you pull on a rope? What happens if you hit the end of a metal rod? Compare the pulses that are traveling through each of these three materials.

29. **Critical Thinking** If a raindrop falls into a pool, it produces waves with small amplitudes. If a swimmer jumps into a pool, he or she produces waves with large amplitudes. Why doesn't the heavy rain in a thunderstorm produce large waves?

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LESSON 3
WAVE BEHAVIOR

FOCUS QUESTION

What happens when two waves meet?

Waves at Boundaries

Recall from Lesson 2 that the speed of a mechanical wave depends only on the properties of the medium it passes through, not on the wave's amplitude or frequency. For example, for waves on a spring, the speed depends on the spring's tension and mass per unit length. Examine what happens when a wave travels from one medium to another. **Figure 12** shows a wave pulse traveling from a larger spring into a smaller one. The pulse that strikes the boundary is called the **incident wave.** One pulse from the larger spring continues in the smaller spring, but the speed is different in the smaller spring. Note that this transmitted wave pulse remains upward.

Some of the energy of the incident wave's pulse is reflected backward into the larger spring. This returning wave is called the reflected wave. Whether the **reflected wave** is upright or inverted depends on the characteristics of the two springs. For example, if the waves in the smaller spring have a greater speed because the spring is stiffer, then the reflected wave will be inverted.

Wave at a Boundary

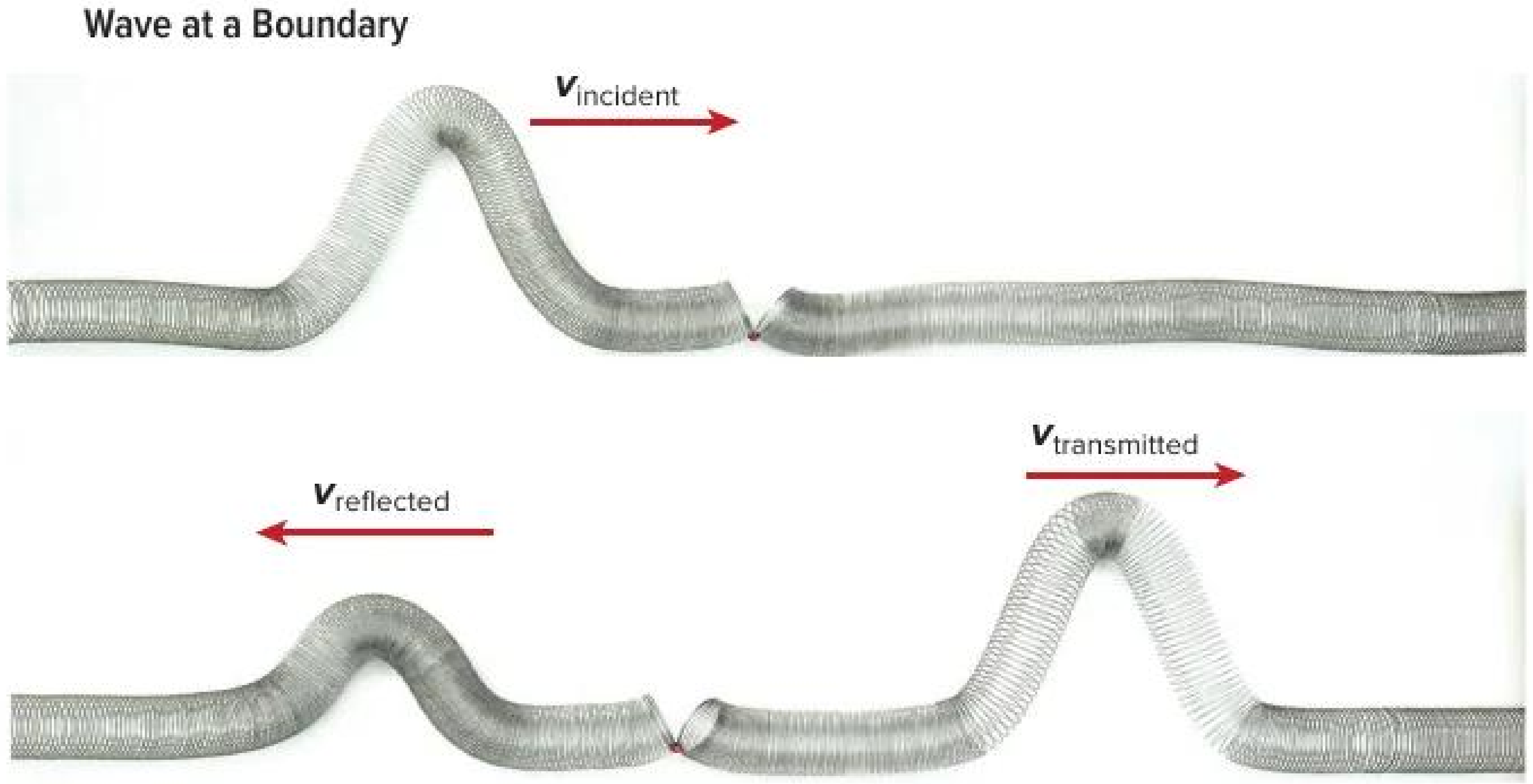

Figure 12 When the wave pulse meets the boundary between the two springs, a transmitted wave pulse and a reflected wave form.

Compare *the energy of the incident wave to the energy of the reflected wave.*

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

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INVESTIGATE

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PhysicsLAB: Reflection and Refraction

Analyze data from wave patterns in a ripple tank to predict the behavior of waves in water.

Review the News

Obtain information from a current news story about mechanical waves, such as seismic or water waves. Evaluate your source and communicate your findings to your class.

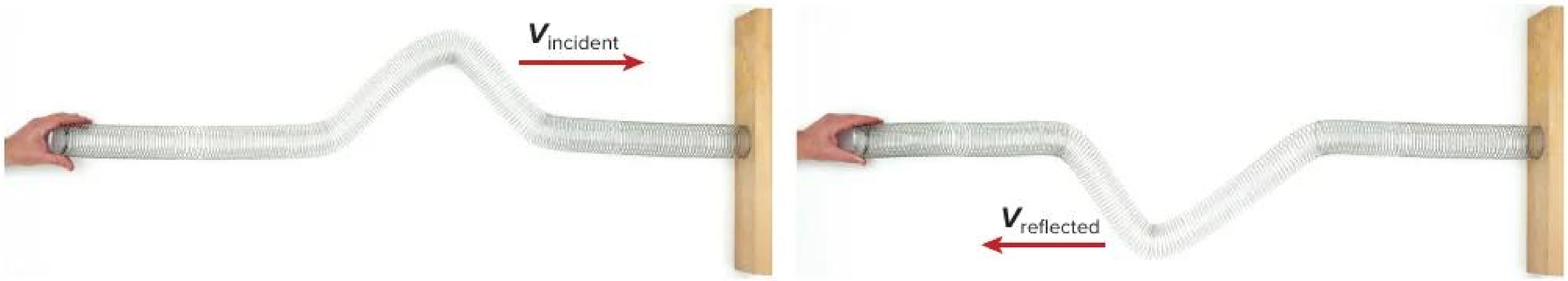


Figure 13 When a wave encounters a rigid boundary, the reflected wave is inverted. Note that the amplitude is not affected by the rigid boundary.

Rigid boundaries When a wave pulse hits a rigid boundary, the energy is reflected back, as shown in **Figure 13.** The wall is the boundary of a new medium through which the wave attempts to pass. Instead of passing through, the pulse is reflected from the wall with almost exactly the same amplitude as the pulse of the incident wave. Thus, almost all the wave's energy is reflected back. Very little energy is transmitted into the wall. Also note that the pulse is inverted.

Superposition of Waves

Suppose a pulse traveling along a spring meets a reflected pulse that is coming back from a boundary, as shown in **Figure 14.** In this case, two waves exist in the same place in the medium at the same time. Each wave affects the medium independently. The **principle of superposition** states that the displacement of a medium caused by two or more waves is the algebraic sum of the displacements caused by the individual waves. In other words, two or more waves can combine to form a new wave. If the waves move in the same medium, they can cancel or add or subtract to form a new wave of lesser or greater amplitude. They emerge unaffected by each other. The result of the superposition of two or more waves is called **interference.**

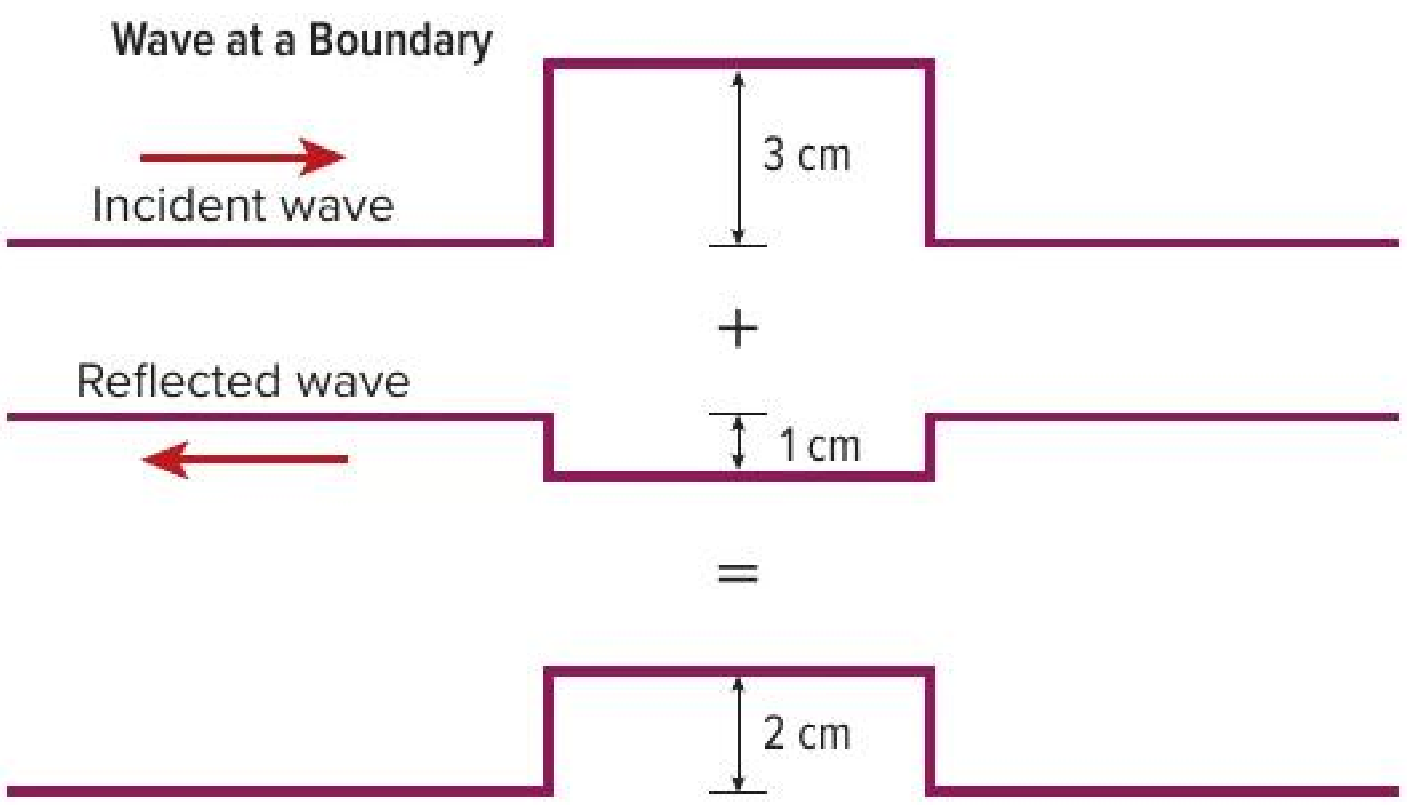


Figure 14 Waves add algebraically during superposition.

SCIENCE USAGE v. COMMON USAGE

Interference

Science usage: the result of superposition of two or more waves

The amplitude of the interference of several waves was much larger than the amplitude of the individual waves.

Common usage: the act of coming between in a way that hinders or impedes

Ehud was ejected from the game for an interference foul.

STEM CAREER Connection

Boat Designer

If you are drawn to the water, the career of boat designer might be for you. Whether designing ocean liners, freighters, yachts, or wakeboard boats, a boat designer must understand how a vessel will perform in various wave conditions.

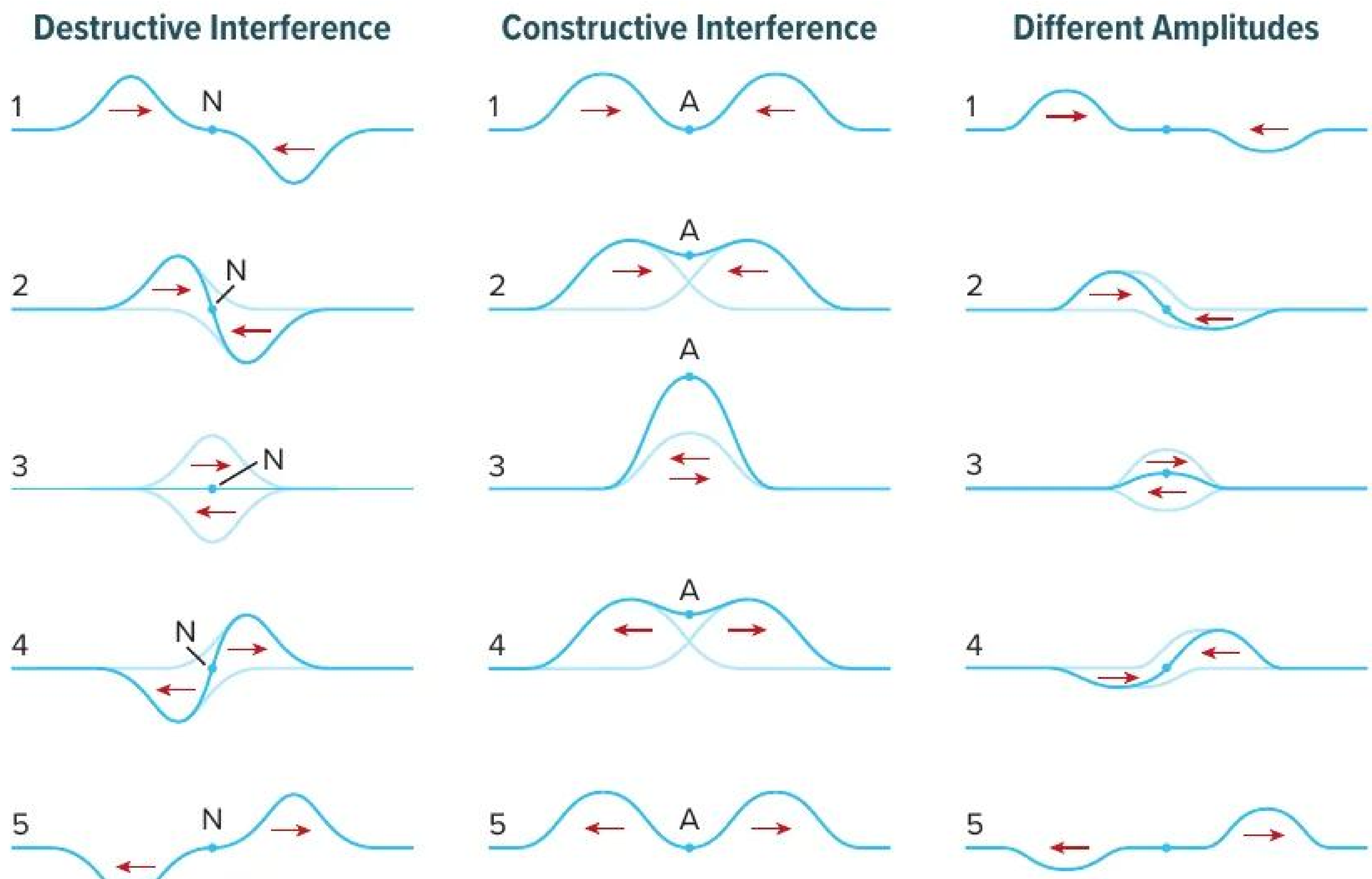


Figure 15 When waves add algebraically, the resulting combined waves can be quite different from the individual waves. **Summarize** *how waves behave during and after superposition.*

Wave interference

Wave interference can be either constructive or destructive. The first panel in **Figure 15** shows the superposition of waves with equal but opposite displacements, causing destructive interference. When the pulses meet and are in the same location, the displacement is zero. Point N, which does not move at all, is called a **node.** The pulses travel horizontally and eventually emerge unaffected by each other.

Constructive interference occurs when wave displacements are in the same direction. The result is a wave that has an amplitude greater than those of the individual waves. A larger pulse appears at point A when the two waves meet. Point A has the largest displacement and is called the **antinode.** The two pulses pass through each other without changing their shapes or sizes. Even if the pulses have unequal amplitudes, the resultant pulse at the overlap is still the algebraic sum of the two pulses, as shown in the final panel of **Figure 15.**

Get It?

Compare the wave medium's displacement at a node and at an antinode.

Two reflections

You can apply the concept of superimposed waves to the control of large-amplitude waves. Imagine attaching one end of a rope to a fixed point, such as a doorknob, a distance *L* away. When you vibrate the free end, the wave leaves your hand, travels along the rope toward the fixed end, is reflected and inverted at the fixed end, and returns to your hand. When it reaches your hand, the reflected wave is inverted and travels back down the rope. Thus, when the wave leaves your hand the second time, its displacement is in the same direction as it was when it left your hand the first time.

Standing waves Suppose you adjust the motion of your hand so that the period of vibration equals the time needed for the wave to make one round-trip from your hand to the door and back. Then, the displacement given by your hand to the rope each time will add to the displacement of the reflected wave. As a result, the amplitude of oscillation of the rope will be much greater than the motion of your hand. This large-amplitude oscillation is an example of mechanical resonance.

The ends of the rope are nodes and an antinode is in the middle, as shown in the top photo in **Figure 16.** Thus, the wave appears to be standing still and is called a **standing wave.** Note, however, that the standing wave is the interference of waves traveling in opposite directions. If you double the frequency of vibration, you can produce one more node and one more antinode on the rope. Then it appears to vibrate in two segments. When you further increase the vibration frequency, it produces even more nodes and antinodes, as shown in the bottom photo in **Figure 16.**

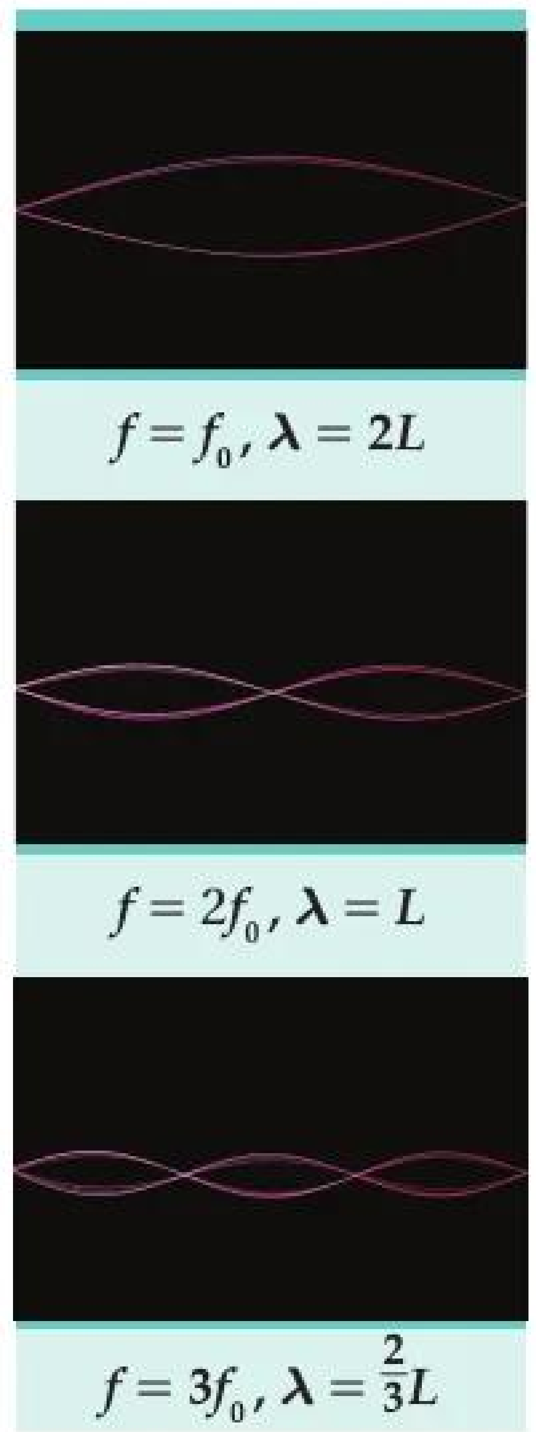


Figure 16 Interference produces standing waves only at certain frequencies.

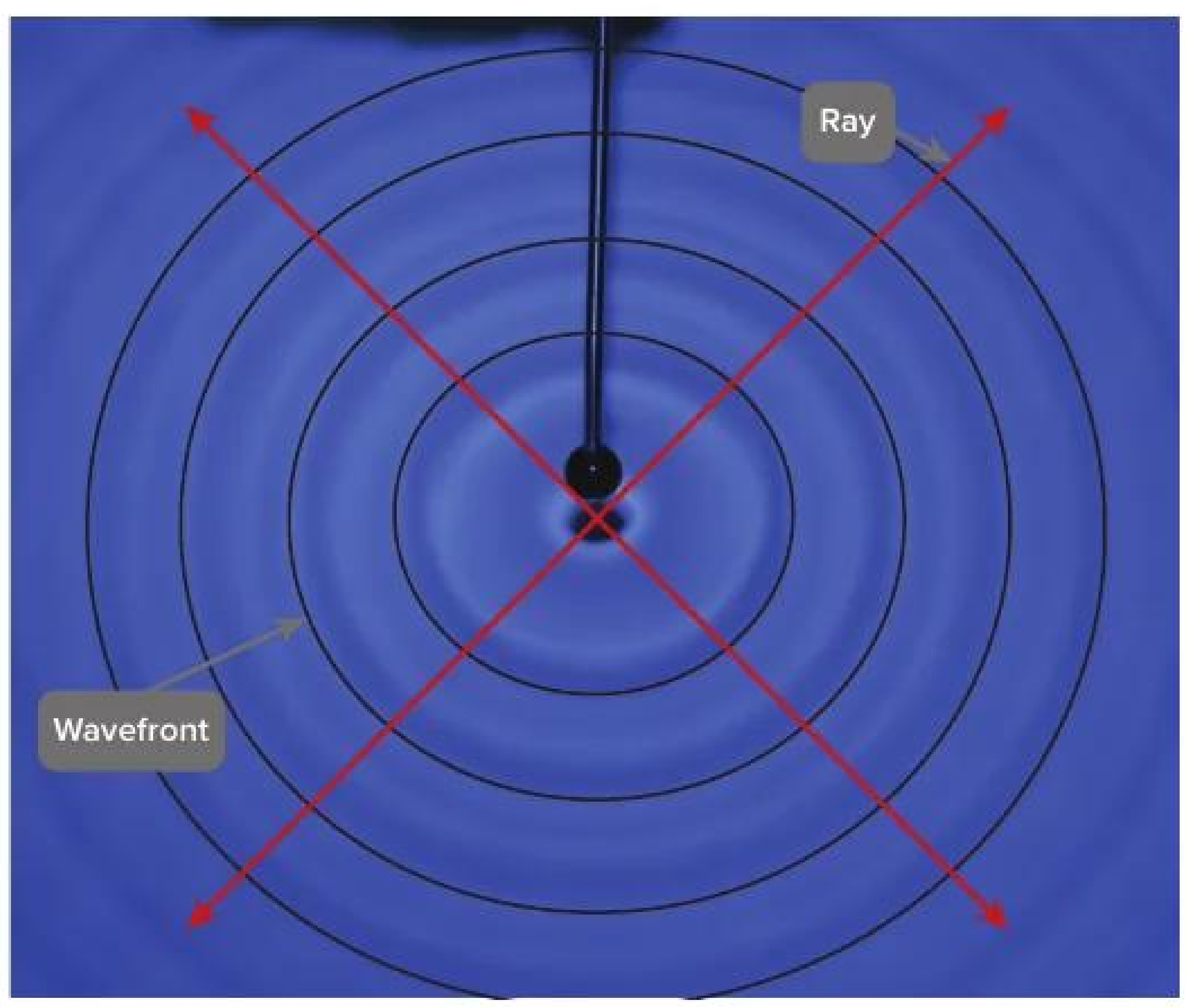
Predict *the wavelength if the frequency is four times the lowest frequency.*

Waves in Two Dimensions

You have studied waves on a rope and on a spring reflecting from rigid supports. During some of these interactions, the amplitude of the waves is forced to be zero by destructive interference. These mechanical waves travel in only one dimension. Waves on the surface of water, however, travel in two dimensions, and sound waves and electromagnetic waves will later be shown to travel in three dimensions. How can two-dimensional waves be represented?

Picturing waves in two dimensions When you throw a small stone into a calm pool of water, you see the circular crests and troughs of the resulting waves spreading out in all directions. You can sketch those waves by drawing circles to represent the wave crests. If you repeatedly dip your finger into water with a constant frequency, the resulting sketch would be a series of concentric circles, called wavefronts, centered on your finger. A **wavefront** is a line that represents the crest of a wave in two dimensions. Wavefronts can be used to show two-dimensional waves of any shape, including circular waves. The photo in **Figure 17** shows circular waves in water. The circles drawn on the diagram show the wavefronts that represent those water waves.

Figure 17 Waves spread out in a circular pattern from the oscillating source.



Whatever their shape, two-dimensional waves always travel in a direction that is perpendicular to their wavefronts. That direction can be represented by a **ray,** which is a line drawn at a right angle to the wavefront. When all you want to show is the direction in which a wave is traveling, it is convenient to draw rays instead of wavefronts. The red arrows in **Figure 17** are rays that show the water waves' direction of motion. One advantage of drawing wavefronts is when wavefronts are drawn to scale, they show the wave's wavelengths. In **Figure 17,** the wavelength equals the distance from one circle to the next.

Creating two-dimensional waves A ripple tank is a piece of laboratory equipment that is used to investigate the properties of two-dimensional waves. The main portion of the ripple tank shown in **Figure 18** is a shallow tank that contains a thin layer of water. A board attached to a mechanical oscillator produces waves with long, straight wavefronts. A lamp above the tank produces shadows below the tank that show the locations of the crests of the waves. The top photo in **Figure 18** shows a wave traveling through the ripple tank. The direction the wave travels is modeled by a ray diagram. For clarity, the wavefronts are not extended the entire length of the wave.

Reflection of two-dimensional waves The bottom row of pictures in **Figure 18** shows an incident ray encountering a rigid barrier placed at an angle to the ray's path. The orientation of the barrier is shown by a line, called the **normal,** drawn perpendicular to the barrier. The angle between the incident ray and the normal is called the angle of incidence and is labeled θ_i in the diagram. The angle between the normal and the reflected ray is called the angle of reflection and is labeled θ_r. The **law of reflection** states that the angle of incidence is equal to the angle of reflection. The law of reflection applies to many different kinds of waves, not just the waves in a ripple tank.

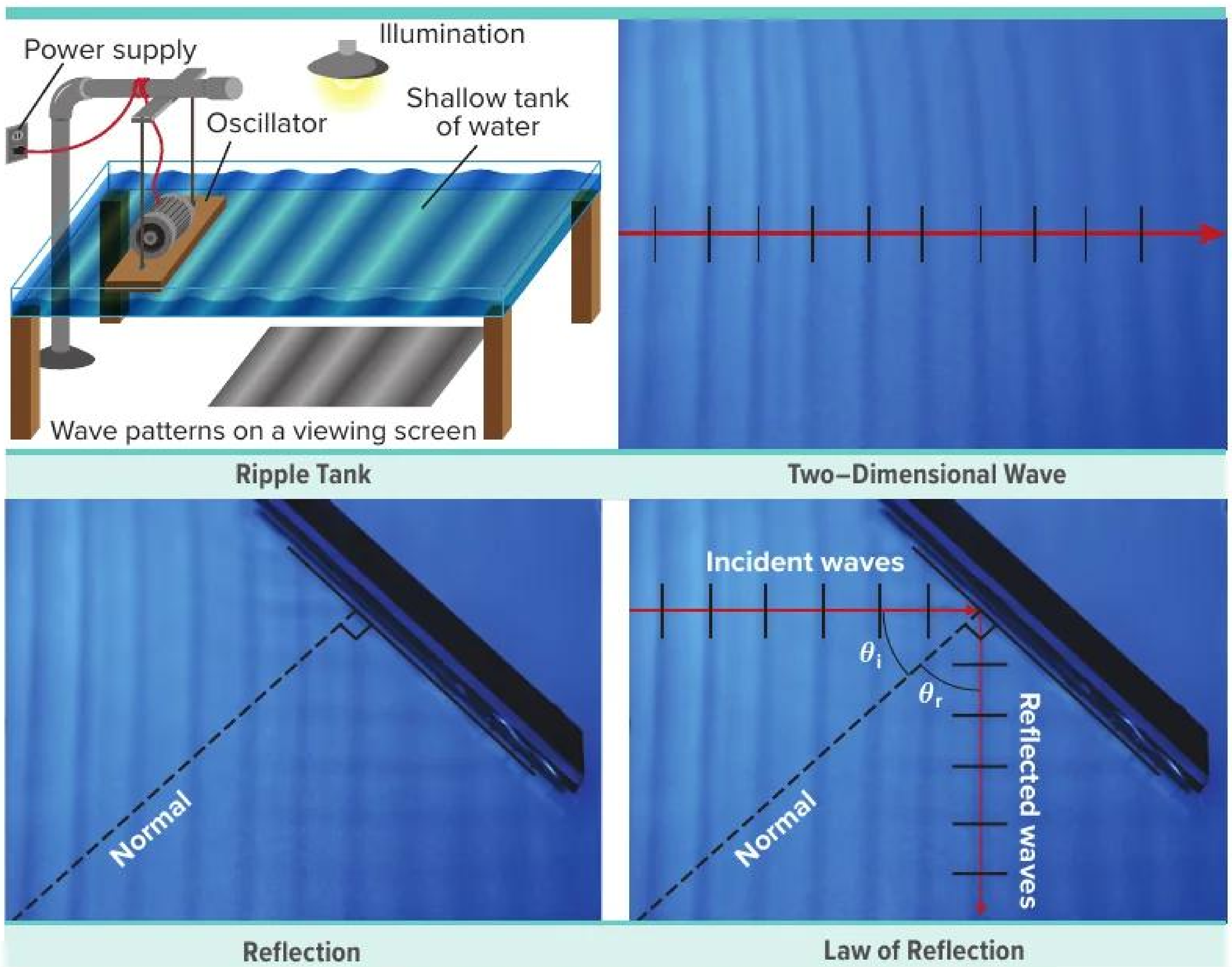


Figure 18 The ripple tank produces uniform waves that are useful for modeling wave behavior.

SCIENCE USAGE v. COMMON USAGE

Normal

Science usage: a line in a diagram that is drawn perpendicular to a surface
As measured from the normal, angles of incidence and reflection are equal.

Common usage: conforming to a type, standard, or regular pattern
Such cold temperatures in July are not normal.

CCC CROSSCUTTING CONCEPTS

Cause and Effect Write a procedure describing how you could use a ripple tank to gather empirical evidence to support the cause-and-effect relationship between the angle of a barrier and the angle of a reflected wave.

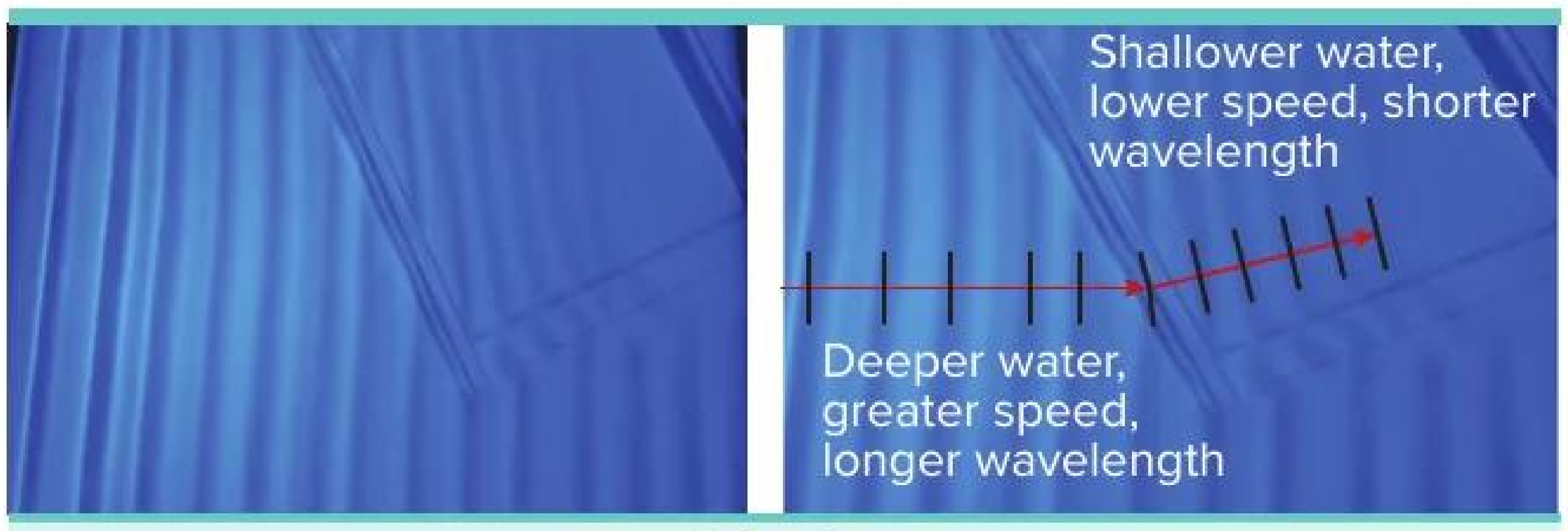


Figure 19 Waves in the ripple tank change direction as they enter shallower water.

Describe *how the wavelength changes as the wave travels into the shallow water.*

Refraction of waves in two dimensions A ripple tank can also model the behavior of waves as they travel from one medium into another. **Figure 19** shows a glass plate placed under the water in a ripple tank. The water above the plate is shallower than the water in the rest of the tank. As the waves travel from deep to shallow water, their speeds decrease and the direction of the waves changes. Such changes in speed are common when waves pass from one medium to another.

The waves in the shallow water are connected to the waves in the deep water. As a result, the frequency of the waves in the two mediums is the same. Based on the equation $\lambda = \frac{v}{f}$, the decrease in the speed of the waves means the wavelength is shorter in the shallower water. The change in the direction of waves at the boundary between two different mediums is known as **refraction.** **Figure 19** shows a wave front and ray model of refraction. Part of the wave will refract through the boundary, and part will be reflected from the boundary. Reflection and refraction occur for many different types of waves. Echoes are an example of reflection of sound waves by hard surfaces, such as the walls of a large gymnasium. Rainbows are the result of the reflection and refraction of light. As sunlight passes through a raindrop, reflection and refraction separate the light into its individual colors, producing a rainbow.

Check Your Progress

30. **Wave Characteristics** Which characteristics remain unchanged when a wave crosses a boundary into a different medium: frequency, amplitude, wavelength, velocity, direction?
31. **Superposition of Waves** Sketch two wave pulses whose interference produces a pulse with an amplitude greater than either of the individual waves.
32. **Refraction of Waves** In **Figure 19,** the wave changes direction as it passes from one medium to another. Can two-dimensional waves cross a boundary between two mediums without changing direction? Explain.
33. **Standing Waves** In a standing wave on a string fixed at both ends, how is the number of nodes related to the number of antinodes?
34. **Critical Thinking** As another way to understand wave reflection, cover the right-hand side of each drawing in the left panel in **Figure 15** with a piece of paper. The edge of the paper should be at point N, the node. Now, concentrate on the resultant wave, shown in darker blue. Note that it acts as a wave reflected from a boundary. Is the boundary a rigid wall? Repeat this exercise for the middle panel in **Figure 15.**

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ENGINEERING & TECHNOLOGY

Harnessing the Motion of the Ocean

Ocean waves represent a huge, almost untapped potential source of energy. Estimates suggest that in the United States, wave power could produce one-quarter to one-third of the electricity used each year. Currently wave power technology lags behind wind and solar power, but around the world, engineers are working to change this and harness the power of ocean waves.

Wave power generators convert mechanical energy from ocean waves to electrical energy.

Wave Power Technologies

One wave power technology, sometimes called a point absorber, looks like a large floating buoy. The buoy has parts that are attached but are able to move independently. As waves rise and fall, the buoy's different parts move relative to each other. This motion drives an energy converter device such as a hydraulic pump, which transforms the mechanical energy of motion into electrical energy. Two different versions of these buoys are being tested off the coast of Hawaii.

Another technology that is designed for offshore use looks like a giant metal sea snake. Its segments can move independently but are attached to one another as it floats on the surface of the water. The whole device is anchored to the ocean floor. The motion of ocean waves causes the segments to move relative to one another. The mechanical energy of the segments is converted by a hydraulic pump or other device to electrical energy. The resulting electrical current is transported to shore via a cable.

A different style of generator, called an oscillating water column or a terminator, is usually designed for onshore use. Waves push water into a column-shaped chamber through an underwater opening. Air is trapped above. The captured water column moves up and down like a piston. Air is forced in and out of an opening at the top of the column. The movement of the air turns a turbine and this mechanical motion is converted to electricity.

Successful wave power devices need to do more than just convert mechanical energy from waves into electricity. They must also be extremely durable to last in harsh ocean conditions. Engineers must design devices that will withstand storms, constant impacts from waves, and corrosive seawater.

So far none of these technologies have been adopted for large-scale use. Engineers and scientists will continue to develop and test prototypes, working towards a goal of wave power devices that are effective, reliable, durable, and affordable.

DEVELOP AND USE MODEL TO ILLUSTRATE

Choose one type of wave power technology. Find out how it converts mechanical energy from waves to electricity. Develop and use a model to illustrate how the technology works.

MODULE 13
STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 PERIODIC MOTION

- Simple harmonic motion results when the restoring force on an object is directly proportional to the object's displacement from equilibrium.
- The elastic potential energy of a spring that obeys Hooke's law is expressed by the following equation:

$$PE_s = \frac{1}{2}kx^2$$

- The period of a pendulum depends on the pendulum's length and the gravitational field strength at the pendulum's location. The period can be found using the following equation

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$

- periodic motion
- period
- amplitude
- simple harmonic motion
- Hooke's law
- simple pendulum
- resonance

Lesson 2 PHOTOSYNTHESIS

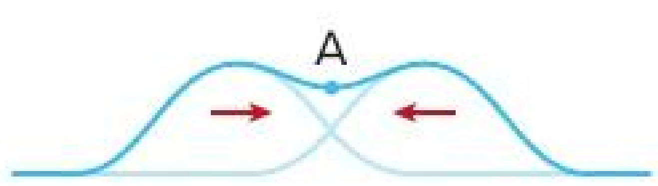
- Waves are disturbances that transfer energy without transferring matter.
- In transverse waves, the displacement of the medium is perpendicular to the direction the wave travels. In longitudinal waves, the displacement is parallel to the direction the wave travels.
- The velocity of a continuous wave is equal to the wave's frequency times its wavelength.

$$v = f\lambda$$

- wave
- wave pulse
- transverse wave
- periodic wave
- longitudinal wave
- surface wave
- trough
- crest
- wavelength
- frequency

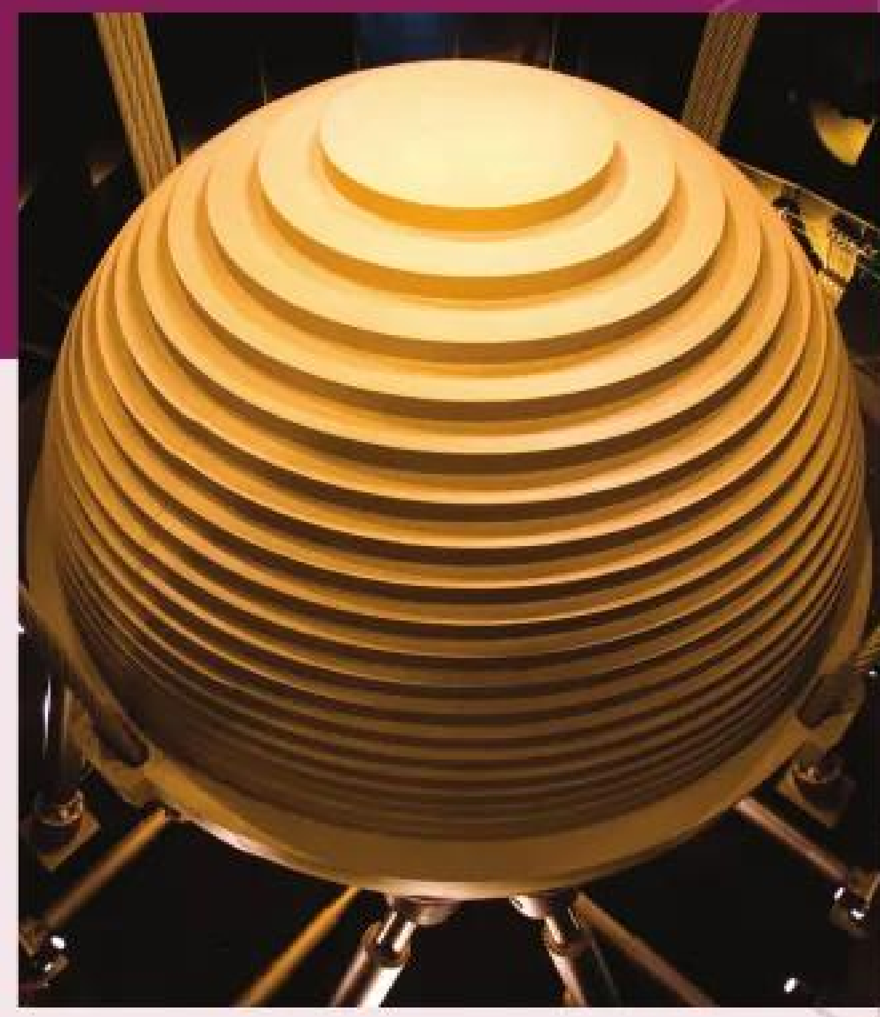
Lesson 3 WAVE BEHAVIOR

- When two-dimensional waves are reflected from boundaries, the angles of incidence and reflection are equal. The change in direction of waves at the boundary between two different mediums is called refraction.
- Interference occurs when two or more waves travel through the same medium at the same time. The principle of superposition states that the displacement of a medium resulting from two or more waves is the algebraic sum of the displacements of the individual waves.



- incident wave
- reflected wave
- principle of superposition
- interference
- node
- antinode
- standing wave
- wavefront
- ray
- normal
- law of reflection
- refraction

THREE-DIMENSIONAL THINKING
Module Wrap-Up



REVISIT THE PHENOMENON

How can this pendulum save a building from earthquake damage?

CER Claim, Evidence, Reasoning

Explain your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

SEP Data Analysis Lab

How does the strength of gravity affect periodic motion?

An astronaut lands on an unknown planet and must determine the value of the gravitational acceleration g. He has the following instruments on hand.

Instrument A rests on the ground and shoots a ball vertically with a known speed. The astronaut can measure the time the ball takes to rise from its launch position and the time it takes to fall back to the launch position.

Instrument B is a simple unmarked weight suspended from a spring with constant $k = 22.5$ N/m.

Instrument C is a simple pendulum at the end of an arm that is 0.500 m long. The astronaut counts exactly 47 full swings in 1.00 min.

CER Analyze and Interpret Data

1. **Claim** Which instrument(s) can be used to determine g?
2. **Evidence and Reasoning** Explain how you made your decision.

MODULE 14
SOUND

Mike Long/Alamy Stock Photo

MODULE 14
SOUND

ENCOUNTER THE PHENOMENON

Why does a fire truck's siren change pitch as it passes you?

GO ONLINE to play a video how pitch changes when a source of sound moves past an observer.

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

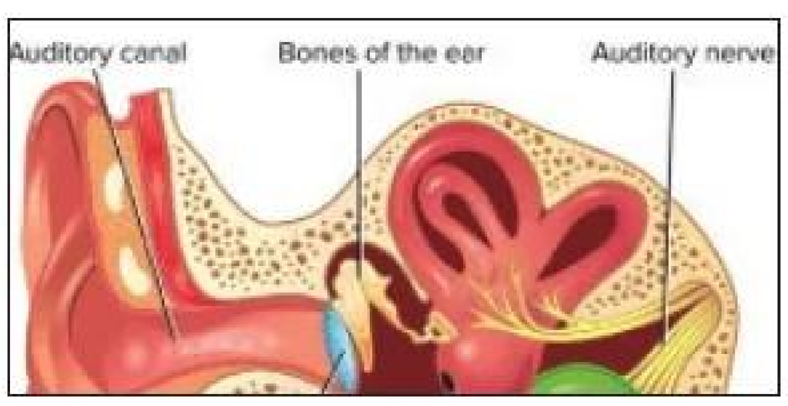
CER Claim, Evidence, Reasoning

Make Your Claim Use your CER chart to make a claim about why a fire truck's siren changes pitch as it passes you.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.



LESSON 1: Explore & Explain: Detecting Sound Waves

LESSON 2: Explore & Explain: Sources of Sound

Smithsonian

Additional Resources

LESSON 1

PROPERTIES AND DETECTION OF SOUND

FOCUS QUESTION

What factors affect the pitch of a sound?

Sound Waves

You already are familiar with several of the characteristics of sound, including volume, tone, and pitch, from your everyday experiences. Without thinking about it, you can use these, and other characteristics, to categorize many of the sounds that you hear.

Pressure variations Put your fingers against your throat as you hum or speak. Can you feel the vibrations? **Figure 1** shows a vibrating bell that can represent your vocal cords, a loudspeaker, or any other sound source. As it moves back and forth, the edge of the bell strikes the particles in the air. When the edge moves forward, air particles bounce off the bell with a greater velocity. When the edge moves backward, air particles bounce off the bell with a lower velocity.

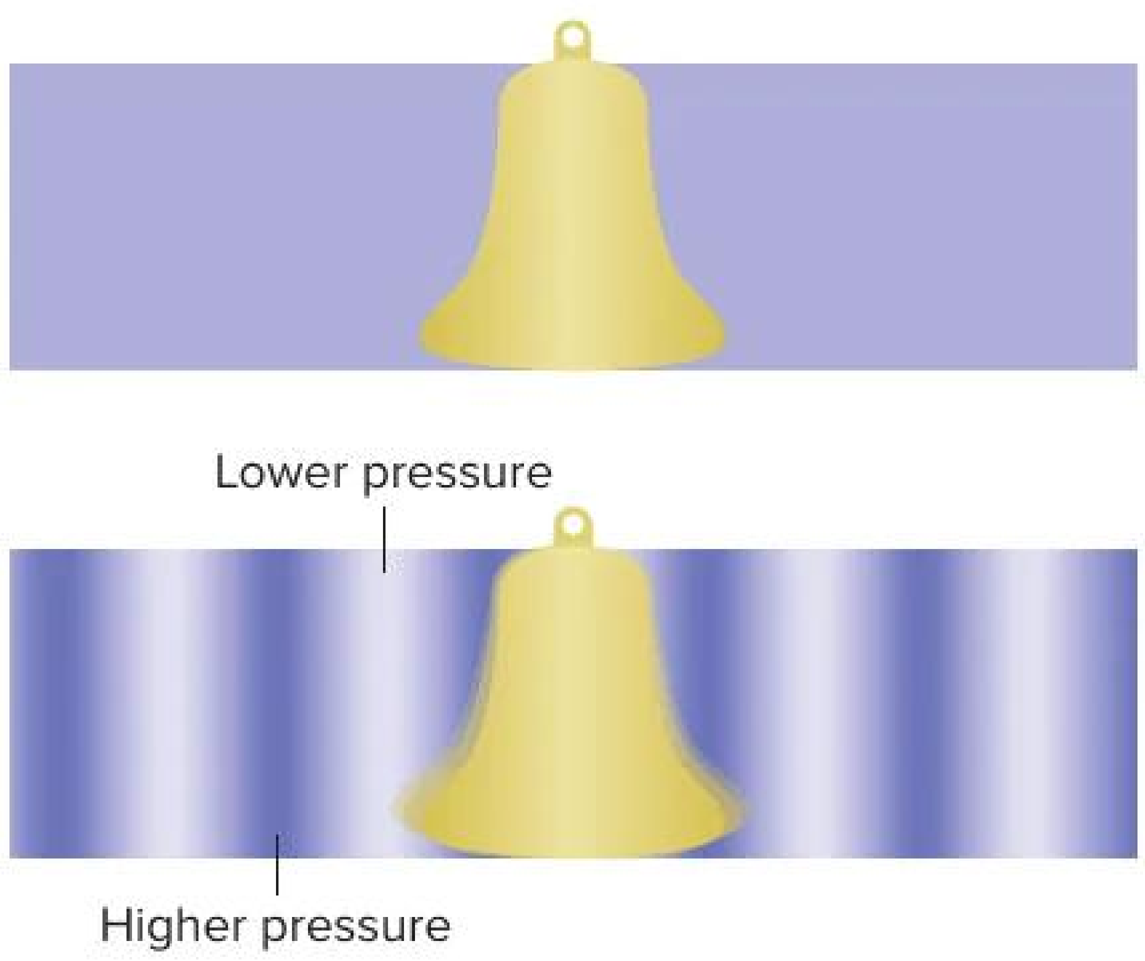


Figure 1 When the bell is at rest (top), the surrounding air is at average pressure. When the bell is struck (bottom), the vibrating edge creates regions of high and low pressure. Although the diagram shows the pressure regions moving in one direction, the waves move out in all directions.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Virtual Investigation: Doppler Effect
Analyze data to determine how a moving source affects the frequency of the detected sound wave.

Revisit the Encounter the Phenomenon Question
What information from this lesson can help you answer the Unit and Module questions?

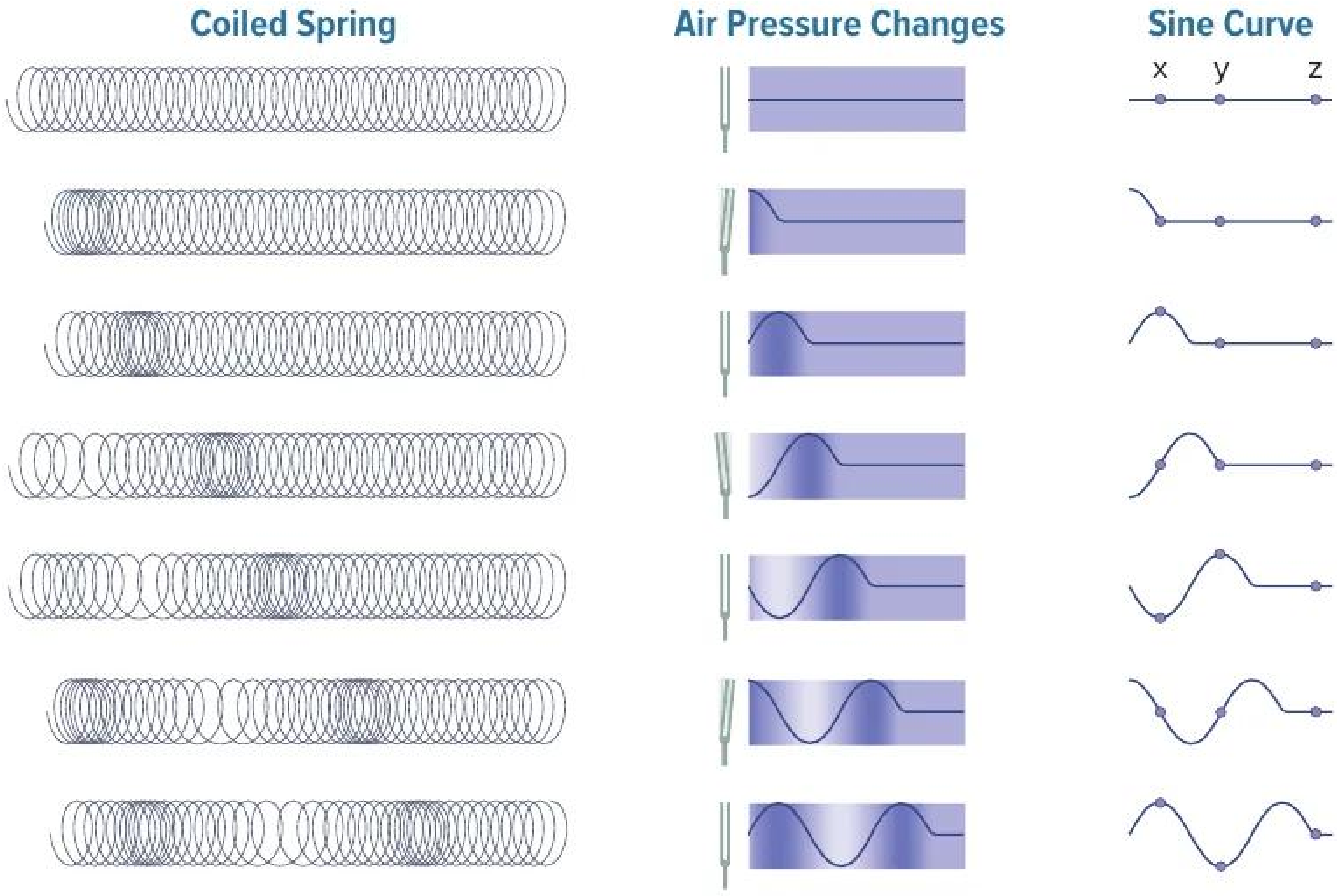


Figure 2 A coiled spring models the oscillations created by a sound wave. As the sound wave travels through the air, the air pressure rises and falls. The changes in the sine curves correspond to the changes in air pressure. Note that the positions of *x*, *y*, and *z* show that the wave, not the matter, travels forward.

The result of these velocity changes is that the forward motion of the bell produces a region where the air pressure is slightly higher than average, as shown in **Figure 1.** The backward motion produces slightly below-average pressure. Collisions of the air particles cause the pressure variations to move away from the bell in all directions. If you were to focus on one spot, you would see the value of the air pressure rise and fall. In this way, the pressure variations are transmitted through matter.

Describing sound

A pressure oscillation that is transmitted through matter is a **sound wave.** Sound waves travel through air because a vibrating source produces regular variations, or oscillations, in air pressure. The air particles collide, transmitting the pressure variations away from the source of the sound. The pressure of the air oscillates about the mean air pressure, as shown in **Figure 2.** The frequency of the wave is the number of oscillations in pressure each second. The wavelength is the distance between successive regions of high or low pressure. Because the motion of the particles in air is parallel to the direction of the wave's motion, sound is a longitudinal wave.

The wavelength and frequency of a wave are related to one another by the speed of travel of the wave. Just like any other wave, the speed of sound depends on the medium through which the sound passes. In air, the speed depends on the temperature, increasing by about 0.6 m/s for each 1°C increase in air temperature. At room temperature (20°C) and sea level, the speed of sound is 343 m/s. For the problems in this book, you may assume these conditions unless otherwise stated.

Get It?

Estimate the speed of sound through air at sea level if the temperature is 25°C.

In general, the speed of sound is greater in solids and liquids than in gases. **Table 1** lists the speeds of sound waves in various media. Sound cannot travel in a vacuum because there are no particles to collide.

Sound waves share the general properties of other waves. For example, they reflect off hard objects, such as the walls of a room. Reflected sound waves are called echoes. The time required for an echo to return to the source of the sound can be used to find the distance between the source and the reflective object. This principle is used by bats, by some cameras, and by ships that employ sonar. Two sound waves can interfere, causing dead spots at nodes where little sound can be heard. Recall that the frequency and wavelength of a wave are related to the speed of the wave by the equation $\lambda = \frac{v}{f}$.

Table 1 Speed of Sound in Various Media

Medium	Speed (m/s)
Air (0°C)	331
Air (20°C)	343
Helium (0°C)	965
Water (25°C)	1497
Seawater (25°C)	1535
Copper (20°C)	4760
Iron (20°C)	4994

Detection of Pressure Waves

Sound detectors transform sound energy—the kinetic energy of the vibrating particles of the transmitting medium—into another form of energy. A common detector is a microphone, which transforms sound energy into electrical energy. A microphone consists of a thin disk that vibrates in response to sound waves and produces an electrical signal.

The human ear As shown in **Figure 3,** the human ear is a sound detector that receives pressure waves and converts them to electrical impulses. The tympanic membrane, also called the eardrum, vibrates when sound waves enter the auditory canal. Three tiny bones in the middle ear then transfer these vibrations to fluid in the cochlea. Tiny hairs lining the spiral-shaped cochlea detect certain frequencies in the vibrating fluid. These hairs stimulate nerve cells, which send impulses to the brain and produce the sensation of sound. The ear detects sound waves over a wide range of frequencies and is sensitive to an enormous range of amplitudes. In addition, human hearing can distinguish many different qualities of sound. Knowledge of both physics and biology is required to understand the complexities of the ear. The interpretation of sounds by the brain is even more complex, and is not totally understood.

The Human Ear

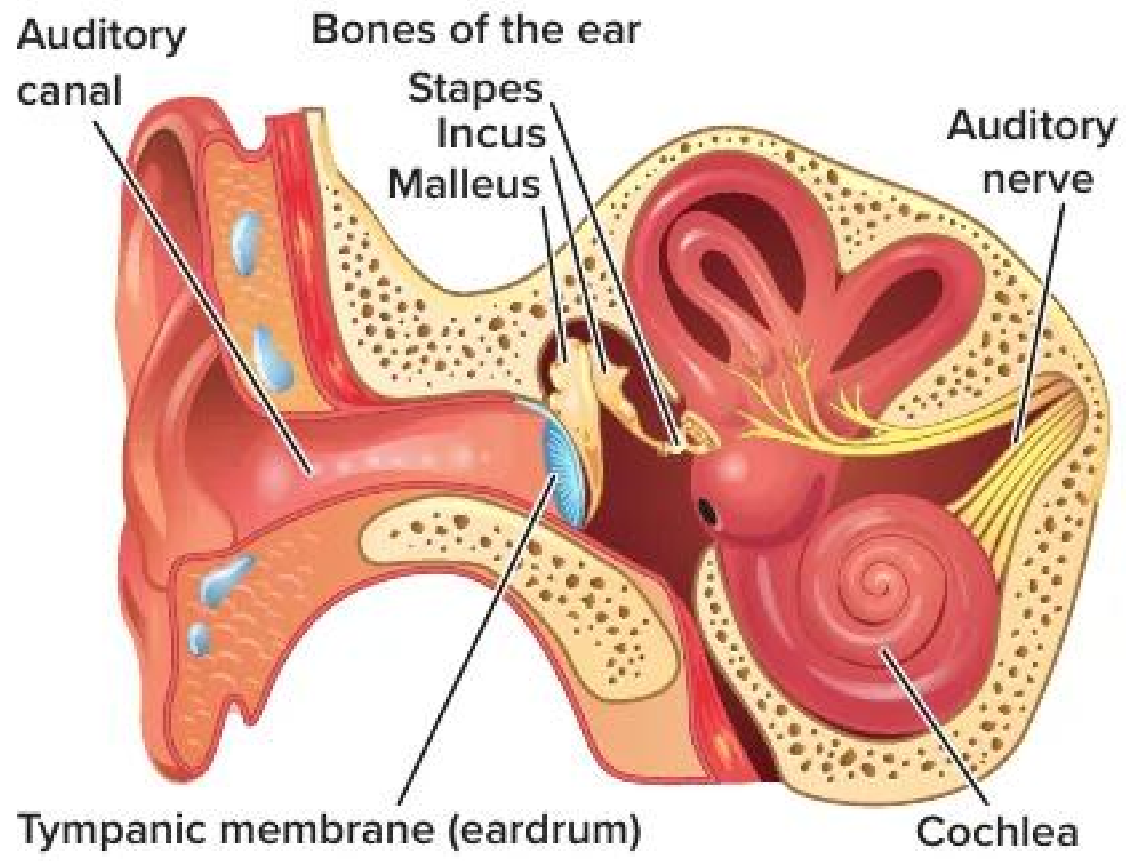


Figure 3 The human ear is a sense organ that translates sound vibrations from the external environment into nerve impulses that are sent to the brain for interpretation. The eardrum vibrates when sound waves enter the auditory canal. The bones in the middle ear—the malleus, the incus, and the stapes—move as a result of the vibrations. The vibrations are then transmitted to the inner ear, where they trigger nerve impulses to the brain. (Note: Diagram is not to scale.)

STEM CAREER Connection

Hearing Aid Specialist

Would you enjoy helping people improve their quality of life? A hearing aid specialist administers hearing tests and helps select and fit hearing aids for people.

Perceiving Sound

How humans perceive sound depends partly on the physical characteristics of sound waves, such as frequency and amplitude.

Pitch
Marin Mersenne and Galileo first determined that the pitch we hear depends on the frequency of vibration. **Pitch** is the highness or lowness of a sound, and it can be given a name on the musical scale. For instance, the note known as middle C has a frequency of 262 Hz. The highest note on a piano has a frequency of 4186 Hz. The human ear is not equally sensitive to all frequencies. Most people cannot hear sounds with frequencies below 20 Hz or above 16,000 Hz. Many animals, such as dogs, cats, elephants, and bats, are capable of hearing frequencies that humans cannot hear.

Get It?
Identify What characteristic of waves is pitch most closely linked to?

Loudness
Frequency and wavelength are two physical characteristics of sound waves. Another physical characteristic of sound waves is amplitude. Amplitude is the measure of the variation in pressure in a wave. The **loudness** of a sound is the intensity of the sound as perceived by the ear and interpreted by the brain. This intensity depends primarily on the amplitude of the pressure wave.

The human ear is extremely sensitive to variations in the intensity of sound waves. Recall that 1 atmosphere of pressure equals 1.01×10^{5} Pa. The ear can detect pressure-wave amplitudes of less than one-billionth of an atmosphere, or 2×10^{-5} Pa. At the other end of the audible range, pressure variations of approximately 20 Pa or greater cause pain. It is important to remember that the ear detects pressure variations only at certain frequencies. Driving over a mountain pass changes the pressure on your ears by thousands of pascals, but this change does not take place at audible frequencies.

Because humans can detect a wide range of intensities, it is convenient to measure these intensities on a logarithmic scale called the **sound level.** The most common unit of measurement for sound level is the **decibel** (dB). The sound level depends on the ratio of the intensity of a given sound wave to that of the most faintly heard sound. This faintest sound is measured at 0 dB. A sound that is ten times more intense registers 20 dB. A sound that is another ten times more intense is 40 dB.

Get It?
Compare How much more intense is a sound that registers 80 dB than one of 40 dB?

SCIENCE USAGE v. COMMON USAGE

Pitch

Science usage: the highness or lowness of a sound, which depends on the frequency of vibration

The flute and the tuba produce very different pitches.

Common usage: the delivery of a ball by a pitcher to a batter

Sharon hit the pitch over the fence for a home run.

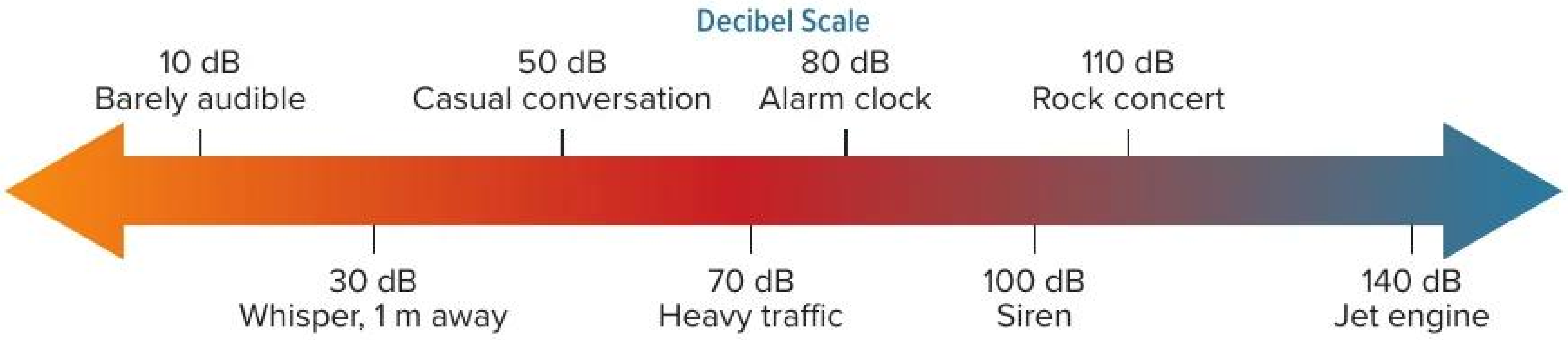


Figure 4 This decibel scale shows the sound level for a variety of sounds.

Infer *About how many times louder does an alarm clock sound than heavy traffic?*

Most people perceive a 10-dB increase in sound level as about twice as loud as the original level. **Figure 4** shows the sound level for a variety of sounds. In addition to intensity, pressure variations and the power of sound waves can be described by decibel scales.

The ear can lose its sensitivity, especially to high frequencies, after exposure to loud sounds in the form of noise or music. The longer a person is exposed to loud sounds, the greater the effect. A person can recover from short-term exposure in a period of hours, but the effects of long-term exposure can last for days or weeks. Long exposure to 100-dB or greater sound levels can produce permanent damage. Hearing loss also can result from loud music being transmitted to stereo headphones from personal music devices. In some cases, the listeners are unaware of just how high the sound levels really are. Cotton earplugs reduce the sound level only by about 10 dB. Special ear inserts can provide a 25-dB reduction. Specifically designed earmuffs and inserts, as shown in **Figure 5,** can reduce the sound level by up to 45 dB.

Figure 5 Hearing loss can occur with continuous exposure to loud sounds. Workers in many occupations, such as construction, wear ear protection. The jackhammer this worker is operating has a sound level of 130 dB.

The Doppler Effect

Have you ever noticed that the pitch of a fast car changed as the vehicle sped past you? The pitch was higher when the vehicle was moving toward you, then it dropped to a lower pitch as the vehicle moved away. The change in frequency of sound caused by the movement of either the source, the detector, or both is called the **Doppler effect.** The Doppler effect is illustrated in **Figure 6.**

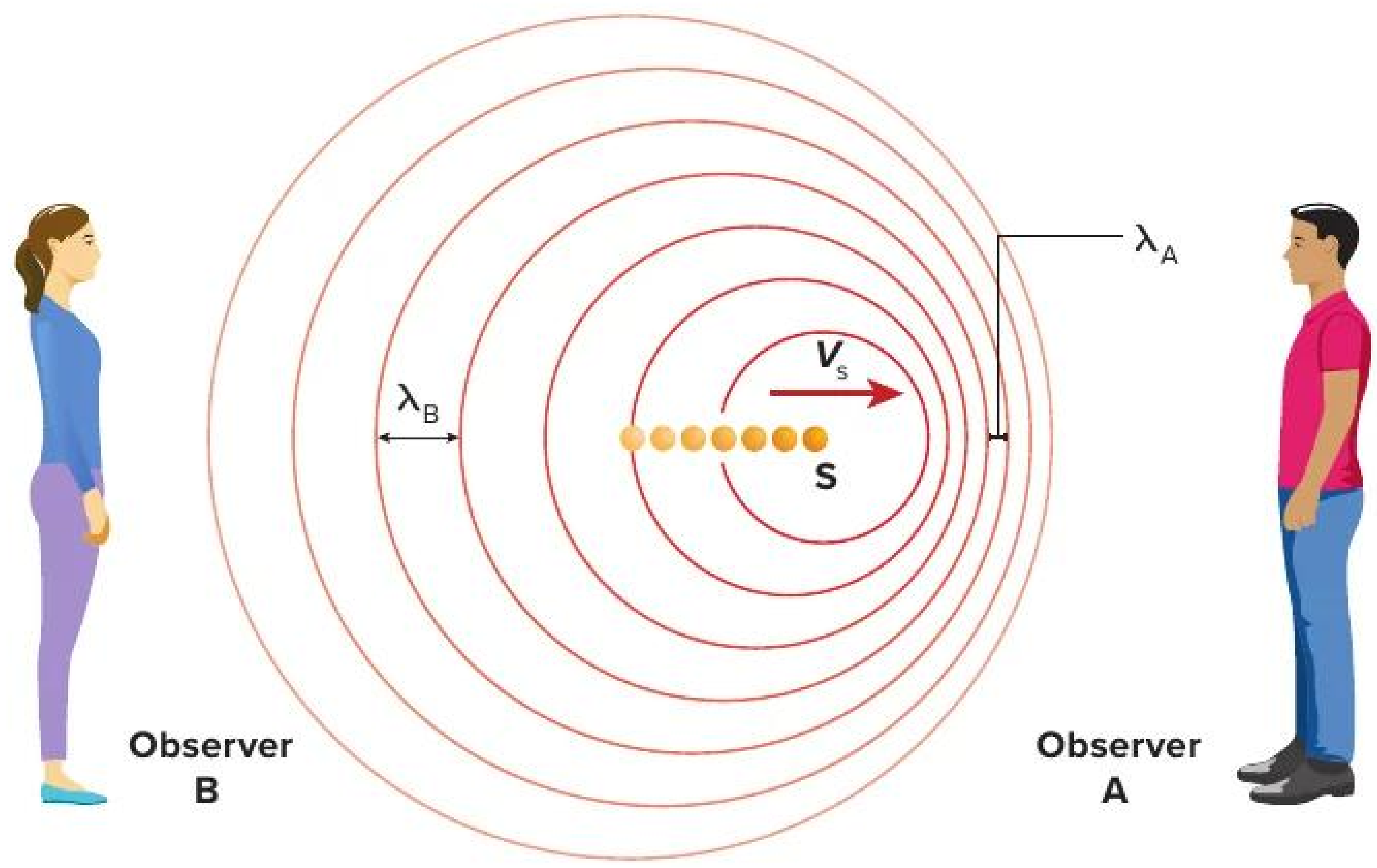


Figure 6 As a sound producing source moves toward observer A, the wavelength is shortened to λ_A. As the source moves away from observer B, the wavelength is lengthened to λ_B.

Describe *What is the relative difference in the frequency of the detected sound for each observer?*

The sound source (S) is moving to the right with a speed of v_s. The waves that the source emits spread in circles centered on the source at the time it produced the waves. As the source moves toward the sound detector, observer A in **Figure 6,** more waves are crowded into the space between them. The wavelength is shortened to λ_A. Because the speed of sound is not changed, more crests reach the ear each second, which means that the frequency of the detected sound increases. When the source is moving away from the detector, observer B in **Figure 6,** the wavelength is lengthened to λ_B, fewer crests reach the ear each second, and the detected frequency is lower.

A Doppler shift also occurs if the detector is moving and the source is stationary. As the detector approaches a stationary source, it encounters more wave crests each second than if it were still, and a higher frequency is detected. If the detector recedes from the source, fewer crests reach it each second, resulting in a lower detected frequency.

Get It?

Compare the wavelength and frequency heard by an observer in front of the moving fire engine at the beginning of the module with the wavelength and frequency heard by an observer behind the fire engine.

For any combination of moving source and moving observer, the frequency that the observer hears can be found using the relationship below.

Doppler Effect

The frequency perceived by a detector is equal to the velocity of the detector relative to the velocity of the wave, divided by the velocity of the source relative to the velocity of the wave, multiplied by the wave's frequency.

$$f_d = f_s \frac{v - v_d}{v - v_s}$$

In the Doppler effect equation, v is the velocity of the sound wave, v_s is the velocity of the sound's source, and v_d is the velocity of the observer of interest, who is detecting the sound. The subscript d is used instead of the letter o to avoid confusion with the number zero. The same subscripts are used to denote the corresponding frequencies.

Defining the coordinate system As you solve problems using the above equation, be sure to define the coordinate system so that the positive direction is from the source to the detector. The sound waves will be approaching the detector from the source, so the velocity of sound is always positive.

Try drawing diagrams to confirm that the term $\frac{v - v_d}{v - v_s}$ behaves as you would predict based on what you have learned about the Doppler effect. Notice that for a source moving toward the detector (positive direction, which results in a smaller denominator compared to a stationary source) and for a detector moving toward the source (negative direction and increased numerator compared to a stationary detector), the detected frequency (f_d) increases.

Similarly, if the source moves away from the detector or if the detector moves away from the source, then f_d decreases. Read the Connecting Math to Physics feature below to see how the Doppler effect equation reduces when the source or observer is stationary.

CONNECTING MATH to Physics

Reducing Equations When an element in an equation is equal to zero, the equation might reduce to a form that is easier to use.

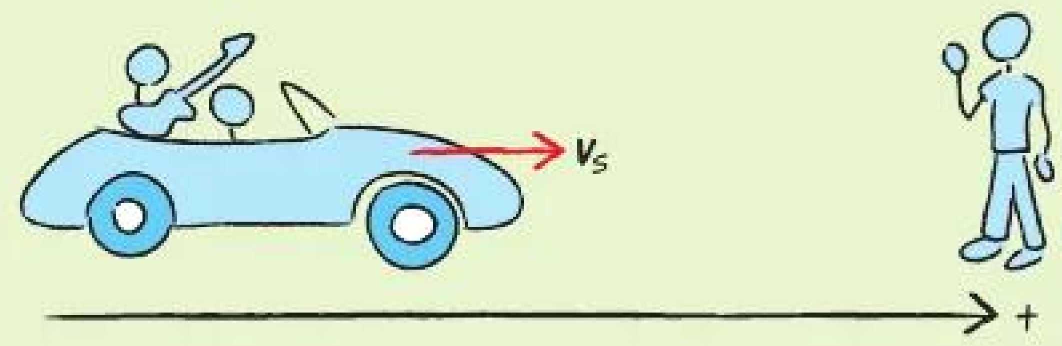
Stationary detector, source in motion: $v_d = 0$	Stationary source, detector in motion: $v_s = 0$
$f_d = f_s \frac{v - v_d}{v - v_s}$	$f_d = f_s \frac{v - v_d}{v - v_s}$
$= f_s \frac{v}{v - v_s}$	$= f_s \frac{v - v_d}{v}$
$= f_s \frac{\frac{v}{v}}{\frac{v}{v} - \frac{v_s}{v}}$	$= f_s\left(\frac{v}{v} - \frac{v_d}{v}\right)$
$= f_s \frac{1}{1 - \frac{v_s}{v}}$	$= f_s\left(1 - \frac{v_d}{v}\right)$

EXAMPLE Problem 1

THE DOPPLER EFFECT A guitar player sounds C above middle C (523 Hz) while traveling in a convertible at 24.6 m/s. If the car is coming toward you, what frequency would you hear? Assume that the temperature is 20°C.

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Establish a coordinate axis. Make sure that the positive direction is from the source to the detector.
- Show the velocities of the source and detector.



Known	Unknown
$v = +343$ m/s	$f_d = ?$
$v_s = +24.6$ m/s	
$v_d = 0$ m/s	
$f_s = 523$ Hz	

2 SOLVE FOR THE UNKNOWN

Use $f_d = f_s \frac{v - v_d}{v - v_s}$ with $v_d = 0$ m/s.

$$f_d = f_s \frac{1}{1 - \frac{v_s}{v}}$$

$$= 523\text{ Hz}\left(\frac{1}{1 - \frac{24.6\text{ m/s}}{343\text{ m/s}}}\right)$$

Substitute $v = +343$ m/s, $v_s = +24.6$ m/s, and $f_s = 523$ Hz.

$$= 564\text{ Hz}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Frequency is measured in hertz.
- **Is the magnitude realistic?** The source is moving toward you, so the frequency should be increased.

PRACTICE Problems

ADDITIONAL PRACTICE

1. Repeat Example Problem 1, but with the car moving away from you. What frequency would you hear?
2. You are in an automobile, like the one in **Figure 7,** traveling toward a pole-mounted warning siren. If the siren's frequency is 365 Hz, what frequency do you hear? Use 343 m/s as the speed of sound.

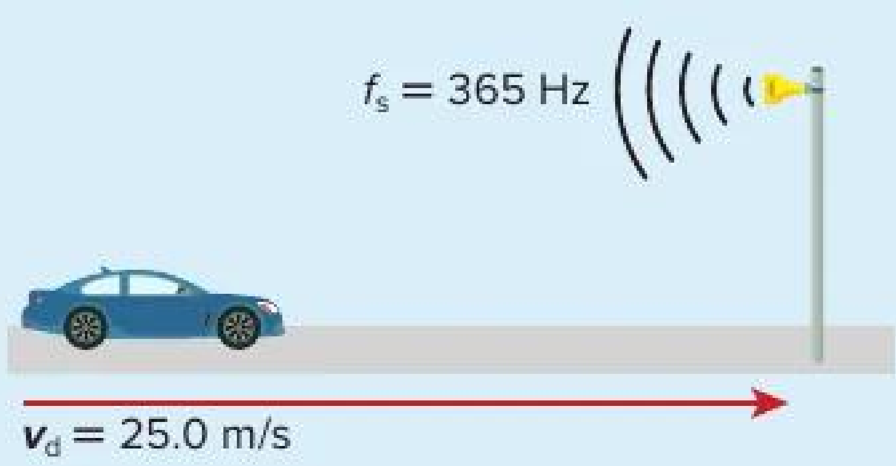


Figure 7

3. You are in an automobile traveling at 55 mph (24.6 m/s). A second automobile is moving toward you at the same speed. Its horn is sounding at 475 Hz. What frequency do you hear? Use 343 m/s as the speed of sound.
4. A submarine is moving toward another submarine at 9.20 m/s. It emits a 3.50-MHz ultrasound. What frequency would the second sub, at rest, detect? The speed of sound in water at the depth the submarines are moving is 1482 m/s.
5. **CHALLENGE** A trumpet plays middle C (262 Hz). How fast would it have to be moving to raise the pitch to C sharp (277 Hz)? Use 343 m/s as the speed of sound.

Applications of the Doppler effect The Doppler effect occurs in all wave motion, both mechanical and electromagnetic. It has many applications. Radar detectors use the Doppler effect to measure the speed of baseballs and automobiles. Astronomers observe light from distant galaxies and use the Doppler effect to measure their speeds. Physicians can detect the speed of the moving heart wall in a fetus by means of the Doppler effect in ultrasound.

BIOLOGY Connection Bats use the Doppler effect to detect and catch flying insects. When an insect is flying faster than a bat, the reflected frequency is lower, but when the bat is catching up to the insect, as in **Figure 8,** the reflected frequency is higher. Not only do bats use sound waves to navigate and locate their prey, but they often must do so in the presence of other bats. This means they must discriminate their own calls and reflections against a background of many other sounds of many frequencies. Scientists continue to study bats and their amazing abilities to use sound waves.

Figure 8 Bats use the Doppler effect to locate and catch flying insects, such as the moth shown here. As the bat catches up to the moth, the frequency of reflected sound waves increases.

Check Your Progress

6. **Wave Characteristics** What physical characteristic of a sound wave should be changed to alter the pitch? The loudness?
7. **Graph** The eardrum moves back and forth in response to the pressure variations of a sound wave. Sketch a graph of the displacement of the eardrum versus time for two cycles of a 1.0-kHz tone and of a 2.0-kHz tone.
8. **Effect of Medium** List two characteristics of sound that are affected by the medium through which the sound passes and two characteristics that are not affected.
9. **Decibel Scale** How many times greater is the sound pressure level of a typical rock concert (110 dB) than a normal conversation (50 dB)?
10. **Early Detection** In the nineteenth century, people put their ears to a railroad track to get an early warning of an approaching train. Why did this work?
11. **Bats** A bat emits short pulses of high-frequency sound and detects the echoes.
    a. In what way would the echoes from large and small insects compare if they were the same distance from the bat?
    b. In what way would the echo from an insect flying toward the bat differ from that of an insect flying away from the bat?
12. **Critical Thinking** Can a trooper using a radar detector at the side of the road determine the speed of a car at the instant the car passes the trooper? Explain.

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LESSON 2
THE PHYSICS OF MUSIC

FOCUS QUESTION

How is pitch controlled in a musical instrument?

Sources of Sound

In the middle of the nineteenth century, German physicist Hermann Helmholtz studied sound production in musical instruments and the human voice. In the twentieth century, scientists and engineers developed electronic equipment that permits a detailed study of sound and the creation of electronic instruments and recording devices so we can listen to music anywhere.

Recall that sound is produced by a vibrating object. The vibrations of the object create particle motions that cause pressure oscillations in the air. In brass instruments, such as the trumpet, the tuba, and the bugle, the lips of the performer vibrate, as shown in **Figure 9.** Reed instruments, such as the clarinet and the saxophone, have a thin wooden strip called a reed that vibrates as a result of air blown across it, as shown in **Figure 9.** In flutes and organ pipes, air is forced across an opening in a pipe. Air moving past the opening sets the column of air in the instrument into vibration.

Figure 9 The sound produced by an instrument is partly determined by the structure of the mouthpiece.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Speed of Sound
Calculate the speed of sound using the relationship among frequency, wavelength, and speed.

Review the News
Obtain information from a current news story about sound waves and their applications. Evaluate your source and communicate your findings to your class.

Stringed instruments, such as the piano, the guitar, and the violin, work by setting wires or strings into vibration. In the piano, the wires are struck; for the guitar, they are plucked; and for the violin, the friction of the bow causes the strings to vibrate. The strings are attached to a sounding board that vibrates with the strings. The vibrations of the sounding board cause the pressure oscillations in the air that we hear as sound. Electric guitars use electronic devices to detect and amplify the vibrations of the guitar strings.

A loudspeaker has a cone that is made to vibrate by electrical currents. The surface of the cone creates the sound waves that travel to your ear and allow you to hear music. Musical instruments such as gongs, cymbals, and drums are other examples of vibrating surfaces that are sources of sound.

The human voice is produced by vibrations of the vocal cords, which are two membranes located in the throat. Air from the lungs rushing through the throat starts the vocal cords vibrating. The frequency of vibration is controlled by the muscular tension placed on the vocal cords. The more tension on the vocal cords, the more rapidly they vibrate, resulting in a higher pitch sound. If the vocal cords are more relaxed, they vibrate more slowly and produce lower-pitched sounds.

Get It?

Describe How does a vocalist sing higher pitched notes?

Resonance in Air Columns

If you have ever used just the mouthpiece of a brass or wind instrument, you know that while the vibration of your lips or the reed alone makes a sound, it is difficult to control the pitch. The long tube that makes up the instrument must be attached if music is to result. When the instrument is played, the air within this tube vibrates at the same frequency, or in resonance, with a particular vibration of the lips or reed. Remember that resonance increases the amplitude of a vibration by repeatedly applying a small external force to the vibrating air particles at the natural frequency of the air column. The length of the air column determines the frequencies of the vibrating air that will resonate. For wind and brass instruments, such as flutes, trumpets, and trombones, changing the length of the column of vibrating air varies the pitch of the instrument. The mouthpiece simply creates a mixture of different frequencies, and the resonating air column acts on a particular set of frequencies to amplify a single note, turning noise into music. A tuning fork above a hollow tube can provide resonance in an air column, as shown in **Figure 10.**

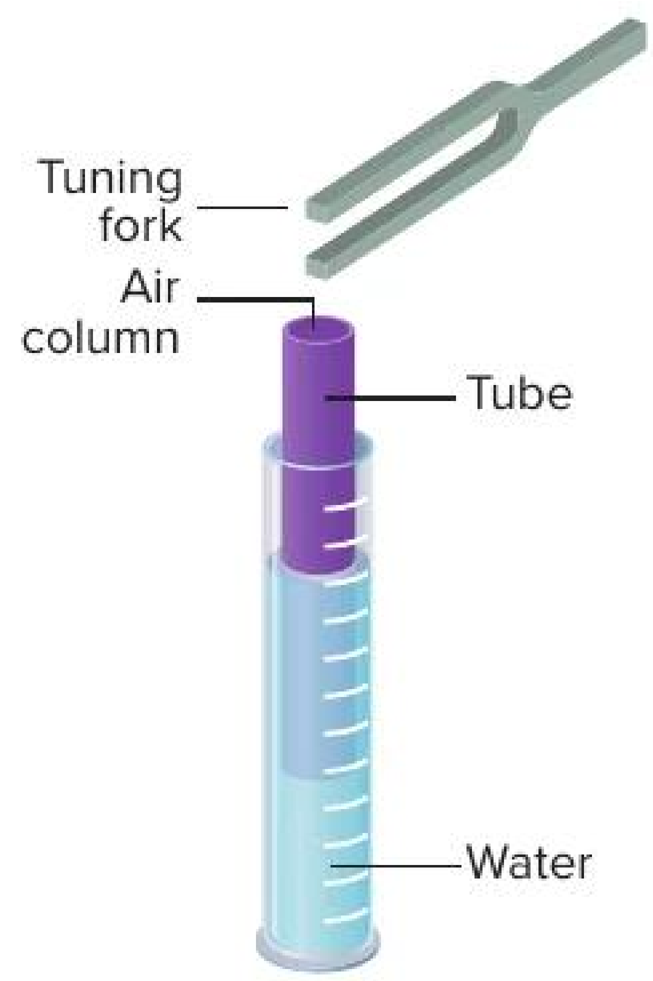


Figure 10 As the tube is raised or lowered, the length of the air column changes, which causes the sound's volume to change.

CCC CROSSCUTTING CONCEPTS

Cause and Effect Moving the tube in **Figure 10** up and down causes the volume of the sound to change. Develop a mathematical representation to relate the frequency, wavelength, speed of sound, and length of air column in the tube to explain this effect.

The tube is placed in water so that the bottom end of the tube is below the water surface. A resonating tube with one end closed to air is called a **closed-pipe resonator.** The length of the air column is changed by adjusting the height of the top of the tube above the water. If the tuning fork is struck with a rubber hammer, the sound alternately becomes louder and softer as the length of the air column is varied by moving the tube up and down in the water. The sound is loud when the air column is in resonance with the tuning fork because the resonating air column intensifies the sound of the tuning fork.

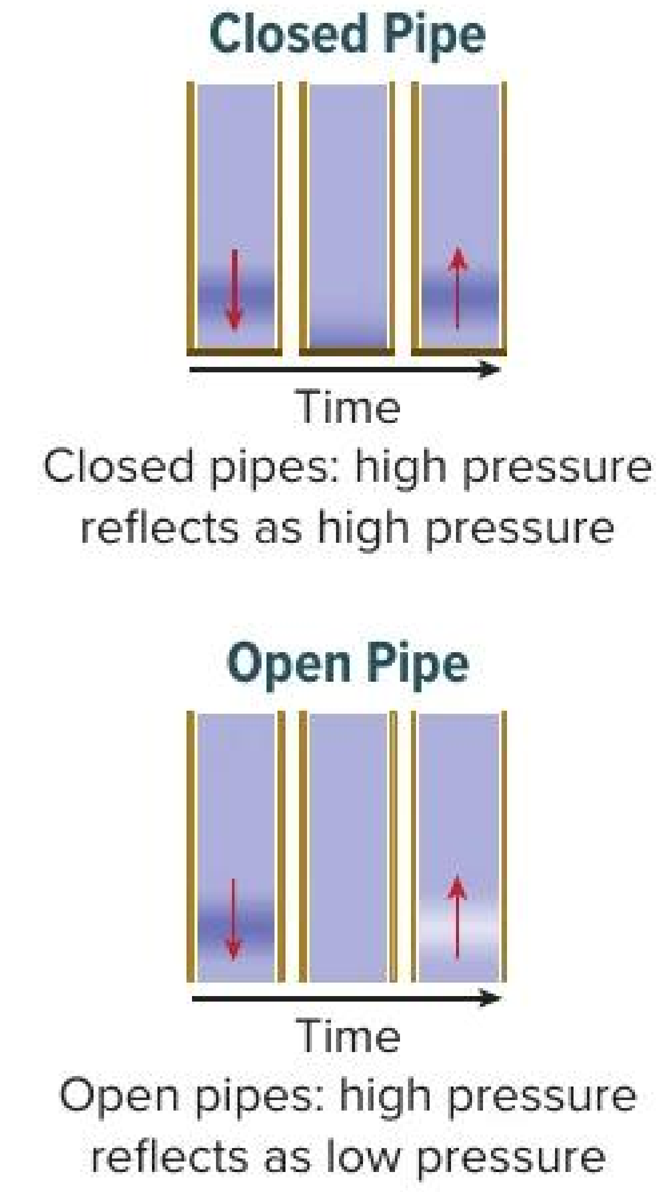


Figure 11 In closed pipes, the sound wave reflects off the closed end. High-pressure waves reflect as high pressure. In open pipes, the sound wave reflects off an open end. High-pressure waves are reflected as low pressure.

Standing pressure wave

How does resonance occur? The vibrating tuning fork produces a sound wave. This wave of alternate high- and low-pressure variations moves down the air column. When the wave hits the water surface, it is reflected back up to the tuning fork, as shown in **Figure 11.** If the reflected high-pressure wave reaches the tuning fork at the same moment that the fork produces another high-pressure wave, then the emitted and returning waves reinforce each other. This reinforcement of waves creates a standing wave, and resonance occurs.

An **open-pipe resonator** is a resonating tube with both ends open that will resonate with a sound source. In this case, the sound wave does not reflect off a closed end, but rather off an open end. If the high-pressure part of the wave strikes the open end, the rebounding wave will be low-pressure at that point, as shown in **Figure 11.**

Resonance lengths

Figure 12 shows a standing sound wave in a pipe represented by a sine wave. Sine waves can represent either the air pressure or the displacement of the air particles. Recall that standing waves have nodes and antinodes. A node is the stationary point where two equal wave pulses meet and are in the same location. An antinode is the place of largest displacement when two wave pulses meet.

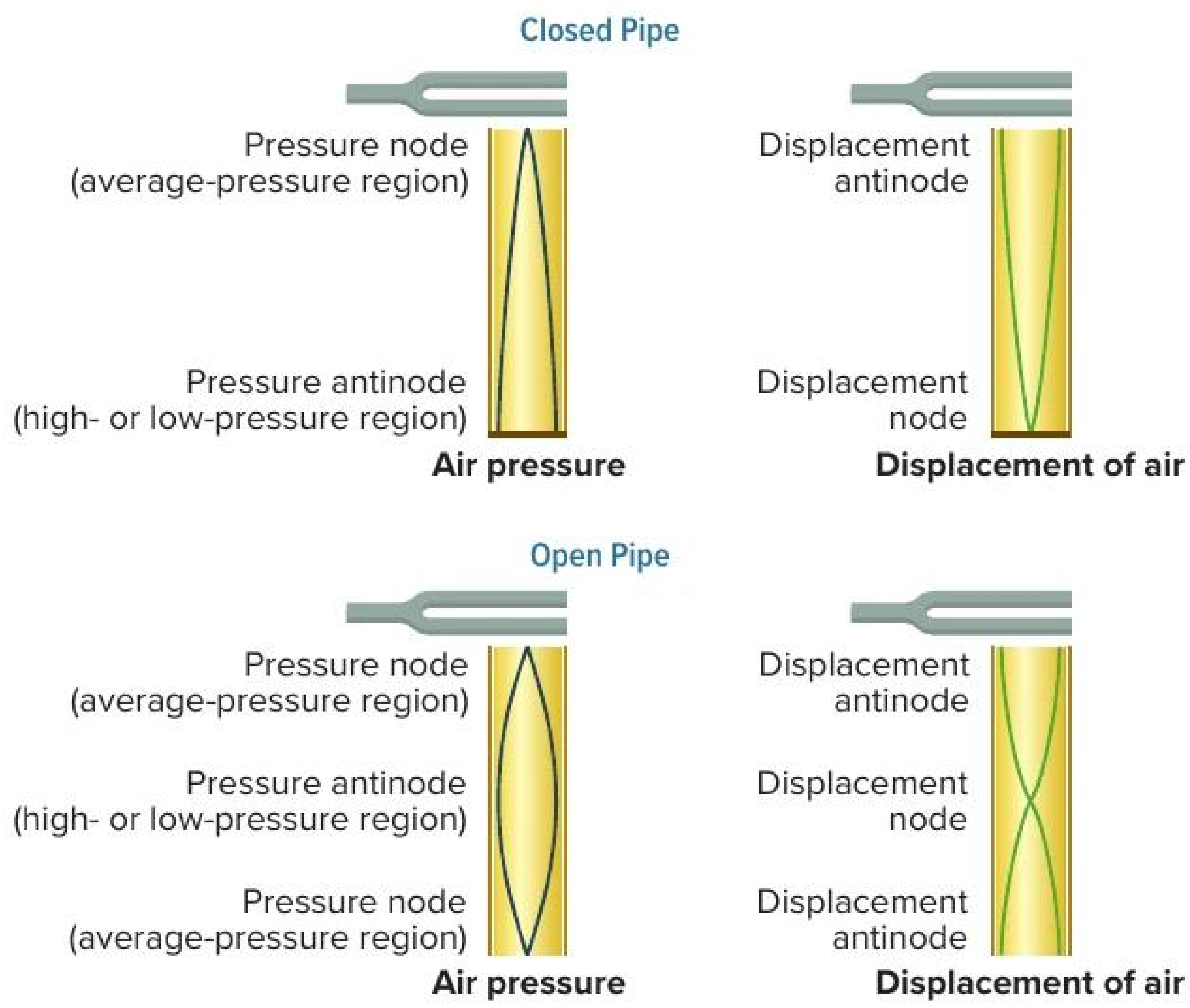


Figure 12 Standing waves in pipes can be represented by sine waves.

Identify *Which are the areas of mean atmospheric pressure in the air pressure graphs?*

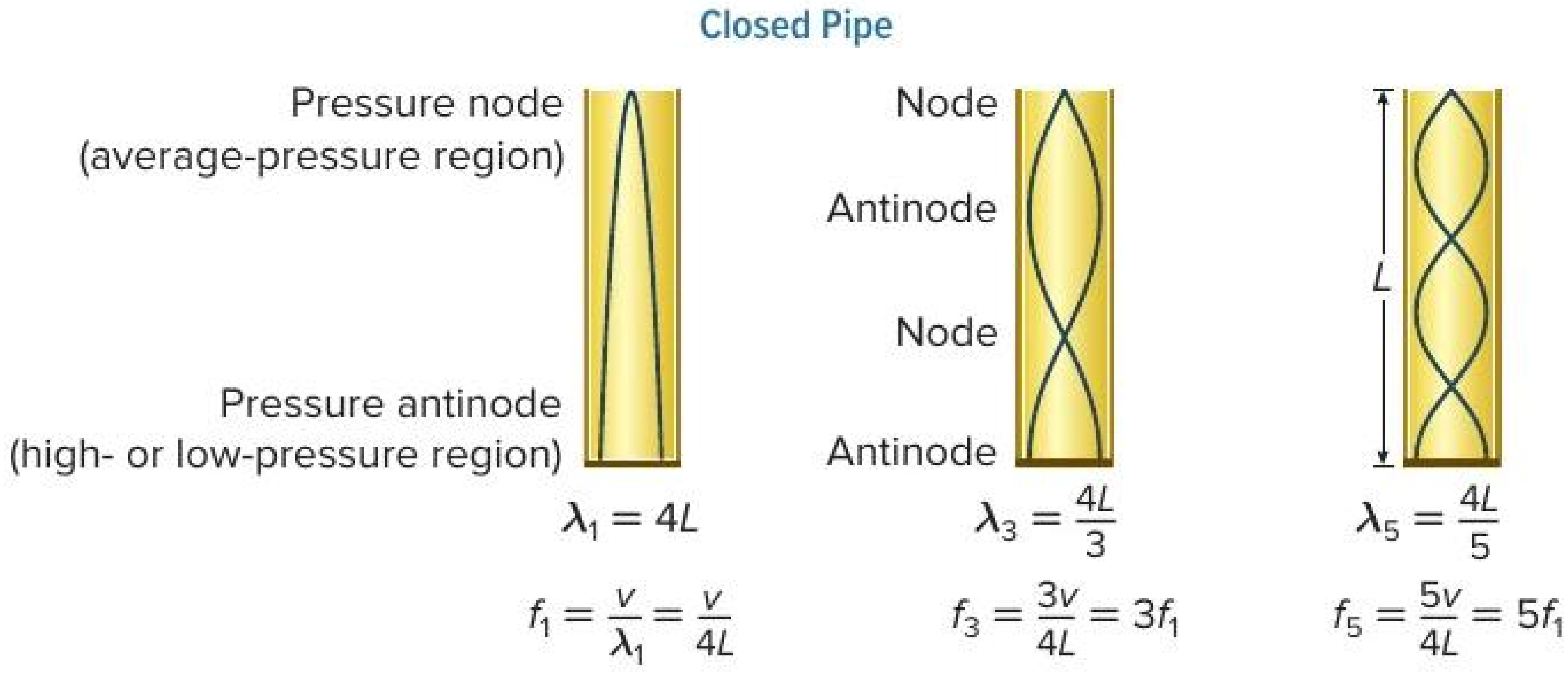


Figure 13 A closed pipe resonates when its length is an odd number of quarter wavelengths.

In the pressure graphs, the nodes are regions of mean atmospheric pressure. At the antinodes, the pressure oscillates between its maximum and minimum values. In the case of the displacement graph, the antinodes are regions of high displacement and the nodes are regions of low displacement. In both cases, two adjacent antinodes (or two nodes) are separated by one-half wavelength.

Get It?

Explain the difference between a node and an antinode on a displacement graph.

Resonance frequencies in a closed pipe If a closed end must act as a node, and an open end must act as an antinode, what is the shortest column of air that will resonate in a closed pipe? **Figure 13** shows that it must be one-fourth of a wavelength. As the frequency is increased, additional resonance lengths are found at half-wavelength intervals. Thus, columns of length $\frac{\lambda}{4}$, $\frac{3\lambda}{4}$, $\frac{5\lambda}{4}$, $\frac{7\lambda}{4}$, and so on will all be in resonance with a tuning fork that produces sound of wavelength λ.

In practice, the first resonance length is slightly longer than one-fourth of a wavelength. This is because the pressure variations do not drop to zero exactly at the open end of the pipe. Actually, the node is approximately 0.4 pipe diameters beyond the end. Additional resonance lengths, however, are spaced by exactly one-half of a wavelength. Measurements of the spacing between resonances can be used to find the velocity of sound in air, as in Example Problem 2.

Resonance frequencies in an open pipe The shortest column of air that can have nodes at both ends is one-half of a wavelength long, as shown in **Figure 14.** As the frequency is increased, additional resonance lengths are found at half-wavelength intervals. Thus, columns of length $\frac{\lambda}{2}$, λ, $\frac{3\lambda}{2}$, 2λ, and so on will be in resonance with a tuning fork.

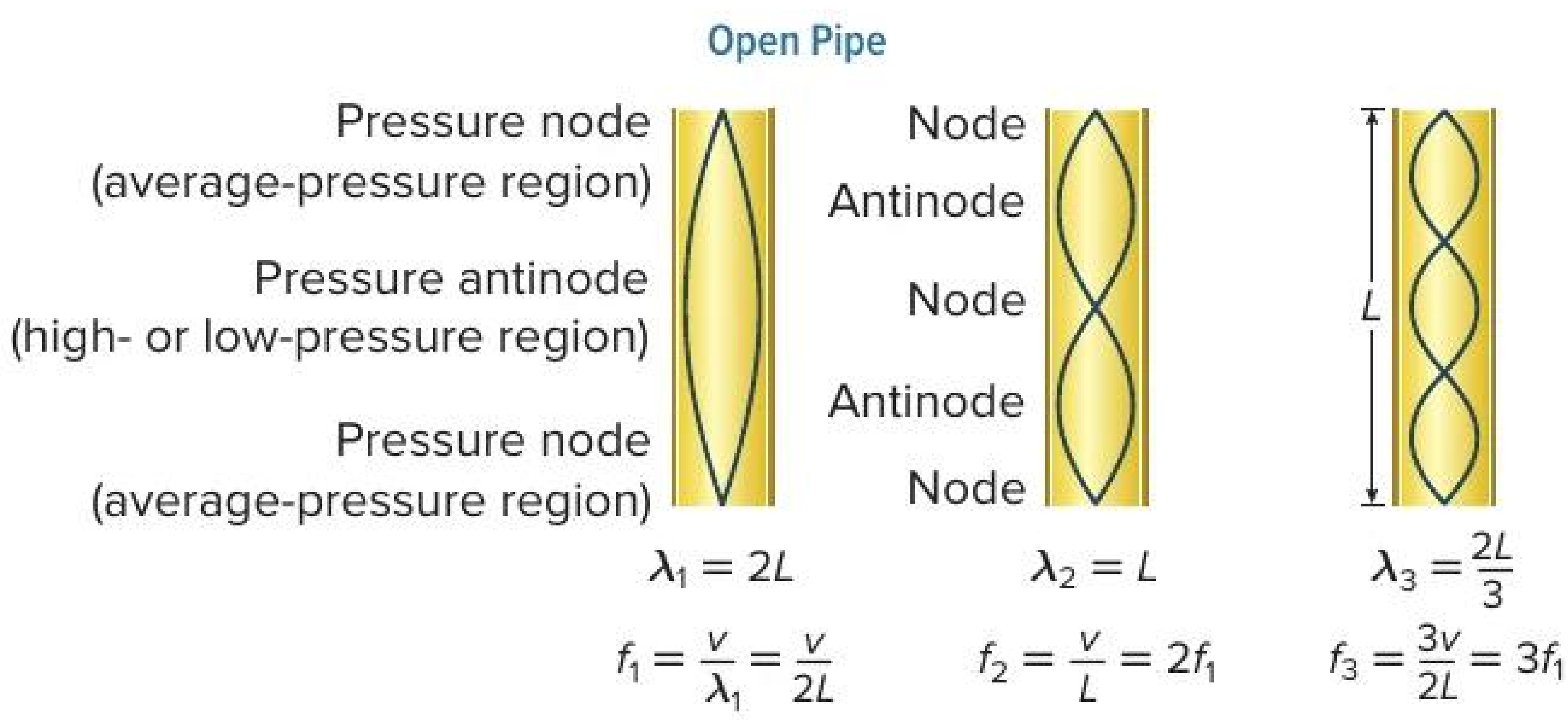


Figure 14 An open pipe resonates when its length is an even number of quarter wavelengths.

Explain *How does the length at which an open pipe resonates differ from the length at which a closed pipe resonates?*

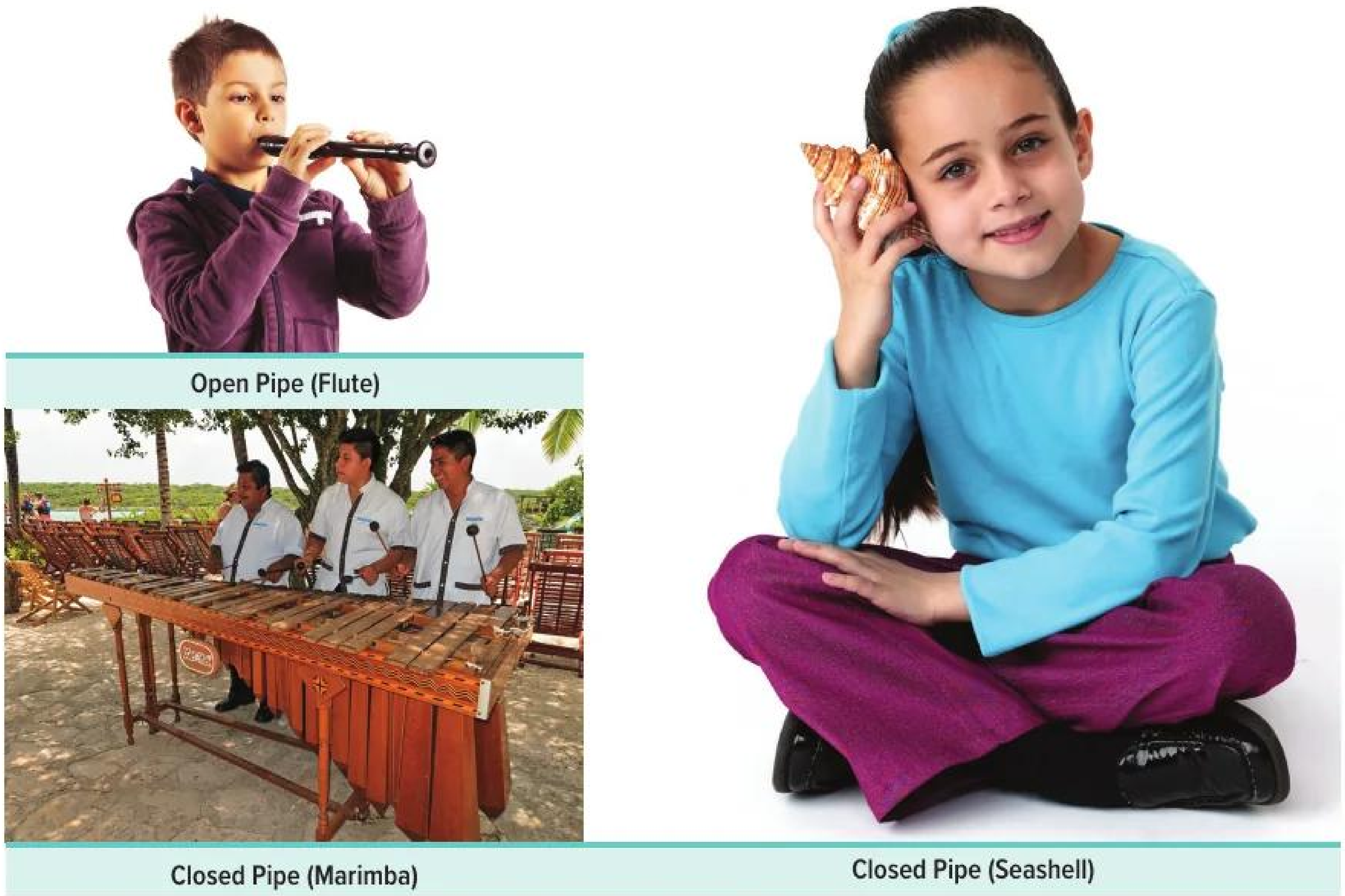


Figure 15 A flute is an example of an open-pipe resonator. The hanging pipes of a marimba and seashells are examples of closed-pipe resonators.

If open and closed pipes of the same length are used as resonators, the wavelength of the resonant sound for the open pipe will be half as long as that for the closed pipe. Therefore, the frequency will be twice as high for the open pipe as for the closed pipe. For both pipes, resonance lengths are spaced by half-wavelength intervals.

Get It?

Predict A tuning fork plays a sound that has a wavelength of 0.78 m. A pipe that is 0.39 m long resonates with the tuning fork. Is the pipe open or closed? Explain your reasoning.

Hearing resonance Musical instruments use resonance to increase the loudness of particular notes. Open-pipe resonators include flutes, shown in **Figure 15.** Clarinets and the hanging pipes under marimbas and xylophones are examples of closed-pipe resonators. If you shout into a long tunnel, the booming sound you hear is the tunnel acting as a resonator. The seashell in **Figure 15** also acts as a closed-pipe resonator.

Real-World Physics

HEARING AND FREQUENCY The human auditory canal acts as a closed-pipe resonator that increases the ear's sensitivity for frequencies between 2000 and 5000 Hz, but the full range of frequencies that people hear extends from 20 to 20,000 Hz. A dog's hearing extends to frequencies as high as 45,000 Hz, and a cat's extends to frequencies as high as 100,000 Hz.

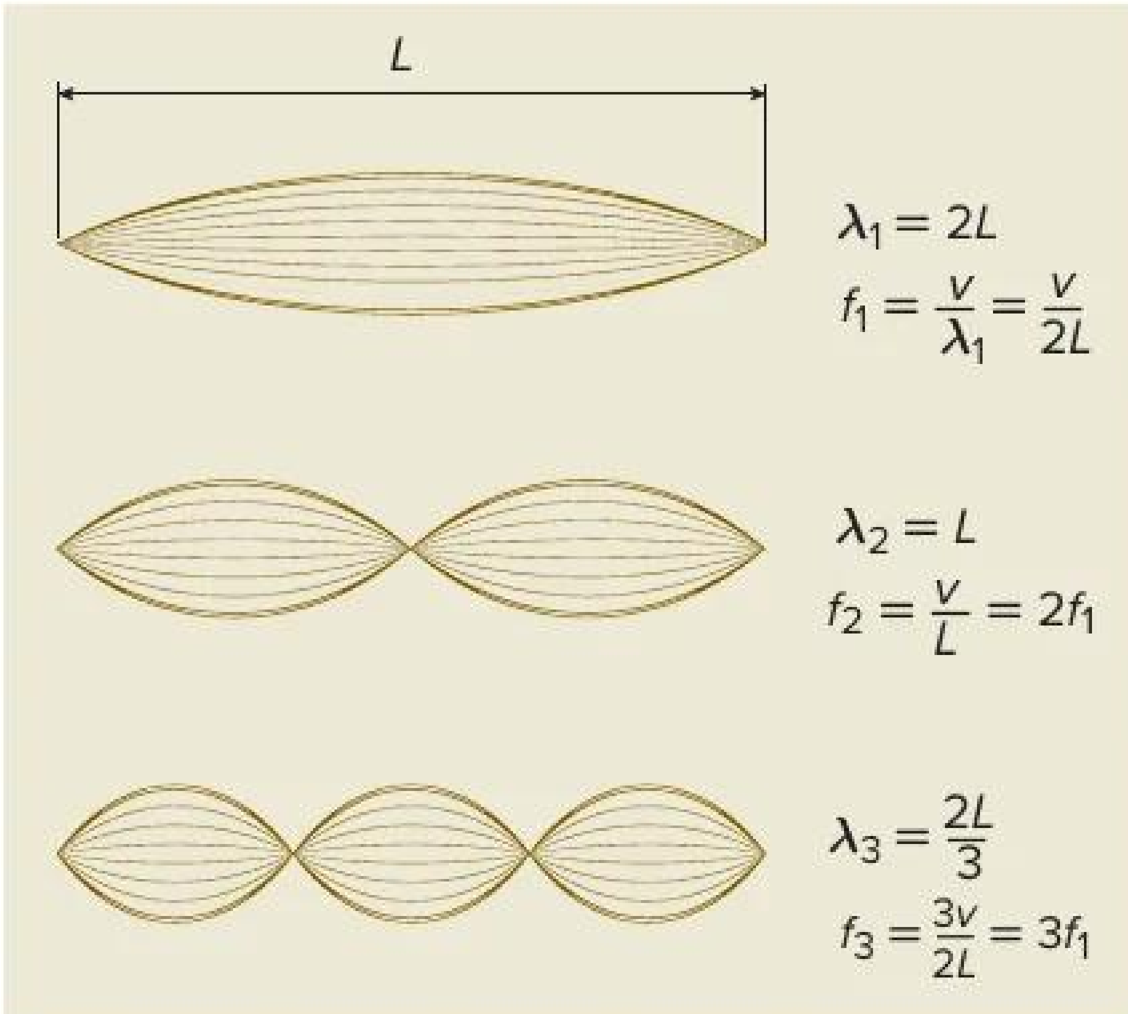


Figure 16 A string resonates with standing waves when its length is a whole number of half wavelengths.

Resonance on Strings

Although plucking, bowing, or striking strings produces variation in waveforms, waveforms on vibrating strings have many characteristics in common with standing waves on springs and ropes. A string on an instrument is clamped at both ends, and therefore, the string must have a node at each end when it vibrates. In **Figure 16,** you can see that the first mode of vibration has an antinode at the center and is one-half a wavelength long. The next resonance occurs when one wavelength fits on the string, and additional standing waves arise when the string length is $\frac{3\lambda}{2}$, 2λ, $\frac{5\lambda}{2}$, and so on. As with an open pipe, the resonant frequencies are whole-number multiples of the lowest frequency.

Recall that the speed of travel of a wave depends on the type of wave and the medium through which it is passing. For a string, the speed depends on the tension of the string, as well as its mass per unit length. The tighter the string, the faster the wave moves along it, and therefore, the higher the frequency of its standing waves. This makes it possible to tune a stringed instrument by changing the tension of its strings. Because strings are so small in cross-sectional area, they move very little air when they vibrate. This makes it necessary to attach them to a sounding board, which transfers their vibrations to the air and produces a stronger sound wave. Unlike the strings themselves, the sounding board should not resonate at any single frequency. Its purpose is to convey the vibrations of all the strings to the air, and therefore it should vibrate well at all frequencies produced by the instrument. Because of the complicated interactions among the strings, the sounding board, and the air, the design and construction of stringed instruments are complex processes, considered by many to be as much an art as a science.

Get It?

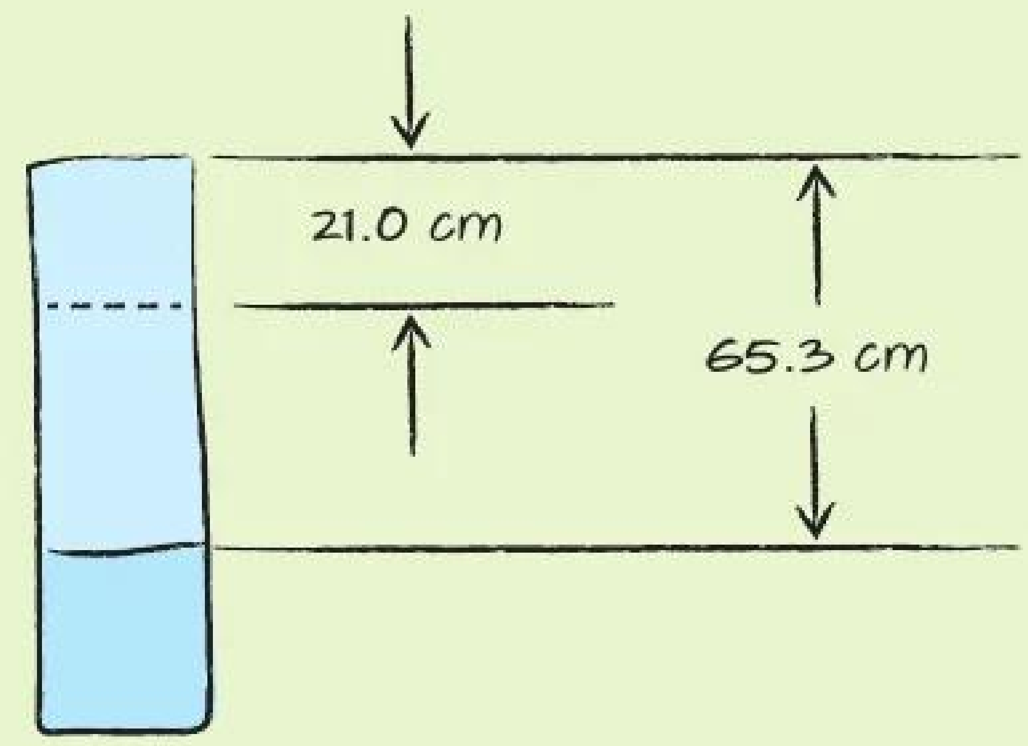
Describe the relationship between the tension of a string and the speed of a wave as it travels along the string.

EXAMPLE Problem 2

FINDING THE SPEED OF SOUND USING RESONANCE When a tuning fork with a frequency of 392 Hz is used with a closed-pipe resonator, the loudest sound is heard when the column is 21.0 cm and 65.3 cm long. What is the speed of sound in this case? Is the temperature warmer or cooler than normal room temperature, which is 20°C? Explain your answer.

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the closed-pipe resonator.
- Mark the resonance lengths.



Known	Unknown
$f = 392$ Hz	$v = ?$
$L_A = 21.0$ cm	
$L_B = 65.3$ cm	

2 SOLVE FOR THE UNKNOWN

Solve for the length of the wave using the length-wavelength relationship for a closed pipe.

$L_B - L_A = \frac{1}{2}\lambda$

$\lambda = 2(L_B - L_A)$ Rearrange the equation for λ.

$= 2(0.653 \text{ m} - 0.210 \text{ m})$ Substitute $L_B = 0.653$ m, $L_A = 0.210$ m.

$= 0.886$ m

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

$v = f\lambda$ Rearrange the equation for v.

$= (392 \text{ Hz})(0.886 \text{ m})$ Substitute $f = 392$ Hz, $\lambda = 0.886$ m.

$= 347$ m/s

The speed is slightly greater than the speed of sound at 20°C, indicating that the temperature is slightly higher than normal room temperature.

3 EVALUATE THE ANSWER

- **Are the units correct?** (Hz)(m) = $\left(\frac{1}{s}\right)$(m) = m/s. The answer's units are correct.
- **Is the magnitude realistic?** The speed is slightly greater than 343 m/s, which is the speed of sound at 20°C.

PRACTICE Problems

ADDITIONAL PRACTICE

13. A 440-Hz tuning fork is used with a resonating column to determine the velocity of sound in helium gas. If the spacing between resonances is 110 cm, what is the velocity of sound in helium gas?

14. The frequency of a tuning fork is unknown. A student uses an air column at 27°C and finds resonances spaced by 20.2 cm. What is the frequency of the tuning fork? Use the speed calculated in Example Problem 2 for the speed of sound in air at 27°C.

15. A 440-Hz tuning fork is held above a closed pipe. Find the spacing between the resonances when the air temperature is 20°C.

16. **CHALLENGE** A bugle can be thought of as an open pipe. If a bugle were straightened out, it would be 2.65-m long.

a. If the speed of sound is 343 m/s, find the lowest frequency that is resonant for a bugle (ignoring end corrections).

b. Find the next two resonant frequencies for the bugle.

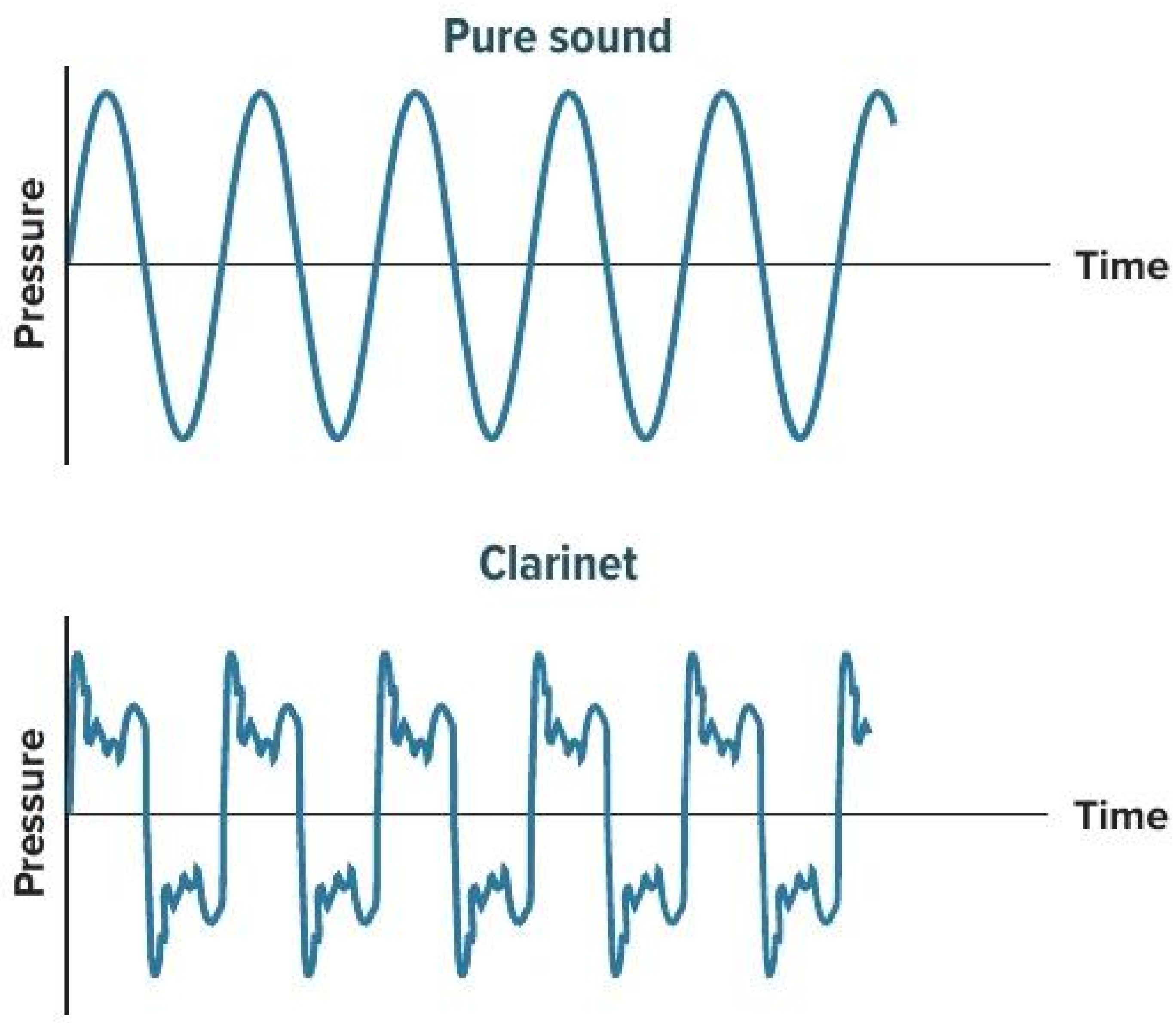


Figure 17 The pure sound produced by a tuning fork is represented by a simple sine wave. The more complex sound produced by a clarinet is represented in the bottom graph.

Sound Quality

A tuning fork produces a soft and uniform sound. This is because its tines vibrate like simple harmonic oscillators and produce the simple sine wave shown in the top graph in **Figure 17.** Sounds made by the human voice and musical instruments are much more complex, like the wave in the bottom graph in **Figure 17.** Both waves have the same frequency, or pitch, but they sound very different.

The complex sound wave is actually a blend of several different frequencies. The shape of the wave depends on the relative amplitudes of these frequencies. Different sources provide different combinations of frequencies. In musical terms, the difference between the waves from different instruments is called timbre (TAM bur), tone quality, or color.

The sound spectrum: fundamental and harmonics The complex sound wave in **Figure 17** was made by a clarinet. Why does the clarinet produce such a sound wave? The air column in a clarinet acts as a closed pipe. Look back at **Figure 13,** which shows three resonant frequencies for a closed pipe. The clarinet acts as a closed pipe, so for a clarinet of length L the lowest frequency (f_1) that will be resonant is $\frac{v}{4L}$.

For a musical instrument, the lowest frequency of sound that resonates is called the **fundamental.** A closed pipe also will resonate at $3f_1$, $5f_1$, and so on. These higher frequencies, which are whole-number multiples of the fundamental frequency, are called **harmonics.** It is the addition of these harmonics that gives a clarinet its distinctive timbre.

Get It?

Explain the relationship between the fundamental and the harmonics of a musical instrument.

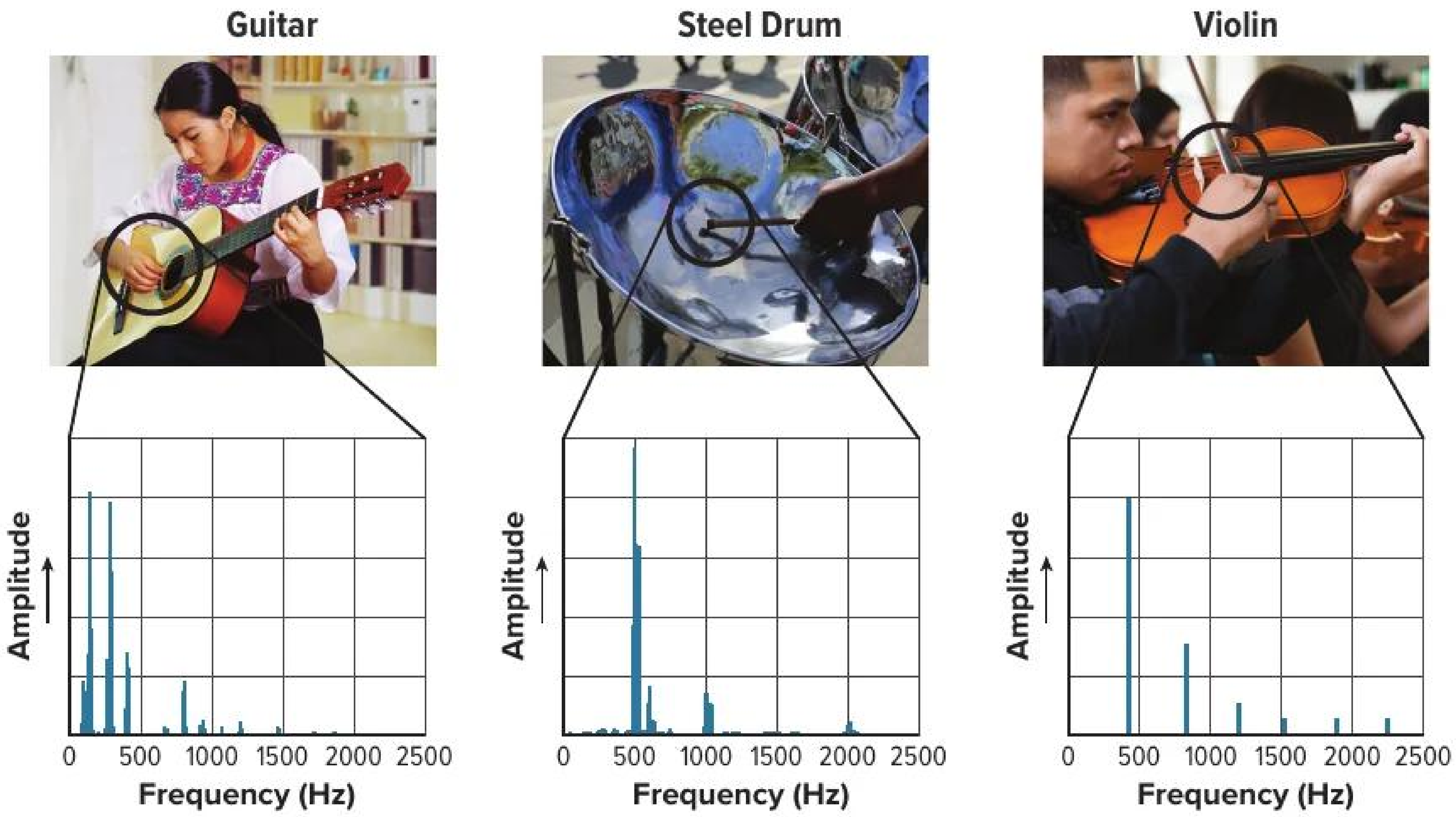


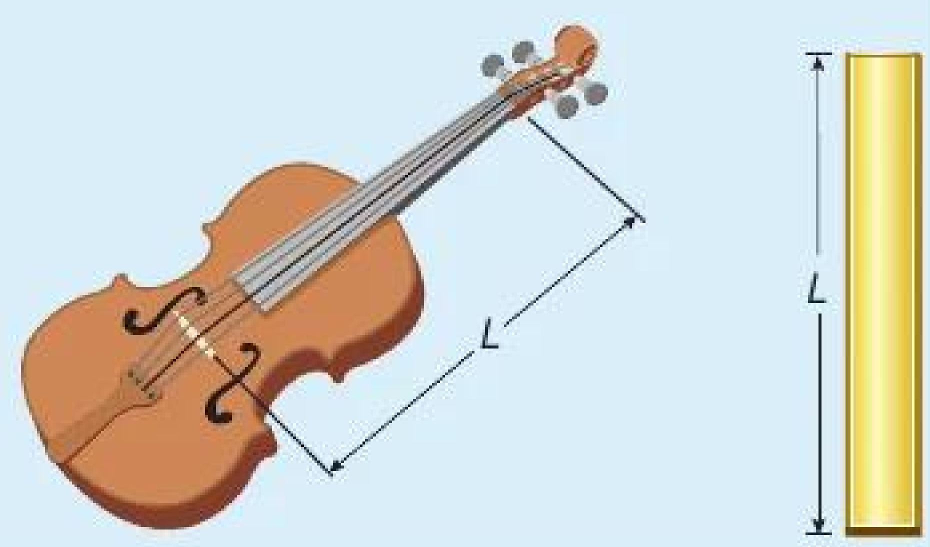
Figure 18 A guitar, a steel drum, and a violin produce characteristic sound spectra. Each spectrum is unique, as is the timbre of the instrument.

Some instruments, such as a flute, act as open-pipe resonators. Their fundamental frequency, which is also the first harmonic, is $f_1 = \frac{v}{2L}$ with subsequent harmonics at $2f_1$, $3f_1$, $4f_1$, and so on. Different combinations of these harmonics give each instrument its own unique timbre. Each harmonic on the instrument can have a different amplitude as well. A graph of the amplitude of a wave versus its frequency is called a sound spectrum. The spectra of three instruments are shown in **Figure 18.**

Consonance and dissonance When two different pitches are played at the same time, the resulting sound can be either pleasant or jarring. In musical terms, several pitches played together are called a chord. An unpleasant set of pitches is called **dissonance.** If the combination of pitches is pleasant, the sounds are said to be in **consonance.** What sounds pleasing varies between cultures, but most Western music is based upon the observations of Pythagoras of ancient Greece. He noted that pleasing sounds resulted when strings had lengths in small, whole-number ratios, such as 1:2, 2:3, or 3:4. This means their pitches (frequencies) will also have small, whole-number ratios.

PHYSICS Challenge

1. Determine the tension, F_T, in a violin string of mass *m* and length *L* that will play the fundamental note at the same frequency as a closed pipe also of length *L*. Express your answer in terms of *m*, *L*, and the speed of sound in air, *v*. The equation for the speed of a wave on a string is $v_{string} = \sqrt{\frac{F_T}{\mu}}$, where F_T is the tension in the string and μ is the mass per unit length of the string.
2. What is the tension in a string of mass 1.0 g and 40.0 cm long that plays the same note as a closed pipe of the same length?



Musical intervals Two notes with frequencies related by the ratio 1:2 are said to differ by an octave. For example, if a note has a frequency of 440 Hz, a note that is one octave higher has a frequency of 880 Hz. The fundamental and its harmonics are related by octaves; the first harmonic is one octave higher than the fundamental, the second is two octaves higher, and so on. It is the ratio of two frequencies, not the size of the interval between them, that determines the musical interval.

In other musical intervals, two pitches may be close together. For example, the ratio of frequencies for a "major third" is 4:5. An example is the notes C and E. The note C has a frequency of 262 Hz, so E has a $\left(\frac{5}{4}\right)(262\text{ Hz}) = 327\text{ Hz}$. In the same way, notes in a "fourth" (C and F) have a frequency ratio of 3:4, and those in a "fifth" (C and G) have a ratio of 2:3. More than two notes sounded together also can produce consonance. The three notes called do, mi, and sol make a major chord. For at least 2500 years, western music has recognized this as the sweetest of the three-note chords; it has the frequency ratio of 4:5:6.

Beats

You have seen that consonance is defined in terms of the ratio of frequencies. When the ratio becomes nearly 1:1, the frequencies become very close. Two frequencies that are nearly identical interfere to produce oscillating high and low sound levels called a **beat.** This phenomenon is illustrated in **Figure 19.** The frequency of a beat is the magnitude of difference between the frequencies of the two waves, $f_{beat} = |f_A - f_B|$. When the difference is less than 7 Hz, the ear detects this as a pulsation of loudness. Musical instruments often are tuned by sounding one against another and adjusting the frequency of one until the beat disappears.

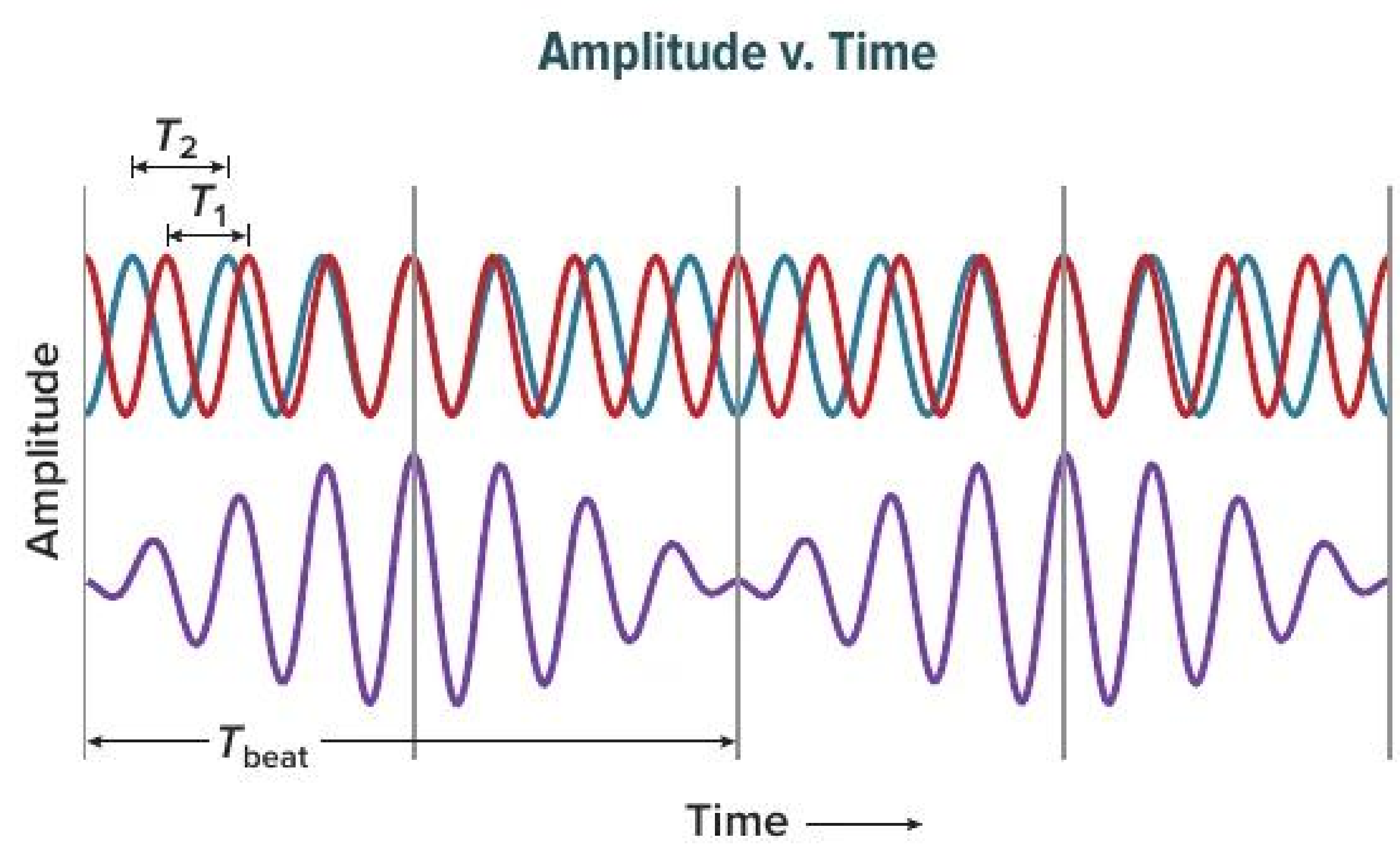


Figure 19 Beats occur as a result of the superposition of two sound waves of slightly different frequencies.

SCIENCE USAGE v. COMMON USAGE

Beat

Science usage: oscillation of wave amplitude that results from the superposition of two sound waves with almost identical frequencies

When the piano tuner no longer heard beats, she knew the piano was tuned properly.

Common usage: to strike repeatedly

Richard beat the drums while John played the guitar.

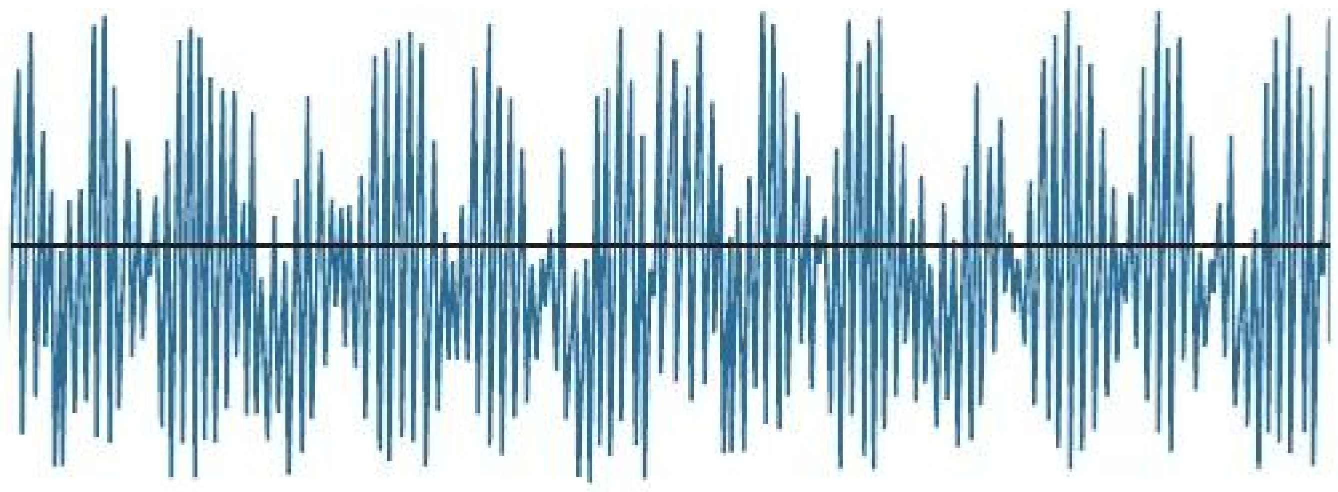


Figure 20 A noise wave consists of many different frequencies, all with about the same amplitude.

Sound Reproduction and Noise

When you listen to a live band or hear your school band practicing, you are hearing music produced directly by a human voice or musical instruments. You may want to hear live music every time you choose to listen to music. Most of the time, however, you likely listen to music that has been recorded and is played via electronic systems. To reproduce the sound faithfully, the system must accommodate all frequencies equally. A good stereo system keeps the amplitudes of all frequencies between 20 and 20,000 Hz to within a range of 3 dB.

A telephone system, on the other hand, needs only to transmit the information in spoken language. Frequencies between 300 and 3000 Hz are sufficient. Reducing the number of frequencies present helps reduce the noise. A noise wave is shown in **Figure 20.** Many frequencies are present with approximately the same amplitude. While noise is not helpful in a telephone system, some people claim that listening to white noise has a calming effect. For this reason, some dentists use noise to help their patients relax.

Check Your Progress

17. **Sound Sources** What is the vibrating object that produces sounds in each of the following?
    a. a human voice
    b. a clarinet
    c. a tuba
    d. a violin
18. **Resonance in Air Columns** Why is the tube from which a tuba is made much longer than that of a cornet?
19. **Resonance in Open Tubes** How must the length of an open tube compare to the wavelength of the sound to produce the strongest resonance?
20. **Resonance on Strings** A violin sounds a note of F sharp, with a pitch of 370 Hz. What are the frequencies of the next three harmonics produced with this note?
21. **Resonance in Closed Pipes** One closed organ pipe has a length of 2.40 m.
    a. What is the frequency of the note played?
    b. When a second pipe is played at the same time, a 1.40-Hz beat note is heard. By how much is the second pipe too long?
22. **Timbre** Why do various instruments sound different even when they play the same note?
23. **Beats** A tuning fork produces three beats per second with a second, 392-Hz tuning fork. What is the frequency of the first tuning fork?
24. **Critical Thinking** Strike a tuning fork with a rubber hammer and hold it at arm's length. Then press its handle against a desk, a door, a filing cabinet, and other objects. What do you hear? Why?

LEARNSMART® Go online to follow your personalized learning path to review, practice, and reinforce your understanding.

SCIENCE & SOCIETY

Out of Sight—Sonar Detection

Animals such as bats, whales, dolphins, and some birds use echolocation, also called bio-sonar, to detect objects when it is difficult for them to see (for example, at night or in cloudy waters). The animals emit high-frequency clicking noises. The sound waves from these noises bounce off nearby objects as echoes. The animals detect the echoes with their ears and process the information to determine the spatial imagery of their surroundings, including the location of prey.

Daniel Kish is blind. He uses echolocation to navigate around in his environment.

Human Echolocation

Some people who are blind also use echolocation to orient to their environment and move around safely without the help of a guide dog or cane. These people produce rapid clicking noises with their mouths and listen for the echoes as they reflect back from different surfaces and objects nearby. This acoustic information received from their ears is interpreted in the same part of the brain where people who have sight process visual information about their surroundings—in essence, they "see" by sound.

Californian Daniel Kish developed retinal cancer as an infant and soon became blind. Without the guidance of anyone, he instinctively used clicking noises at a young age as a compass to navigate in his environment—before the concept of human echolocation existed. Daniel is known as the "real-life batman" and can even mountain bike and sketch his surroundings using echolocation.

Daniel received his Master's degree in developmental psychology and developed the first step-by-step methods for teaching echolocation. He now trains visually impaired people to use echolocation as a valuable skill to move around in day-to-day life. Scientists have also found that it is possible to train people who are not blind to use echolocation.

Developing Echolocation Technologies

New assistive devices that are based on echolocation are being developed for people who are visually impaired. These include vibrating clothing and a wrist band that detects echoes bouncing off objects up to 14 feet away. Echolocation research may also be useful in the development of technology that uses artificial sonar, such as self-driving cars.

COMMUNICATE TECHNICAL INFORMATION

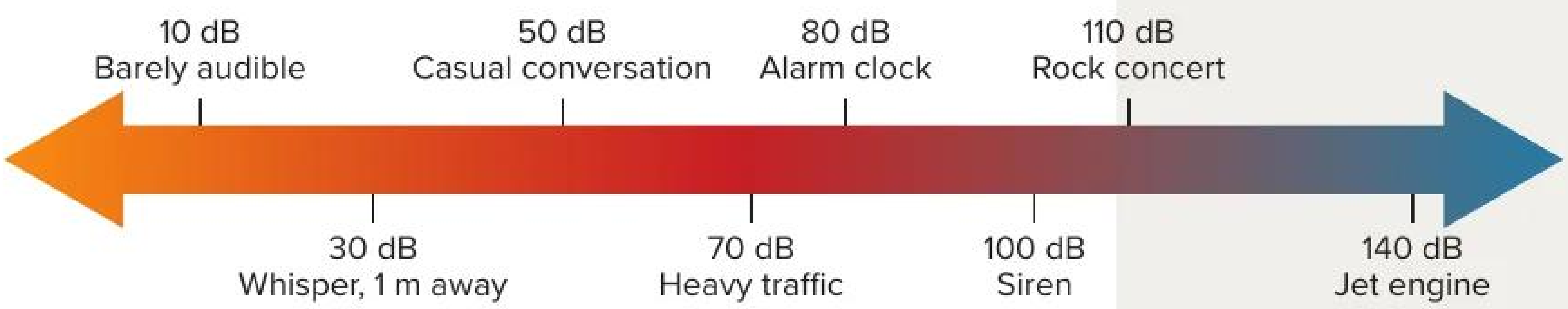
Research and choose a technology that uses echolocation. Summarize how the technology works in a short paragraph.

MODULE 14
STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 PROPERTIES AND DETECTION OF SOUND

- Sound is a pressure variation transmitted through matter as a longitudinal wave. A sound wave has frequency, wavelength, speed, and amplitude. Sound waves reflect and interfere.
- Sound detectors convert the energy carried by a sound wave into another form of energy. The human ear is a highly efficient and sensitive detector of sound waves. The frequency of a sound wave is heard as its pitch. The loudness of sound as perceived by the ear and brain depends mainly on its amplitude. The pressure amplitude of a sound wave can be measured in decibels (dB).



- The Doppler effect is the change in frequency of sound caused by the motion of either the source or the detector.
- The Doppler effect is used in radar detectors, in medical ultrasound machines, and by astronomers. Bats also use the Doppler effect to detect and catch flying insects.

- sound wave
- pitch
- loudness
- sound level
- decibel
- Doppler effect

Lesson 2 THE PHYSICS OF MUSIC

- Sound is produced by a vibrating object in a medium.
- An air column can resonate with a sound source, thereby increasing the amplitude of its resonant frequency. A closed pipe resonates when its length is $\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$, and so on. Its resonant frequencies are odd-numbered multiples of the fundamental. An open pipe resonates when its length is $\frac{\lambda}{2}, \frac{2\lambda}{2}, \frac{3\lambda}{2}$, and so on. Its resonant frequencies are whole-number multiples of the fundamental.
- A clamped string has a node at each end and resonates when its length is $\frac{\lambda}{2}, \frac{2\lambda}{2}, \frac{3\lambda}{2}$, and so on, just as with an open pipe. The string's resonant frequencies are also whole-number multiples of the fundamental.
- The frequencies and intensities of the complex waves produced by a musical instrument determine the timbre that is characteristic of that instrument.
- Two waves with almost the same frequency interfere to produce beats.

- closed-pipe resonator
- open-pipe resonator
- fundamental
- harmonics
- dissonance
- consonance
- beat

THREE-DIMENSIONAL THINKING

Module Wrap-Up

REVISIT THE PHENOMENON

Why does a fire truck's siren change pitch as it passes you?

CER Claim, Evidence, Reasoning

Explain your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

SEP Data Analysis Lab

Can you test the Doppler effect?

In 1845, Dutch astronomer Christoph Buys Ballot tested the Doppler effect. A trumpet player sounded an A (440 Hz) while riding on a flatcar pulled by a train. Your project team wants to repeat the experiment. Rather than using a train and listening for beats, you plan to have a trumpet played in a rapidly moving car and have the car move fast enough so that the moving trumpet sounds one major third above a stationary trumpet.

CER Analyze and Interpret Data

1. **Claim** Should you try your experiment?
2. **Evidence and Reasoning** Justify your claim.

MODULE 15
FUNDAMENTALS OF LIGHT

NASA, ESA, J. Hester and A. Loll (Arizona State University)

MODULE 15
FUNDAMENTALS OF LIGHT

ENCOUNTER THE PHENOMENON

What does the light from a distant star or supernova tell us about it?

GO ONLINE to play a video about measuring the speed of light.

SEP Ask Questions

Do you have other questions about the phenomenon? If so, add them to the driving question board.

CER Claim, Evidence, Reasoning

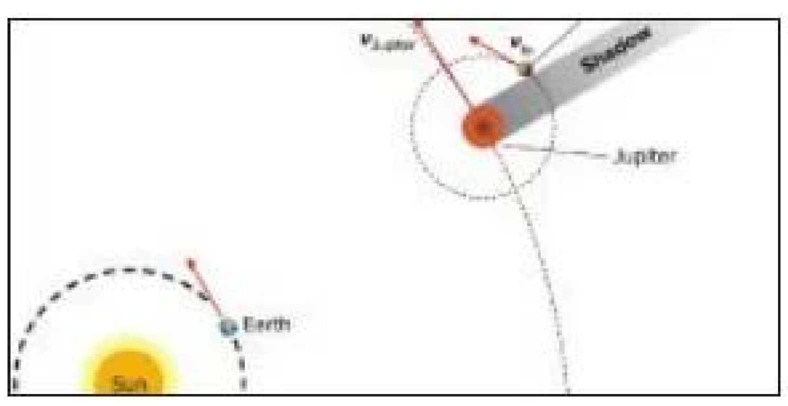
Make Your Claim Use your CER chart to make a claim about what light from a distant star or supernova tells us about it. Explain your reasoning.

Collect Evidence Use the lessons in this module to collect evidence to support your claim. Record your evidence as you move through the module.

Explain Your Reasoning You will revisit your claim and explain your reasoning at the end of the module.

GO ONLINE to access your CER chart and explore resources that can help you collect evidence.

LESSON 1: Explore & Explain: How Light Travels



LESSON 2: Explore & Explain: Speed of Light

Smithsonian

Additional Resources

LESSON 1

ILLUMINATION

FOCUS QUESTION

How does distance affect how bright a star appears?

Light

Light is electromagnetic radiation, like radio and microwaves. It can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. In this module, you will learn about the wave properties of light. You will learn about photons in a later module.

Light's path How does your body receive information? Many people respond to this question with the five senses, starting with sight and hearing. The sense of sight depends on light from your surroundings reaching your eyes. Did you ever wonder how light travels? Think of how a narrow beam of light, such as that of a flashlight or sunlight streaming through a small window, is made visible by dust particles in the air. You see the path of the light as a straight line. When your body blocks sunlight, you see your outline in a shadow, a result of light's straight path. **Figure 1** depicts light's straight path.

Figure 1 Light rays traveling in straight lines are evident in many situations.
Explain *how this photo demonstrates the wave properties of light.*

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Quick Investigation: The Speed of Light
Use the relationship among the frequency, wavelength, and speed of a wave to calculate the speed of light.

Probeware Lab: Light Intensity and Distance
Analyze data to determine how distance from the source affects the intensity of light.

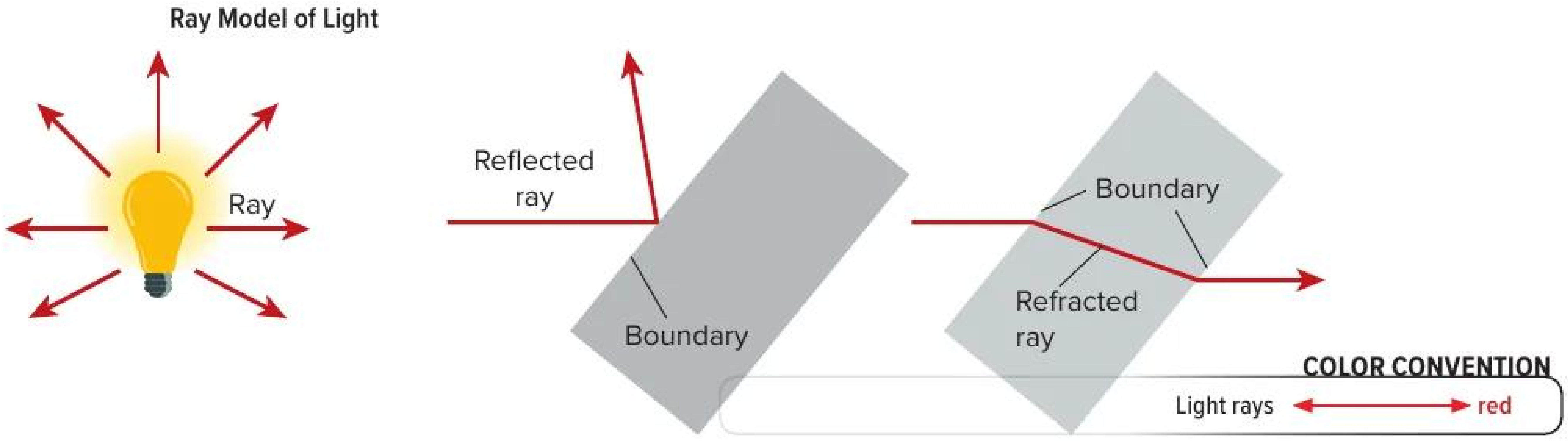


Figure 2 Light's straight-line path is demonstrated by the ray model. Light rays change direction when they are reflected or refracted by matter. In either case, light rays continue in a straight path.

Ray Model of Light

Imagine being in an empty, dark room when a small lightbulb is turned on in the center of the room. You can see around the room, and you can look at the bulb and see it. This must mean the bulb sends light in all directions. You could visualize the light coming from the bulb as an infinite number of arrows traveling straight away from the bulb in all directions. Each arrow represents a ray of light, which travels in a straight path until it reaches a boundary, as shown in **Figure 2.**

After interacting at a boundary, the ray still moves in a straight line, but its direction is changed. These basic principles—that light travels in straight lines and that its direction can be changed by encountering a boundary—constitute the **ray model of light.** The study of light interacting with matter is called ray optics or geometric optics.

Sources of light

What is the difference between sunlight and moonlight? For one, sunlight is much brighter. Another important fundamental difference is that the Sun produces and emits its own light, while the Moon is only visible because it reflects the Sun's light. Everything you see fits into one of these two categories. Objects such as the Sun and other stars that emit their own light are **luminous sources,** while those that you see due to light reflecting from them are illuminated sources, like the Moon and planets.

Luminous sources include natural sources such as flames and fireflies and human-made devices such as television screens, computer monitors, lasers, and tiny, light-emitting diodes. In **Figure 3,** the luminous source is fluorescent bulbs. They produce light from electrical energy. The other objects in the room are illuminated when the light from the bulbs is reflected off of them. In a room with no light, it would be impossible to see anything, because there is no light reflecting off of objects into your eyes.

Figure 3 Objects in the room are visible because of reflected light.

Recognize *What, if anything, would be visible if the room had no luminous source? Explain.*

Figure 4 Light is transmitted through the transparent and translucent candle holders. The candle cannot be seen clearly in the opaque holder because the light is absorbed.

Light and matter Objects can absorb, reflect, or transmit light. Objects that reflect and absorb light but do not transmit it are **opaque.** Many common objects—such as books, people, and backpacks—are opaque. Mediums that transmit and reflect light but do not allow objects to be seen clearly through them are **translucent** mediums. The frosted glass in **Figure 4** is a translucent medium. A **transparent** medium, such as air or glass, transmits most of the light that reaches it. **Figure 4** illustrates objects that are opaque, translucent, and transparent. Transparent mediums transmit light, but they also often reflect some light. For example, you can see the glass of the transparent candle holder. This is possible because light is reflected off the glass.

All three types of objects also absorb some light. There are various factors that determine how much light will be absorbed, but opaque objects usually absorb a greater portion of light than translucent or transparent objects.

Get It?
Explain why it is possible to see a fish through a glass fishbowl and also see the glass of the bowl.

Quantity of Light

If you were to have a flashlight shone at you from across the room, what factors would determine how bright that light would appear to you? Three main factors determine the brightness: the quantity of light the flashlight produces, the distance between the lightbulb and your eye, and the angle at which the light rays hit your eye. In this lesson, you will read about the first two of these factors.

Luminous flux With the ray model of light, a source that is brighter produces more light rays than a less bright source. Imagine again a single lightbulb sending rays in nearly all directions. How could you capture all the light it emits? You would need to construct a surface that completely encloses the bulb, as in **Figure 5.** The rate at which the bulb, a luminous source, produces light energy is called the **luminous flux** (P) and is measured in lumens (lm). The total amount of light that strikes the surface in a given unit of time depends only on the luminous flux of the source.

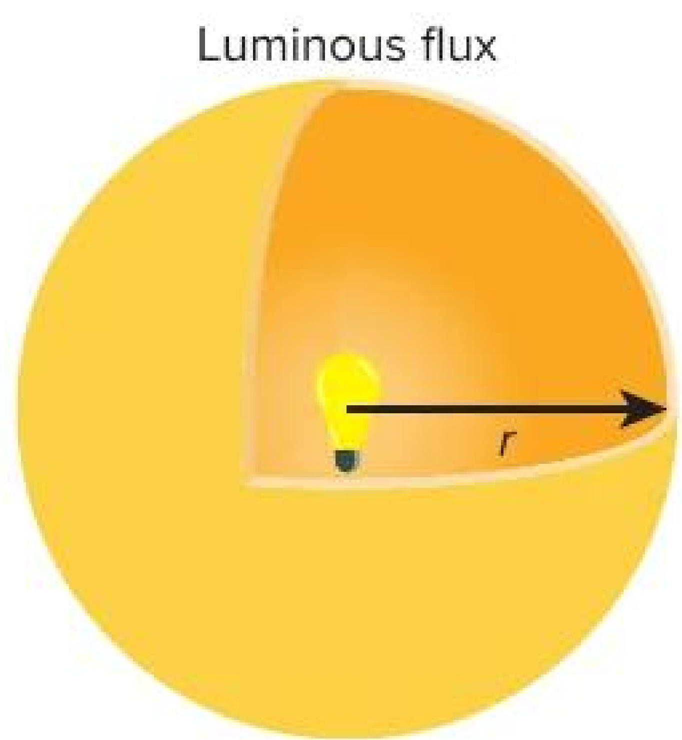


Figure 5 Luminous flux is the rate at which light rays are emitted from a luminous source.

Iluminance Once you know the quantity of light being emitted by a luminous source, you can determine the amount of illumination the source provides to an object, such as a book. The luminous flux falling on a given surface area at any instant is called **illuminance** (E). It is measured in lux (lx), which is equivalent to lumens per square meter (lm/m^2). In this module, we assume, for simplification, that all light sources are point sources.

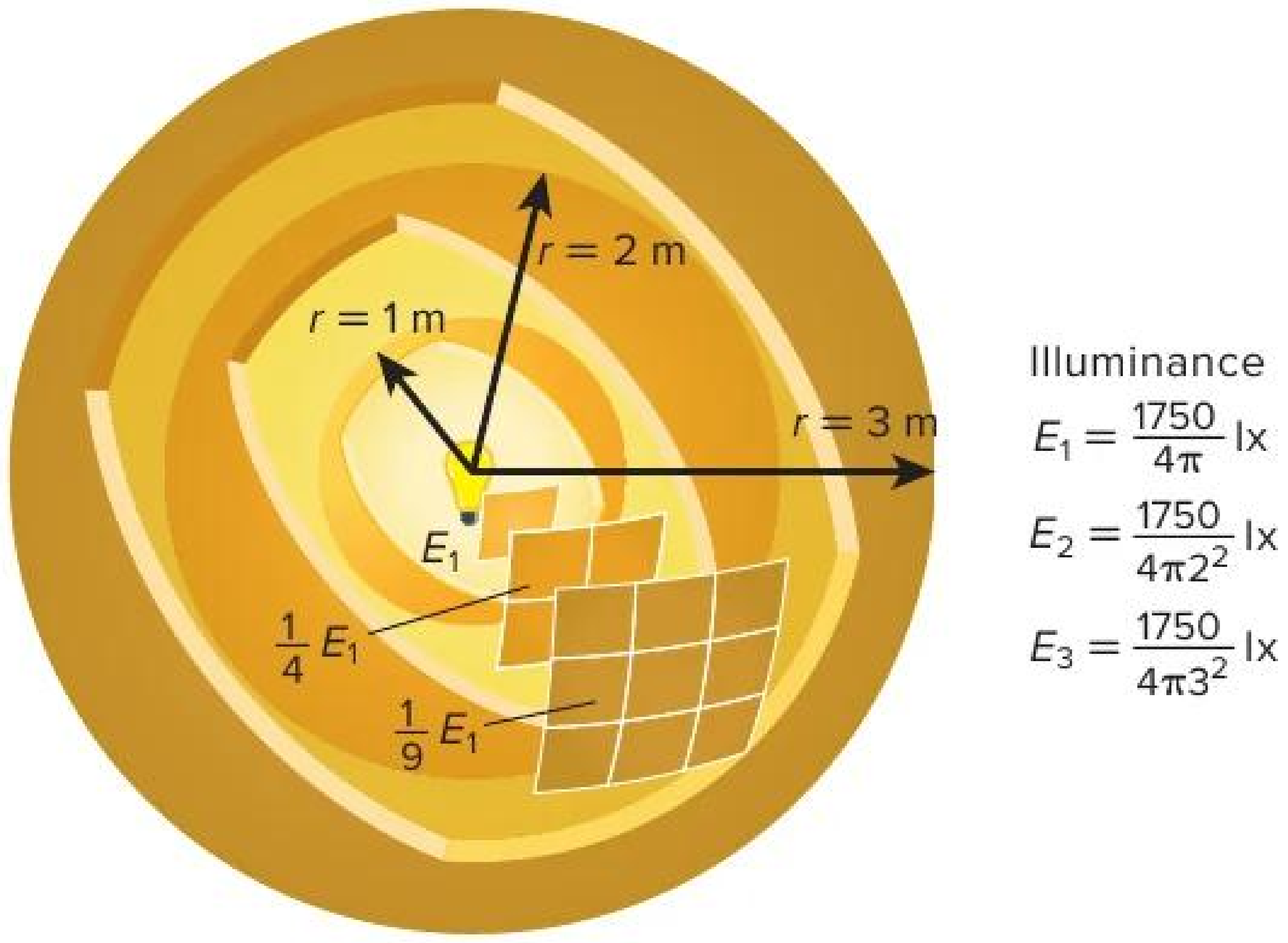


Figure 6 Illuminance (E) is the quantity of light that strikes a surface. As the distance from the luminous source (r) increases, E decreases. E depends on the inverse of r squared.

Consider the setup shown in **Figure 6.** The luminous flux of the source is 1750 lm (typical of a 26-W compact fluorescent bulb). What is the illuminance of the sphere's inside surface at r = 1 m? Because all the bulb's luminous flux strikes the surface, divide the luminous flux by the surface area of the sphere, $4\pi r^2$. The surface area is $4\pi(1.00\text{ m})^2 = 4\pi\text{ m}^2$, so the illuminance is $\frac{1750\text{ lm}}{4\pi\text{ m}^2} = 139$ lx. This mathematical relationship means that at a distance of 1.00 m from the bulb, 139 lm strikes each square meter.

Get It?

Define *illuminance*, and state the units that are used for illuminance.

Inverse-square relationship What if the sphere surrounding the lamp were larger? If the sphere's radius were 2.00 m, the luminous flux still would total 1750 lm because it only depends on the bulb. With a radius of 2.00 m, however, the area of the sphere would now be equal to $4\pi(2.00\text{ m})^2 = 16.0\pi\text{ m}^2$. The new area is four times larger than that of the 1.00-m sphere, as shown in **Figure 6.** The illuminance of the inside of the 2.00-m sphere is $\frac{1750\text{ lm}}{(160\pi\text{ m}^2)} = 34.8$ lx, so 34.8 lm strikes each square meter.

The illuminance on the inside surface of the 2.00-m sphere (E_2) is one-fourth the illuminance on the inside of the 1.00-m sphere. In the same way, the inside of a sphere with a 3.00-m radius has an illuminance only one-ninth $\left[\left(\frac{1}{3}\right)^2\right]$ as large as that of the 1.00-m sphere. **Figure 6** shows that the illuminance produced by a point source is proportional to $\frac{1}{r^2}$: an inverse-square relationship. In the case of the 3.00-m radius, only 15.5 lm strike each square meter inside the sphere. As the light rays spread out in straight lines in all directions from a point source, the number of light rays that illuminate a unit of area decreases as the square of the distance from the point source.

CCC CROSSCUTTING CONCEPTS

Systems and System Models Write a paragraph explaining how mathematical models were used in the study of light. Include information about the system and system boundaries that scientists used.

CONNECTING MATH to Physics

Direct and Inverse Relationships The illuminance provided by a source of light has both a direct and an inverse relationship.

Math	Physics
$y = \frac{x}{az^2}$	$E = \frac{P}{4\pi r^2}$
If z is constant, then y is directly proportional to x. • When x increases, y increases. • When x decreases, y decreases.	If r is constant, then E is directly proportional to P. • When P increases, E increases. • When P decreases, E decreases.
If x is constant, then y is inversely proportional to z^2. • When z^2 increases, y decreases. • When z^2 decreases, y increases.	If P is constant, then E is inversely proportional to r^2. • When r^2 increases, E increases. • When r^2 decreases, E decreases.

Luminous intensity Some luminous sources are specified in candelas (cd). A candela is not a measure of luminous flux but of luminous intensity. The luminous intensity of a point source is the luminous flux that falls on 1 m^2 of the inside of a 1-m-radius sphere, so luminous intensity is luminous flux divided by 4π. A bulb with 1750 lm of flux has an intensity of $\frac{1750 \text{ lm}}{4\pi} = 139$ cd.

In **Figure 7,** the lightbulb is twice as far away from the screen as the candle. For the bulb to provide the same illuminance on its side of the screen as the candle does on the candle side of the screen, the bulb would have to be four times brighter than the candle. The lightbulb's luminous intensity, therefore, would have to be four times the candle's luminous intensity. If both sources in **Figure 7** had the same luminous intensity, the source at $2r$ would only provide one-quarter the illuminance to the screen. This is consistent with the inverse-square relationship we just developed.

Get It?

Describe what luminous intensity is a measure of and what its relationship is to illuminance.

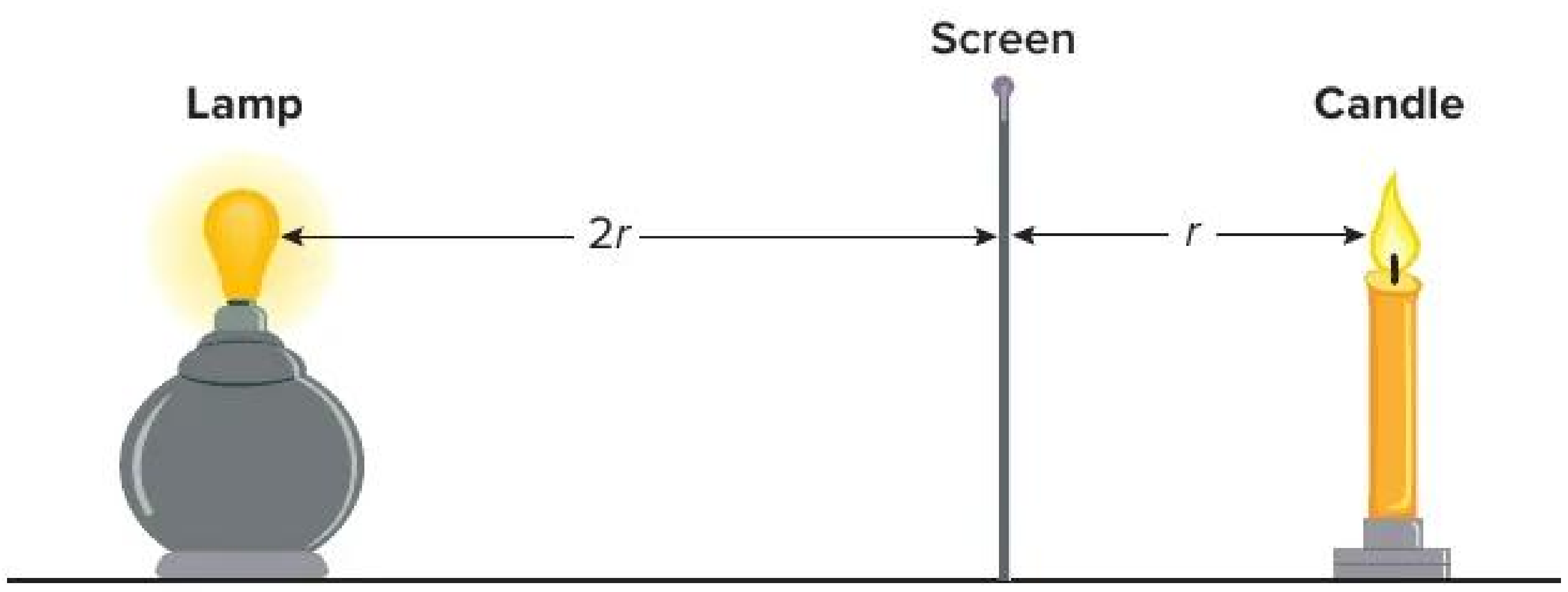


Figure 7 For the lightbulb and the candle to provide the same illuminance to the screen, the luminous intensity of the lightbulb is four times that of the candle.

Surface Illumination

Think again about the scenario in which a flashlight is shining at you from across the room. If the bulb has a small luminous intensity, the light will not be very bright. To increase the brightness, you could use a brighter bulb, thereby increasing the luminous flux, or you could move so that your eyes are closer to the light, decreasing the distance between the light source and your eyes. Following the simplification that we are treating all light sources as point sources, the illuminance and distance will follow the inverse-square relationship. In this case, and in all the cases we will deal with in this book, the illuminance caused by a point light source is represented by the following equation.

Real-World Physics

Illuminated Minds

When deciding how to achieve the correct illuminance on students' desktops in a classroom, architects must consider the luminous flux of the lights as well as the distance of the lights above the desktops. In addition, the efficiencies of the light sources are an important economic factor.

Point-Source Illuminance

If an object is illuminated by a point source of light, then the illuminance at the object is equal to the luminous flux of the light source divided by the surface area of the sphere whose radius is equal to the distance the object is from the light source.

$$E = \frac{P}{4\pi r^2}$$

Remember that the luminous flux of the light source is spreading out in all directions, so only some fraction of the luminous flux is available to illuminate the object. Use of this equation is valid only if the light from the luminous source strikes perpendicular to the surface it is illuminating. It is also only valid if the luminous source is small enough or far enough away to be considered a point source. Thus, the equation does not give accurate values of illuminance for long fluorescent lamps or lightbulbs that are close to the surfaces they illuminate.

Engineers who design lighting systems must understand how the light will be used. If an even illumination is needed to prevent dark areas, the common practice is to evenly space normal lights over the area to be illuminated, as was most likely done with the lights in your classroom. Because such light sources do not produce truly uniform light, however, engineers also design special light sources that control the spread of the light, such that they produce even illuminations over large surface areas. For safety reasons, this is extremely important for automobile headlights, as in **Figure 8.** Automobile engineers must consider these factors when designing headlights.

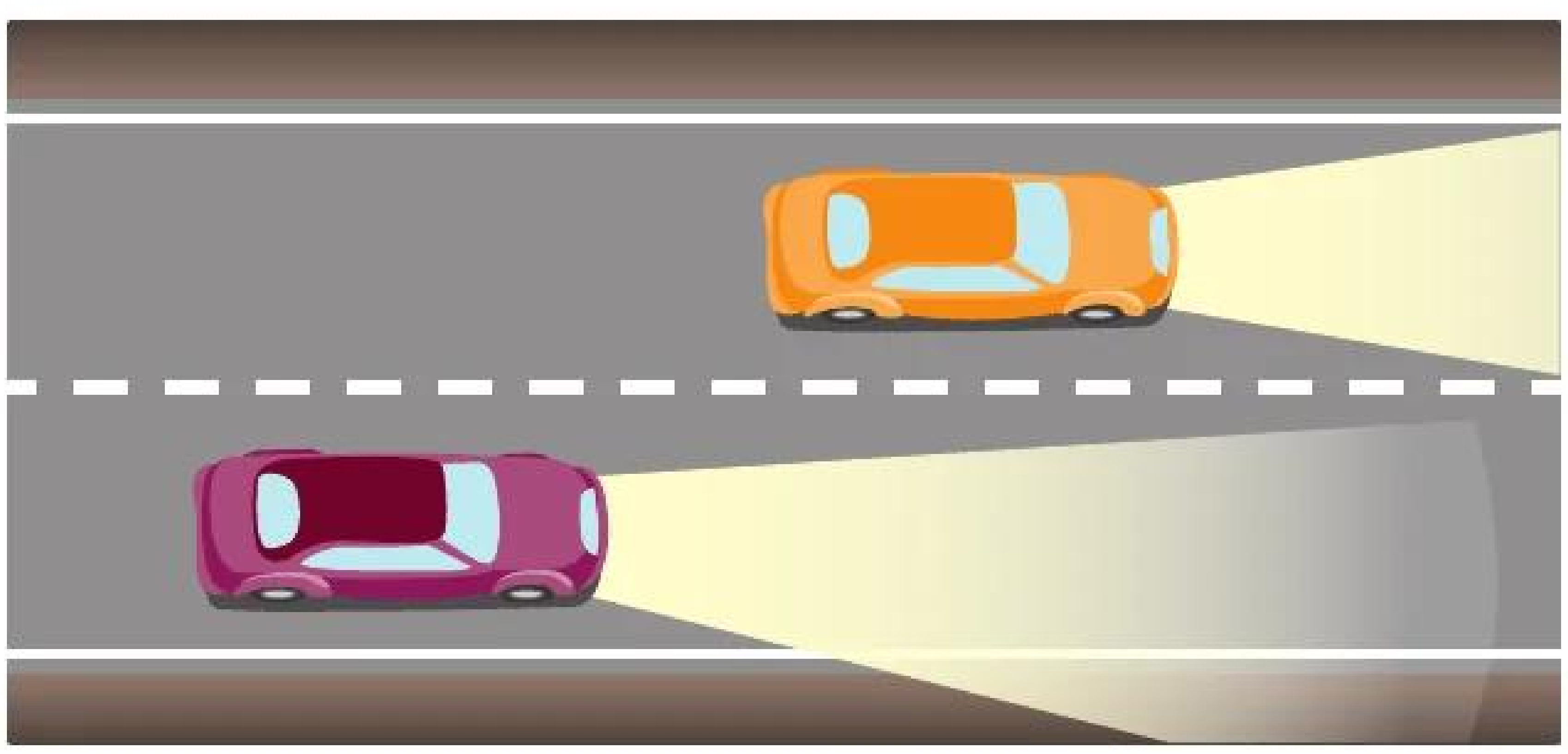
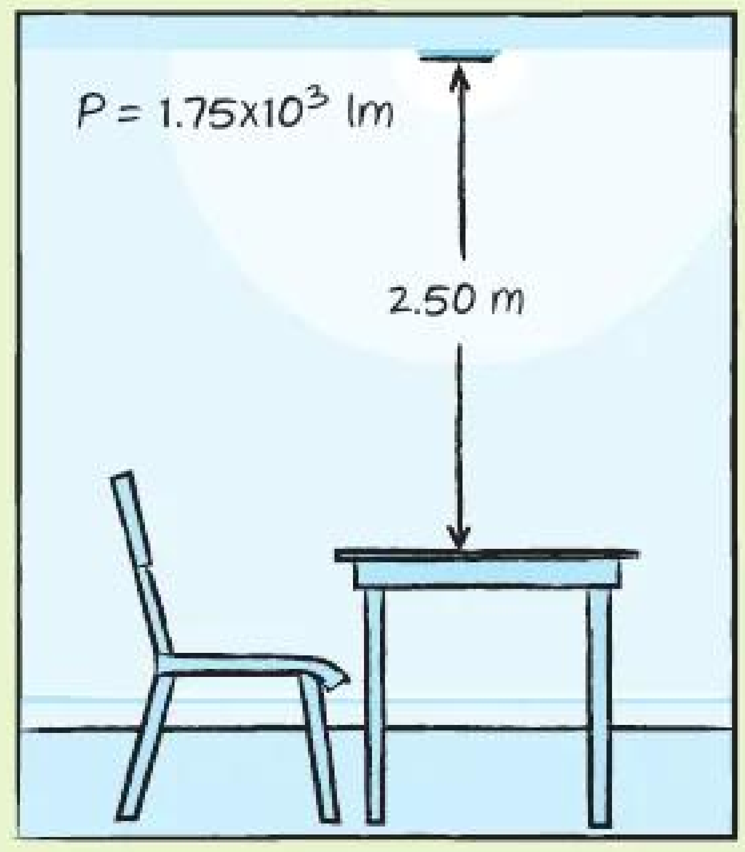


Figure 8 Dark areas can occur if headlights on cars are not set at the correct angles to adequately illuminate the road.

EXAMPLE Problem 1

ILLUMINATION OF A SURFACE What is the illuminance on your desktop if it is lit by a 1750-lm lamp that is 2.50 m above your desk?



1 ANALYZE AND SKETCH THE PROBLEM

- Assume the lightbulb is the point source.
- Diagram the position of the bulb and the desktop. Label *P* and *r*.

Known	Unknown
$P = 1.75\times10^3$ lm	$E = ?$
$r = 2.50$ m	

2 SOLVE FOR THE UNKNOWN

The surface is perpendicular to the direction in which the light ray is traveling, so you can use the point-source illuminance equation.

$$E = \frac{P}{4\pi r^2}$$

$$= \frac{1.75\times10^3\ \text{lm}}{4\pi(2.50\ \text{m})^2} \quad \text{Substitute } P = 1.75\times10^3\ \text{lm},\ r = 2.50\ \text{m}$$

$$= 22.3\ \text{lm/m}^2$$

$$= 22.3\ \text{lx}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** The units of luminance are $\text{lm/m}^2 = \text{lx}$, which the answer agrees with.
- **Do the signs make sense?** All quantities are positive, as they should be.
- **Is the magnitude realistic?** Illuminance from an 1800-lm lamp at a distance of 2 m is about 20 lx.

PRACTICE Problems

ADDITIONAL PRACTICE

1. A lamp is moved from 30 cm to 90 cm above the pages of a book. Compare the illumination on the book before and after the lamp is moved.
2. Draw a graph of the illuminance produced by a lamp with a luminous flux of 2275 lm at distances from 0.50 m and 5.0 m.
3. A 64-cd point source of light is 3.0 m away from a painting. What is the illumination on the painting in lux?
4. A screen is placed between two lamps so that they illuminate the screen equally, as shown in **Figure 9.** The first lamp emits a luminous flux of 1445 lm and is 2.5 m from the screen. What is the distance of the second lamp from the screen if the luminous flux is 2375 lm?

Figure 9

5. What is the illumination on a surface that is 3.0 m below a 150-W incandescent lamp that emits a luminous flux of 2275 lm?
6. A public school law requires a minimum illuminance of 160 lx at the surface of each student's desk. An architect's specifications call for classroom lights to be located 2.0 m above the desks. What is the minimum luminous flux that the lights must produce?
7. **CHALLENGE** Your local public library is planning to remodel the computer lab. The contractors have purchased fluorescent lamps with a rated luminous flux of 1750 lm. The desired illumination on the keyboard surfaces is 175 lx. Assume a single lamp illuminates each keyboard. What distance above the surface should the lights be placed to achieve the desired illumination? If the contractors had also already purchased fixtures to hold the lights that when installed would be 1.5 m above the keyboard surface, would the desired illuminance be achieved? If not, would the illuminance be greater or less than desired? What change in the lamp's luminous flux would be required to achieve the desired illuminance?

The Speed of Light

Arguments that light must travel at a finite speed have existed for more than 2400 years. By the seventeenth century, several scientists had performed experiments that supported the view that light travels at a finite speed, but that this speed is much faster than the speed of sound.

Actually measuring the speed of light was not an easy task in the seventeenth century. As you know from studying motion, if you can measure the time light takes to travel a certain distance, you can calculate the speed of light. However, the time that it takes light to travel between objects on Earth is much shorter than a human's reaction time. How could a seventeenth-century scientist solve this problem?

Clues from Io Danish astronomer Ole Roemer was the first to measure the time it took for light to travel between two points with any success. Between 1668 and 1674, Roemer made 70 measurements of the 1.8-day orbital period of Io, one of Jupiter's moons. He recorded the times when Io emerged from Jupiter's shadow, as shown in **Figure 10.** He made his measurements as part of a project to improve maps by calculating the longitude of locations on Earth. This is an early example of the needs of technology driving scientific advances.

After making many measurements, Roemer was able to predict when the next eclipse of Io would occur. He compared his predictions with the actual measured times and found that Io's observed orbital period increased on average by about 13 s per orbit when Earth was moving away from Jupiter and decreased on average by about 13 s per orbit when Earth was approaching Jupiter. Roemer believed that Jupiter's moons were just as regular in their orbits as Earth's moon; thus, he wondered what might cause this discrepancy in the measurement of Io's orbital period. He considered another variable within the system, the movement and position of Earth relative to Jupiter.

The Eclipse of Io

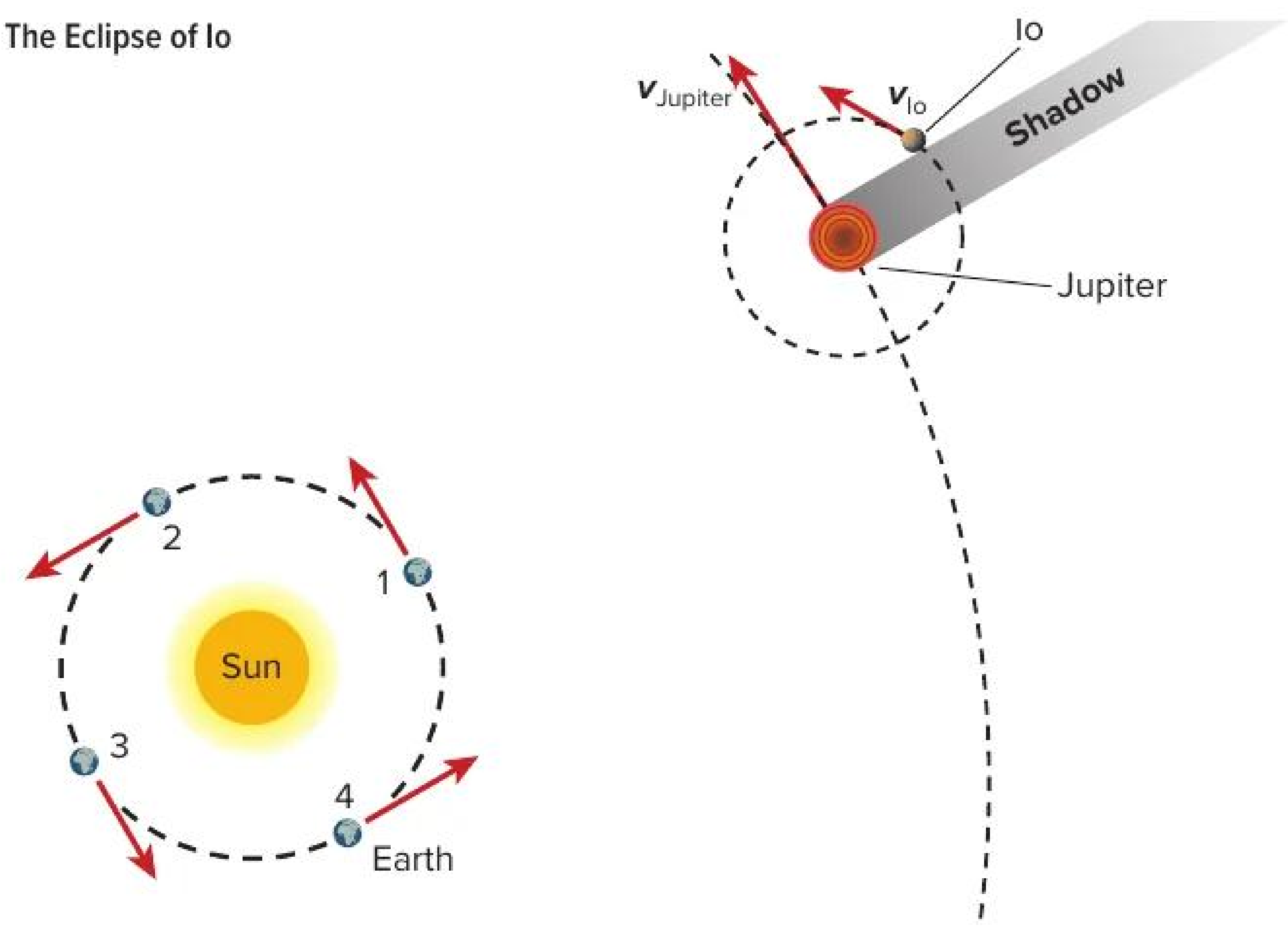


Figure 10 As Earth approaches Jupiter, the light reflected from Io takes less time to reach Earth than when Earth moves away from Jupiter. (Illustration is not to scale.)

Measuring the speed of light Roemer concluded that as Earth moved away from Jupiter, the light from each new appearance of Io took longer to reach Earth because it traveled farther. As Earth moved toward Jupiter, Io's orbital period seemed to decrease. During the 182.5 days it took for Earth to travel from position 1 to position 3, shown in **Figure 10,** there were (182.5 days)(1 Io eclipse/1.8 days) = 1.0×10^2 Io eclipses. Thus, for light to travel the diameter of Earth's orbit, he calculated that it takes (1.0×10^2 eclipses)(13 s/eclipse) = 1.3×10^3 s, or 22 min.

Using the presently known value of the diameter of Earth's orbit (2.93×10^{11} m), Roemer's value of 22 min gives a value for the speed of light of 2.9×10^{11} m/((22 min)(60 s/min)) = 2.2×10^8 m/s. Today, the speed of light is known to be closer to 3.0×10^8 m/s, so light takes 16.5 min, not 22 min, to cross Earth's orbit. Nevertheless, Roemer had successfully proved that light travels at a finite speed.

Michelson's measurements Although many measurements of the speed of light have been made, the most notable were performed by American physicist Albert A. Michelson. Between 1880 and the 1920s, he developed Earth-based techniques to measure the speed of light. In 1926 Michelson measured the time required for light to make a round trip between two California mountains 35 km apart. Michelson's best result was $(2.99796 \pm 0.00004)\times10^8$ m/s. For this work, he became the first American to receive a Nobel Prize in science.

The speed of light in a vacuum has its own special symbol, c. The International Committee on Weights and Measurements has measured and defined the speed of light in a vacuum to be c = 299,792,458 m/s. For many calculations, the value c = 3.00×10^8 m/s is precise enough. At this speed, light travels 9.46×10^{12} km in a year. This distance is called a light-year.

Check Your Progress

8. **Light** What evidence have you observed that light travels in a straight line?
9. **Light Properties** Why might you choose a window shade that is translucent? Opaque?
10. **Illuminance** Does one lightbulb provide more or less illuminance than two identical light-bulbs at twice the distance? Explain.
11. **Luminous Intensity** Two lamps illuminate a screen equally from distances shown in **Figure 11.** If Lamp A is rated 75 cd, what is Lamp B rated?

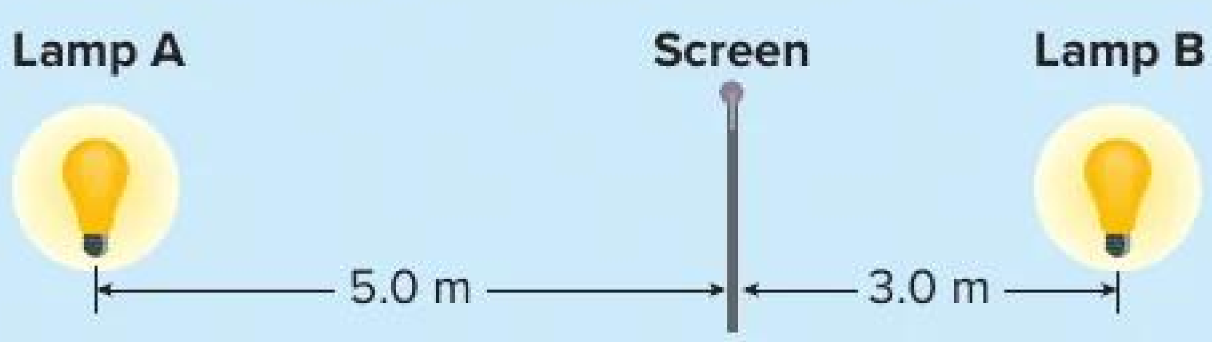


Figure 11

12. **Distance of a Light Source** A lightbulb illuminating your computer keyboard provides only half the illuminance that it should. If it is currently 1.0 m away, how far should it be to provide the correct illuminance?
13. **Light and Sound Travel** How far does light travel in the time it takes sound to travel 1 cm in air at 20°C?
14. **Distance of Light Travel** The distance to the Moon can be found with the help of mirrors left on the Moon by astronauts. A pulse of light is sent to the Moon and returns to Earth in 2.562 s. Using the defined value for the speed of light to the same precision, calculate the distance from Earth to the Moon.
15. **Critical Thinking** The correct time taken for light to cross Earth's orbit is 16.5 min, and the diameter of Earth's orbit is 2.98×10^{11} m. Calculate the speed of light using Roemer's method. Does this method appear to be accurate? Why or why not?

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LESSON 2
THE WAVE NATURE OF LIGHT

FOCUS QUESTION

How do scientists use the Doppler shift to determine how stars and galaxies are moving?

Diffraction and the Wave Model

In 1665 Italian scientist Francesco Maria Grimaldi observed that the edges of shadows are not perfectly sharp. He introduced a narrow beam of light into a dark room and held a rod in front of the light such that it cast a shadow on a white surface. The shadow cast by the rod was wider than the shadow should have been if light traveled in a straight line past the edges of the rod. Grimaldi also noted that the shadow was bordered by colored bands. He determined that both of these observations could be explained if light bent slightly. He called the bending of light as it passes the edge of a barrier **diffraction.**

Huygens' principle In 1678 Dutch scientist Christiaan Huygens used a wave model to explain diffraction. According to Huygens' principle, all the points of a wavefront of light can be thought of as new sources of smaller waves. These smaller waves, or wavelets, expand in every direction and are in step with one another. A flat, or plane, wavefront of light consists of an infinite number of point sources in a line. **Figure 12** illustrates Huygen's principle.

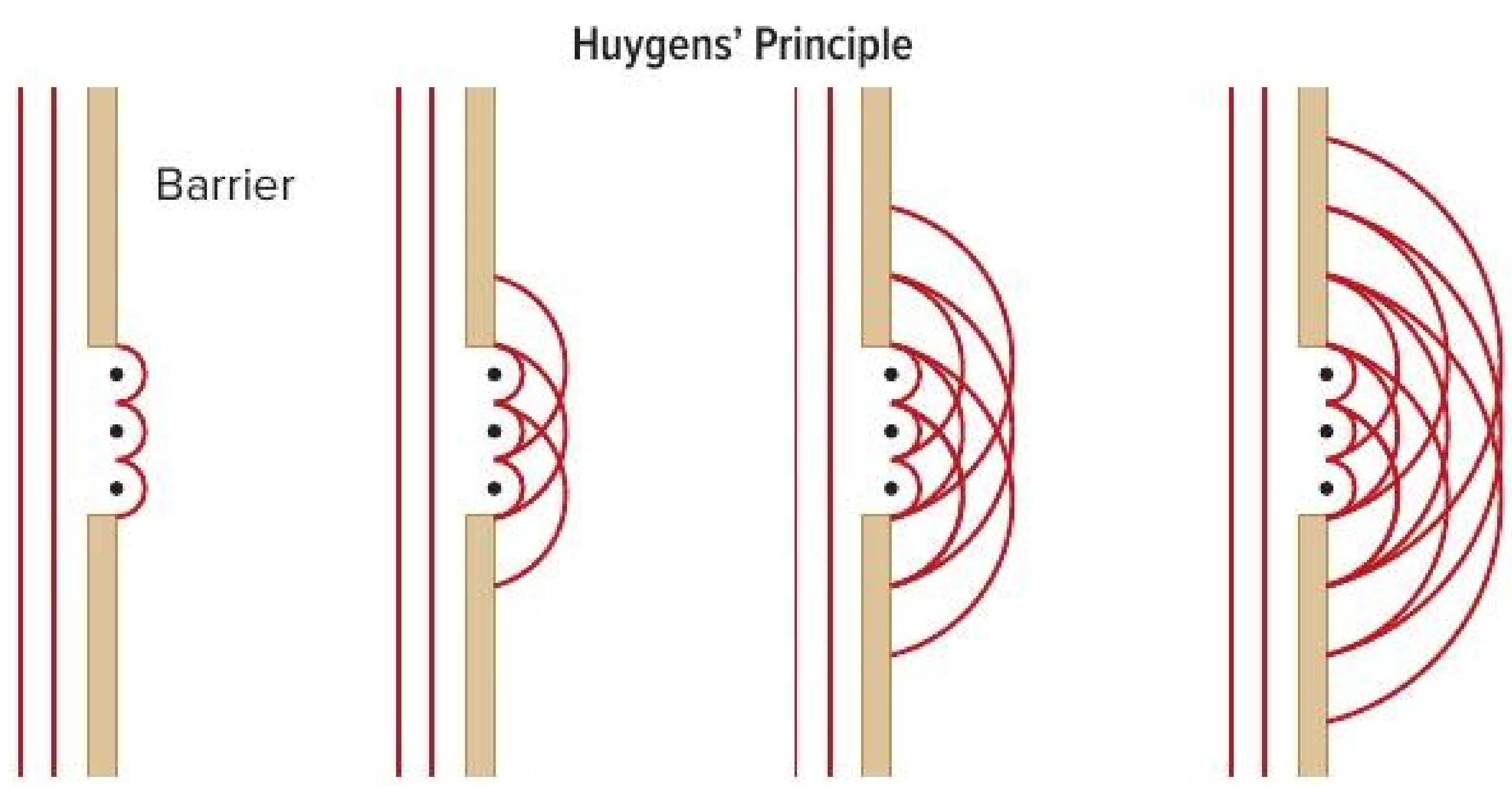

Figure 12 Huygens' wavelets combine to form a straight wavefront, except at the edges of the wave. The wavelets spread out in a circular manner when a barrier creates an edge.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

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INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Polarization

Carry out an investigation to determine the effect of polarizing filters on light.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the Unit and Module questions?

As a wavefront passes by an edge, the edge cuts the wavefront such that each circular wavelet generated by each Huygens' point will propagate as a circular wave in the region where the original wavefront was bent. This wave model explained the diffraction Grimaldi.

Color

In 1666 Newton performed experiments on the colors produced when a narrow beam of sunlight passed through a glass prism, as shown in **Figure 13.** Newton called the ordered arrangement of colors a spectrum. Using his later-disproved corpuscle (or particle) model of light, he thought that particles of light interacted with some unevenness in the glass to produce the spectrum.

To test this assumption, Newton allowed the spectrum from one prism to fall on a second prism. If the spectrum was caused by irregularities in the glass, he reasoned that the second prism would increase the spread in colors. Instead, the second prism reversed the spreading of colors and recombined them to form white light. After more experiments, Newton concluded that white light is composed of colors and that a property of the glass other than unevenness caused the light to separate into colors.

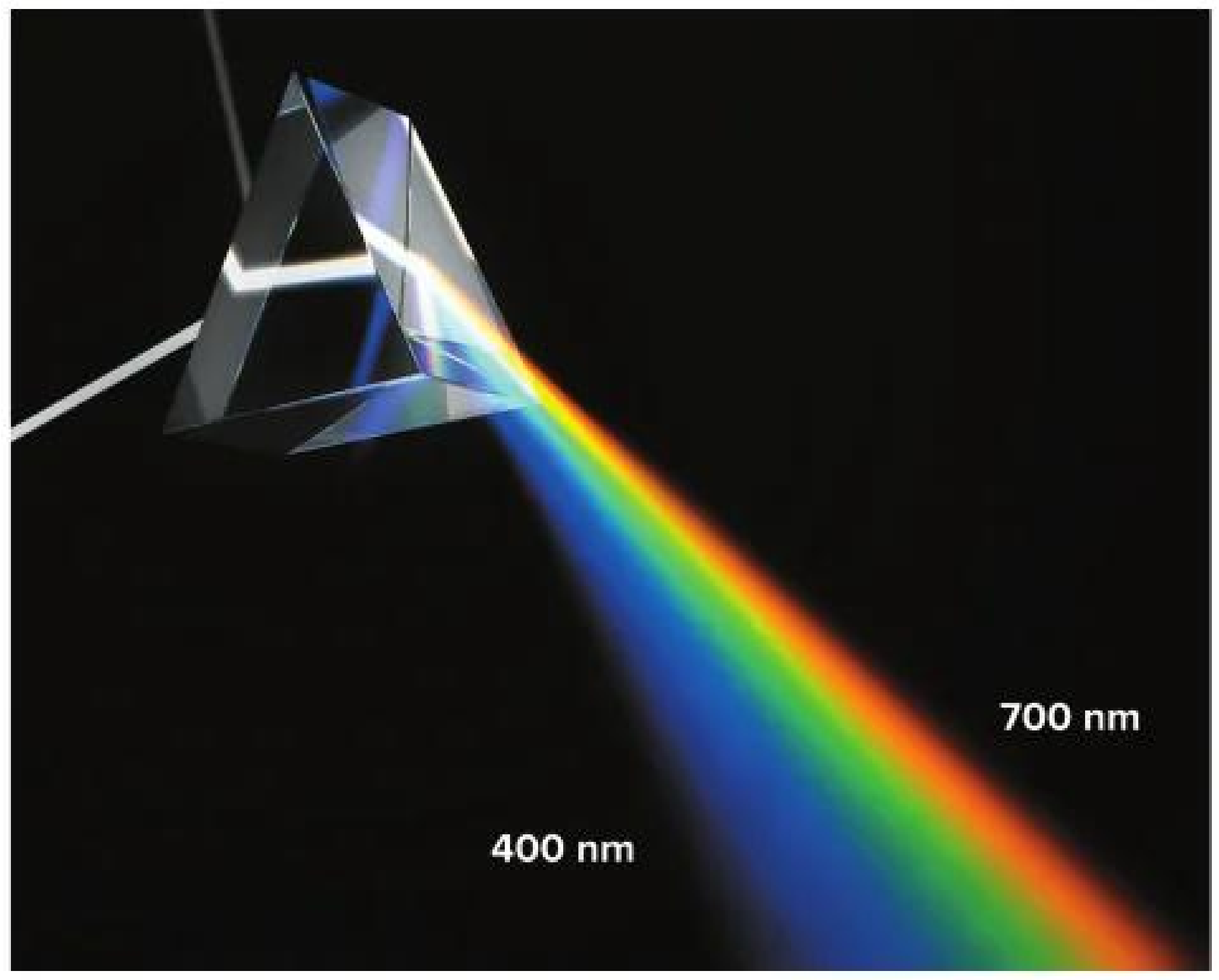


Figure 13 White light is separated into bands of color by a prism. Each color has a different wavelength.

Different wavelengths

Can the wave model of light explain Newton's observations? For light to be a wave, it must have wavelength and frequency. The work of Grimaldi, Huygens, Newton, and others suggested that the color of light is related to wavelength. Visible light falls within the range of wavelengths from about 400 nm (4.00×10^{-7} m) to 700 nm (7.00×10^{-7} m), as shown in **Figure 13.** The longest visible wavelengths are seen as red light and the shortest as violet.

As white light crosses the boundary from air into glass and back into air in **Figure 13,** its wave nature causes each different color of light to be bent at a different angle. The shorter the wavelength, the more the light is bent. This unequal bending of the different colors causes the white light to be spread into a spectrum.

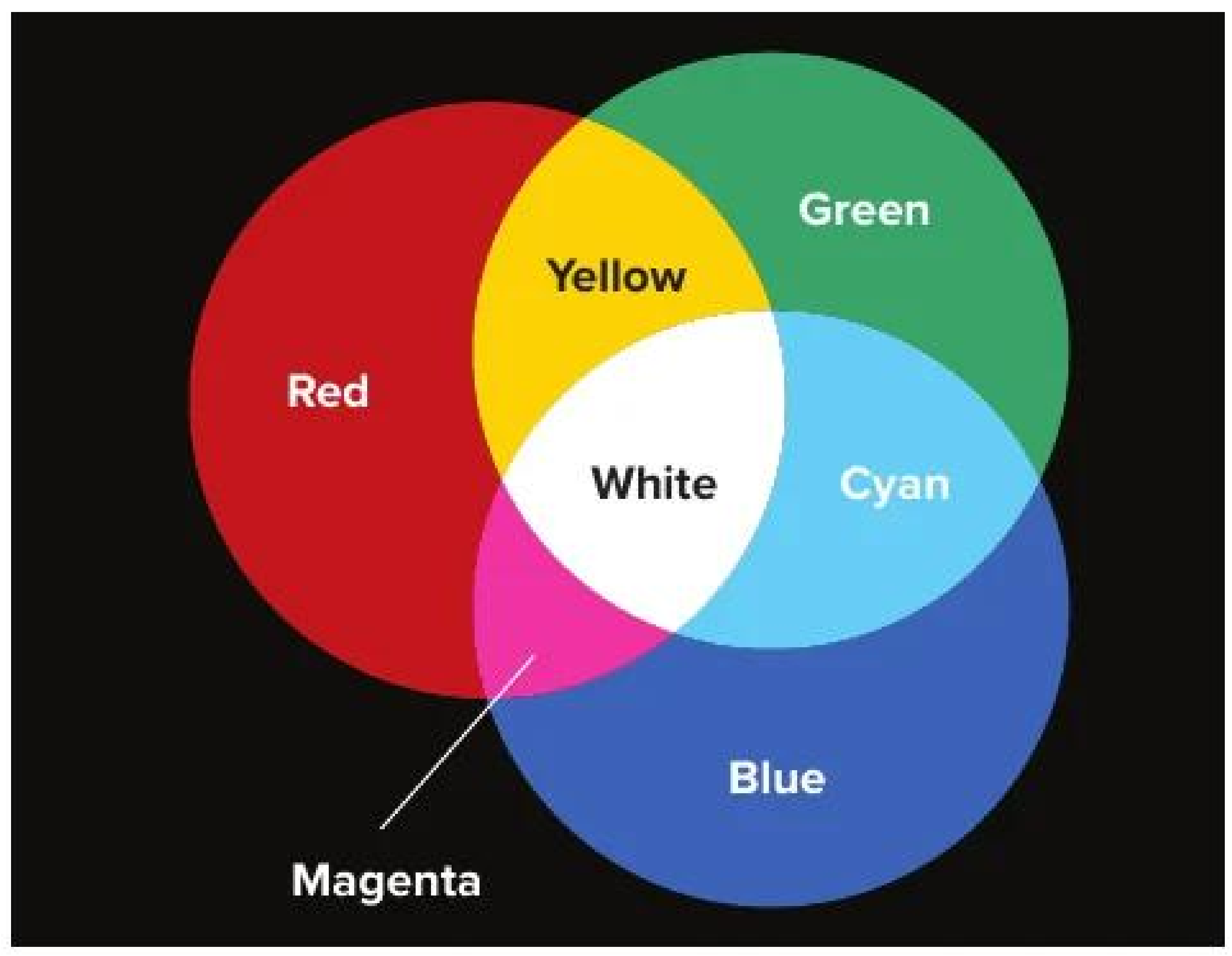


Figure 14 Red, green, and blue light, the primary colors, combine in pairs to produce yellow, cyan, or magenta light. The region where these three colors overlap on the screen appears white.

Color by addition of light

White light can be formed from colored light in a variety of ways. For example, when the correct intensities of red, green, and blue light are projected onto a white screen, as in **Figure 14,** white light is formed. This is called the additive color process, which is used in many television screens. A television screen uses three colors—red, green, and blue. Combinations of these produce the colors you see.

The correct intensities of red, green, and blue light appear on a screen as white light when combined. Because of this phenomenon, they are called the **primary colors** of light. The primary colors can be mixed in pairs to form three additional colors, as shown in **Figure 14.** Red and green light together produce yellow light, blue and green light produce cyan, and red and blue light produce magenta. The colors yellow, cyan, and magenta are called secondary colors. A **secondary color** is a combination of two primary colors. Note that these are slightly different from the primary and secondary colors you might have learned in art class; the reasons for this will be explained later in this module.

As shown in **Figure 14,** yellow light can be made from red light and green light. If yellow light and blue light are projected onto a white screen with the correct intensities, the surface will appear to be white. **Complementary colors** are two colors of light that can be combined to produce white light. Thus, yellow is a complementary color of blue, and vice versa, because the two colors of light combine to make white light. In the same way, cyan and red are complementary colors. Magenta and green are the other pair of complementary colors. A practical application of this is that yellowish laundry can be whitened with a bluing agent added to detergent.

Figure 15 The colors of objects we see are determined by which wavelengths of light are absorbed and which are reflected.

Explain *why the die that is yellow in the white light appears red in red light.*

Color by subtraction of light

As you learned in the first lesson of this module, objects can reflect and transmit light. They also can absorb light. The color of an object depends on the wavelengths present in the light that illuminates the object. The color also depends on which wavelengths are absorbed by the object and which wavelengths are reflected. The natural existence or artificial placement of dyes in the material of an object, or pigments on its surface, gives the object color.

Dyes You are probably familiar with dyes that are used to color cloth. Dyes can be made from plant or insect extracts. For example, purple dye can be extracted from the berries of a black mulberry tree. The saffron crocus is a source of yellow dye. One type of red dye is extracted from an insect called a cochineal. A dye is a molecule that absorbs certain wavelengths of light and transmits or reflects others. When light is absorbed, its energy is transferred to the object that it strikes and is transformed into other forms of energy. A red shirt is red because the dyes in it reflect mostly red light to our eyes. When white light falls on the red object shown in **Figure 15,** the dye molecules in the object absorb most of the blue and green light and reflect mostly red light. When only blue light falls on the red object, very little light is reflected and the object appears to be almost black.

Get It?

Distinguish the difference between color by subtraction and color by addition.

Pigments The difference between a dye and a pigment is that pigments usually are made of crushed minerals rather than plant or insect extracts. For example, hematite produces a red pigment, and blue pigment can be obtained from azurite. Pigment particles can be seen with a microscope. A pigment that absorbs only one primary color and reflects two from white light is called a **primary pigment.** Yellow pigment absorbs blue light and reflects red and green light. Yellow, cyan, and magenta are the colors of primary pigments.

A pigment that absorbs two primary colors and reflects one color is called a **secondary pigment.** The colors of secondary pigments are red (which absorbs green and blue light), green (which absorbs red and blue light), and blue (which absorbs red and green light). Note that the primary pigment colors are these secondary colors of light. In the same way, the secondary pigment colors are light's primary colors.

The primary and secondary pigments are shown in **Figure 16.** When the primary pigments yellow and cyan are mixed, the yellow absorbs blue light and the cyan absorbs red light. **Figure 16** shows yellow and cyan combining to make green pigment. When yellow pigment is mixed with the secondary pigment blue, which absorbs green and red light, all the primary colors are absorbed, and the result is black. Yellow and blue are complementary pigments. Cyan and red, as well as magenta and green, are also complementary pigments.

Figure 16 Magenta, cyan, and yellow are the primary pigments. Secondary pigments, red, green, and blue, are produced from mixing the primary pigments in pairs.

CHEMISTRY Connection A color printer uses yellow, magenta, and cyan dots of pigment to make a color image on paper. Often, pigments that are used are finely ground compounds, such as titanium(IV) oxide (white), chromium(III) oxide (green), and cadmium sulfide (yellow). Pigments mix to form suspensions rather than solutions. Their chemical form is not changed in a mixture, so they still absorb and reflect the same wavelengths.

BIOLOGY Connection You can now begin to understand the colors that you see in **Figure 17.** The plants on the mountain look green because of the chlorophyll in them. One type of chlorophyll absorbs mostly red light and the other absorbs mostly blue light, but they both reflect green light. The energy in the red and blue light that is absorbed is used by the plants during photosynthesis to make food.

Figure 17 Chlorophyll in green leaves reflects mostly green light, giving the leaves their color.

Explain *why the plants are various shades of green.*

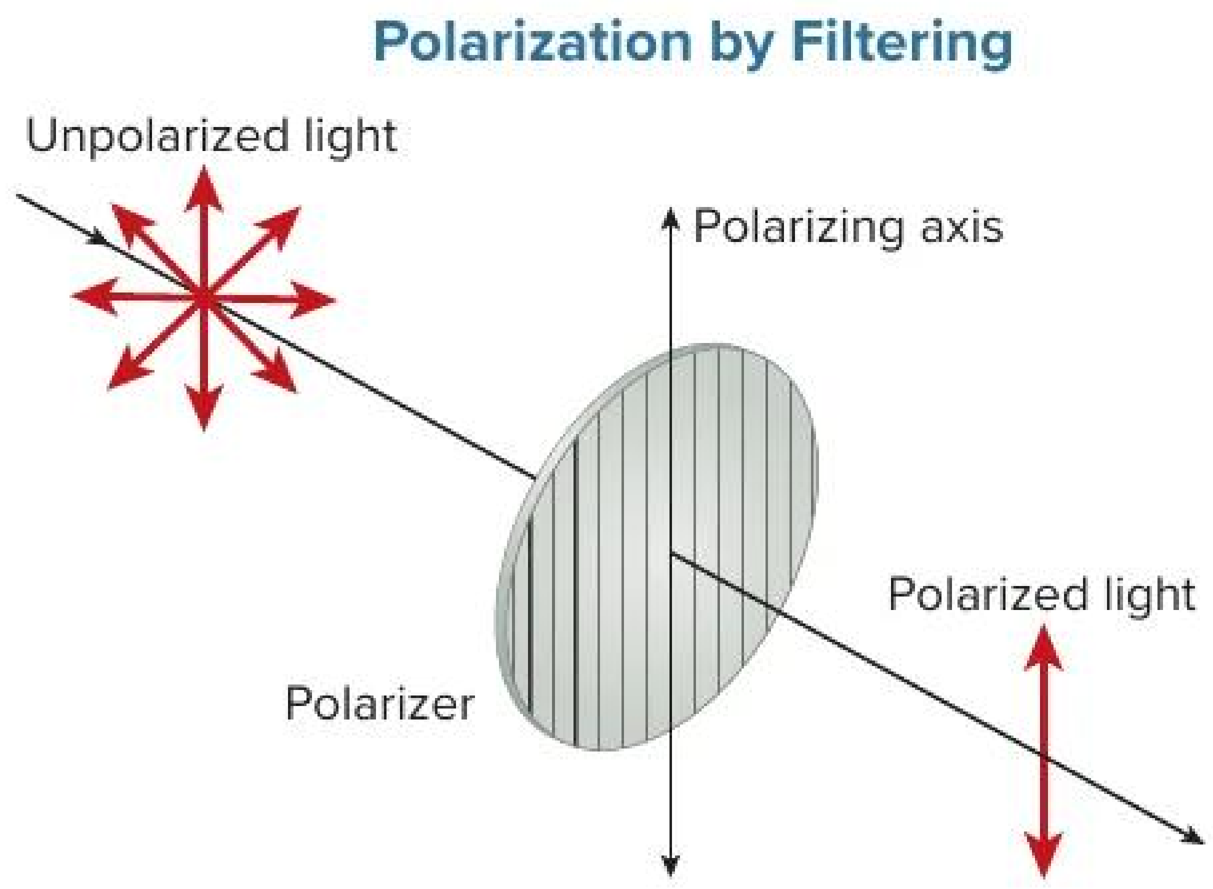


Figure 18 Nonpolarized light rays vibrate randomly in every direction perpendicular to the direction they travel. A polarizing medium blocks light that is not parallel to the polarizing axis.

Polarization of Light

Have you ever looked at light reflected off a road through polarizing sunglasses? If you rotate the glasses, the road first appears to be dark, then light, and then dark again. Light from a lamp, however, changes very little as the glasses are rotated. Why is there a difference? Normal lamp-light is not polarized. However, the light that is coming from the road is reflected and has become polarized. **Polarization** is the production of light with a specific pattern of oscillation.

Recall that light behaves as a transverse wave. For waves on a rope, the oscillating medium is the rope. For light waves, the oscillating medium is the electric field. When this electric field oscillates in random directions, the light is nonpolarized. How can you filter nonpolarized light so that whatever passes through the filter is polarized light?

Get It?
Draw a diagram, with text explanations, showing nonpolarized light.

Polarization by filtering The lines in the polarizer in **Figure 18** represent a polarizing axis. The light with the portion of the electric field that oscillates parallel to these lines passes through. The light with the portion of the electric field that oscillates perpendicular to these lines is absorbed. If a polarizer is placed in a beam of nonpolarized light, only the components of the waves in the same direction as the polarizing axis can pass through. As a result, half of the total light passes through, reducing the intensity of the light by half.

Get It?
Draw a second diagram, with text explanations, showing nonpolarized light passing through a filter as polarized light.

CHEMISTRY Connection Polarizing mediums contain long molecules in which electrons can oscillate, or move back and forth, all in the same direction. As light travels past the molecules, the electrons absorb light waves that oscillate in the same direction as the electrons. This allows light waves vibrating in one direction to pass, while the waves vibrating in the other direction are absorbed. The direction of a polarizing medium perpendicular to the long molecules is called the polarizing axis. Only waves oscillating parallel to that axis can pass through.

Polarization by reflection When you look through a polarizing filter at the light reflected by a sheet of glass and rotate the filter, you will see the light brighten and dim. The light is partially polarized parallel to the plane of the glass when it is reflected. Polarized reflected light causes glare. Polarizing sunglasses reduce glare from the polarized light reflected off roads. Photographers can use polarizing filters over camera lenses to block reflected light. This result is shown in **Figure 19.**

Malus's law Suppose you produce polarized light with a polarizing filter. What would happen if you place a second polarizing filter in the path of the polarized light? If the polarizing axis of the second filter is parallel to that of the first, the light will pass through. If the polarizing axis of the second filter is perpendicular to that of the first, no light will pass through, as shown in **Figure 20.**

If the light intensity after the first polarizing filter is I_1 and the intensity after the second filter is I_2, how can you control I_2? I_2 depends only on I_1 and the angle between the axes of the filters, θ. If θ is 0, I_2 equals I_1; if θ is 90°, all of the light is blocked, resulting in I_2 being 0. This indicates that the intensity might depend on the cosine of θ. The actual relationship is a that of a cosine squared. The law that explains the reduction of light intensity as light passes through a second polarizing filter is **Malus's law.**

Malus's Law

The intensity of light coming out of a second polarizing filter is equal to the intensity of polarized light coming out of a first polarizing filter multiplied by the cosine, squared, of the angle between the polarizing axes of the two filters.

$$I_2 = I_1 \cos^2 \theta$$

Without Polarizing Filter

With Polarizing Filter

Figure 19 Glare is light that has been polarized by reflection. Photographers use polarizing filters to reduce glare.

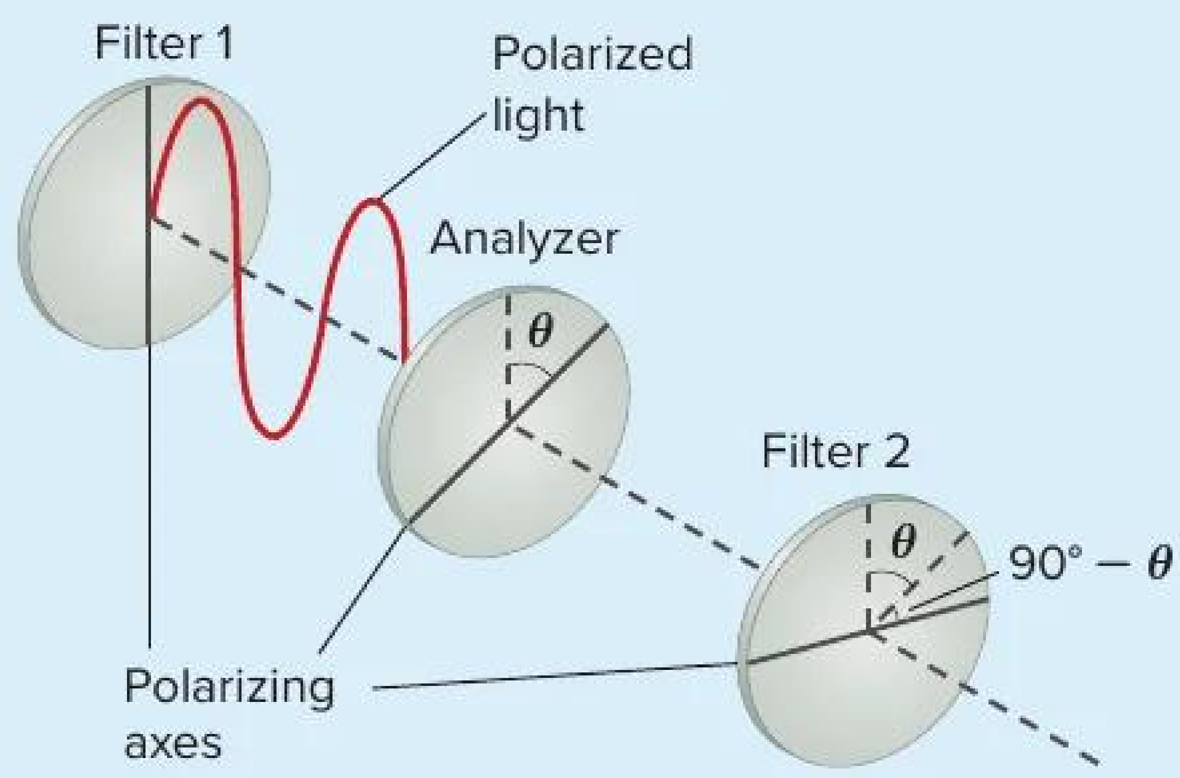
Axes Parallel | Axes at 45° | Axes Perpendicular

Figure 20 Polarizing filters with their axes parallel will allow the light with the same orientation to pass. With the polarizing axes at a 45° angle, the filters allow some light to pass. If the axes of the filters are perpendicular, the second filter will block the light that has passed through the first filter.

PHYSICS Challenge

You place an analyzer filter between the two cross-polarized filters, such that its polarizing axis is not parallel to either of the two filters, as shown in the figure to the right.

1. You observe that some light passes through filter 2, though no light passed through filter 2 before you inserted the analyzer filter. Why does this happen?
2. The analyzer filter is placed at an angle of θ relative to the polarizing axis of filter 1. Derive an equation for the intensity of light coming out of filter 2 compared to the intensity of light coming out of filter 1.



Speed, Wavelength, and Frequency of Light

As you have learned, the source of a wave determines that wave's frequency (f), and the medium and the frequency together determine the wavelength (λ) of a wave. Because light has wave properties, the same mathematical models used to describe waves in general can be used to describe light. For light of a given frequency traveling through a vacuum, wavelength is a function of the speed of light (c), which can be written as $\lambda_o = c/f$. The development of the laser in the 1960s provided new ways to measure the speed of light. The frequency of light can be measured with extreme precision using lasers and the time standard of atomic clocks. Measurements of wavelengths of light, however, are much less precise.

All colors of light travel at c in a vacuum, though the wavelengths are different. Since $\lambda_o = c/f$, once the frequency of a light wave in a vacuum is measured, the wavelength can be determined.

Relative motion and light What happens if a light source travels toward you or you move toward the source? You have learned that the frequency of a sound heard by a listener changes if either the source or the listener of the sound is moving. The same is true for light. However, when you consider the velocities of a sound source and the observer, you are really considering each one's velocity relative to the medium through which the sound travels. This is not the case for light.

Get It?
Explain how the wavelength, frequency, and speed of light are mathematically related.

The Doppler effect The nature of light waves is such that they are not vibrations of the particles of a medium. The Doppler effect for light can involve only the relative velocity between the source and the observer. Remember that the only factors in the Doppler effect are the velocity components along the axis between the source and the observer, as shown in **Figure 21** on the next page.

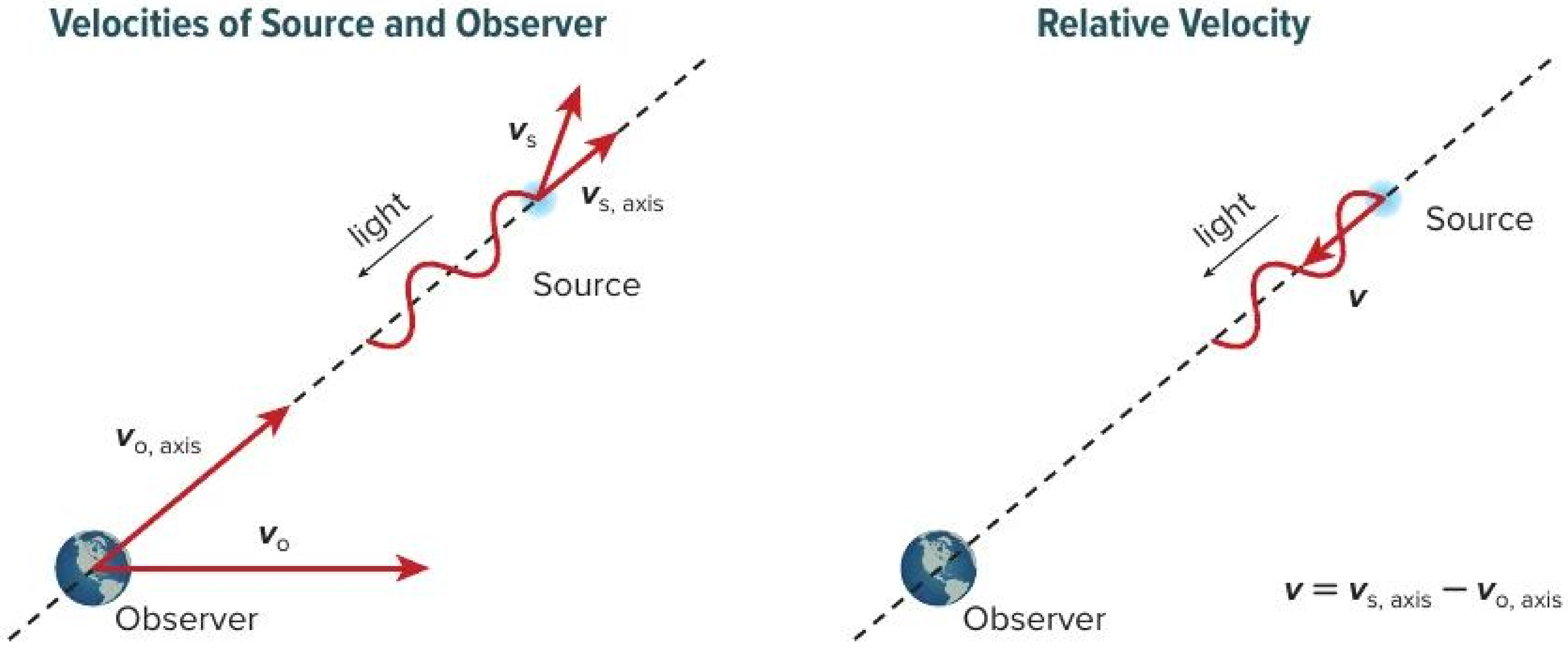


Figure 21 The Doppler effect describes how light frequency changes if an observer and a light source are moving toward or away from each other.

Doppler effect for light problems can be simplified by considering axial relative speeds that are much less than the speed of light ($v << c$). This simplification is used to develop the equation for the observed light frequency (f_{obs}), shown below.

Observed Light Frequency

The observed frequency of light from a source is equal to the actual frequency of the light generated by the source, times the quantity 1 plus the relative speed along the axis, divided by the speed of light, between the source and the observer if they are moving toward each other, or 1 minus the relative speed, divided by the speed of light, if they are moving away from each other.

$$F_{obs} = f\left(1 \pm \frac{v}{c}\right)$$

Applications Most applications of the Doppler effect for light are in astronomy, where phenomena are discussed more in terms of wavelength. Using the relationship $\lambda = c/f$ and the $v << c$ simplification, the following equation describes the Doppler shift ($\Delta\lambda$), the difference between the observed and the actual wavelengths.

Doppler Shift

The difference between the observed wavelength of light and the actual wavelength of light generated by a source is equal to the actual wavelength of light generated by the source, times the relative speed of the source and observer, divided by the speed of light.

$$(\lambda_{obs} - \lambda) = \Delta\lambda = \pm\left(\frac{v}{c}\right)\lambda$$

A positive change in wavelength occurs when the relative velocity of the source is away from the observer. In this case, the observed wavelength is longer than the original wavelength. The light appears closer to the red end of the spectrum than it normally would. We say this light is red shifted. A negative change in wavelength occurs when the relative velocity of the source is in a direction toward the observer. In this case, the observed wavelength is shorter than the original wavelength. This is known as a blue shift.

Because the speed of light is constant, when the wavelength is red shifted, the observed frequency is lower than the original due to the inverse relationship between the two variables. When light is blue shifted, the observed frequency is higher.

ASTRONOMY Connection Astronomers can determine how objects, such as galaxies, are moving relative to Earth by observing the Doppler shift of their light. This is done by observing the spectrum of light coming from stars in the galaxy using a spectrometer, as shown in **Figure 22.** The same elements that are present in the stars of galaxies emit light of specific wavelengths in labs on Earth. By comparing wavelength, astronomers can learn the velocities of objects toward or away from Earth.

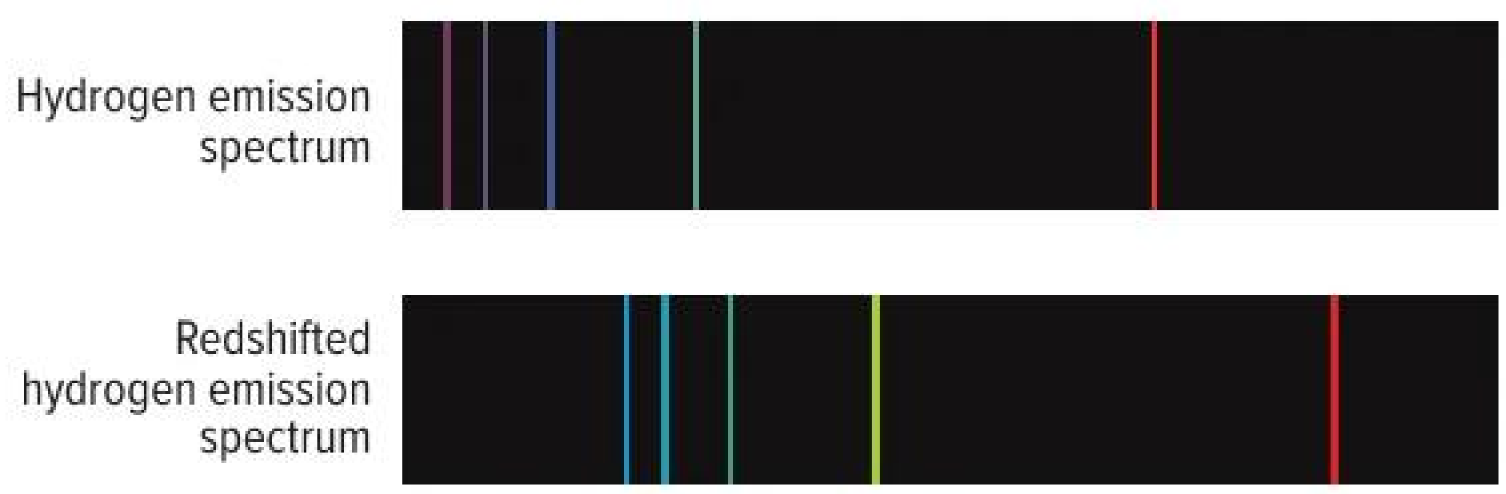


Figure 22 The bottom hydrogen emission spectrum is red shifted compared to the laboratory spectrum, indicating the light source is moving away from Earth.

PRACTICE Problems

ADDITIONAL PRACTICE

16. Oxygen can be made to produce light with a wavelength of 513 nm. What is the frequency of this light?

17. A hydrogen atom in a galaxy moving with a speed of 6.55×10^6 m/s away from Earth emits light with a frequency of 6.16×10^{14} Hz. What frequency of light from that hydrogen atom would be observed by an astronomer on Earth?

18. A hydrogen atom in a galaxy moving with a speed of 6.55×10^6 m/s away from Earth emits light with a wavelength of 486 nm. What wavelength would be observed on Earth from that hydrogen atom?

19. CHALLENGE An astronomer is looking at the spectrum of a galaxy and finds that it has an oxygen spectral line of 525 nm, while the laboratory value is measured at 513 nm. Calculate how fast the galaxy would be moving toward or away from Earth and how you know.

STEM CAREER Connection

Photographer

Do you like capturing important events with a camera? Photographers must use light to compose a perfect picture or to achieve a desired effect. Understanding the fundamentals of light is an important part of being a good photographer.

In 1929, Edwin Hubble analyzed the light from many galaxies like the one shown in **Figure 23.** He observed that the light produced by familiar elements were at longer wavelengths than he had expected them to be. The light was shifted toward the red end of the spectrum. No matter what area of the sky he observed, almost all the galaxies were sending red shifted light to Earth. What do you think caused the spectral lines to be red shifted?

Figure 23 Edwin Hubble observed that galaxies were sending red shifted light to Earth, indicating that they were moving away from Earth and the universe was expanding.

Hubble concluded that galaxies are moving away from Earth and suggested that the universe is expanding. Additional studies since then have supported this conclusion. As galaxies move, they sometimes collide and merge. The results of the collision depend on the size and speed of the galaxies.

You have learned that some characteristics of light can be explained with a simple ray model of light, whereas others require a wave model of light. You can use both of these models to study how light interacts with mirrors and lenses. There are some aspects of light that can be understood only through the use of the wave model of light.

Check Your Progress

20. **Doppler Effect** Describe the relative motions of objects when light is red shifted and when light is blue shifted. Answer using the term *Doppler effect.*
21. **Addition of Light Colors** What color of light must be combined with blue light to obtain white light?
22. **Light and Pigment Interaction** What color will a yellow banana appear to be when illuminated by each of the following?
    a. white light
    b. green and red light
    c. blue light
23. **Pigment Colors** What are the secondary pigment colors, and why do they give objects the appearance of those colors?
24. **Combination of Pigments** What primary pigment colors must be mixed to produce red? Explain your answer in terms of color subtraction for pigment colors.
25. **Polarization** Describe a simple experiment you could do to determine whether sunglasses in a store are polarizing.
26. **Polarizing Sunglasses** Use **Figure 24** to determine the direction the polarizing axis of polarizing sunglasses should be oriented to reduce glare from the surface of a road: vertically or horizontally? Explain.

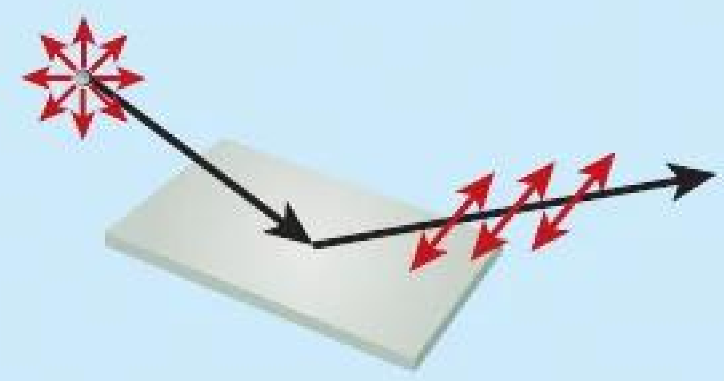


Figure 24

27. **Red Light** The speed of red light is slower in air and water than in a vacuum. The frequency, however, does not change when red light enters water. Does the wavelength change? If so, how?
28. **Critical Thinking** Astronomers have determined that our galaxy, the Milky Way, is moving toward Andromeda, a neighboring galaxy. Explain how they determined this. Can you think of a possible reason why the Milky Way is moving toward Andromeda?

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SCIENTIFIC BREAKTHROUGHS

Super-Efficient Solar Cells

Solar panels on homes and businesses are an increasingly popular alternative source of energy in today's society. This technology converts energy from the Sun into electricity people can use for the needs of everyday life. Solar energy is an inexhaustible source of clean energy. However, the current technology used to convert solar energy to electricity has limitations. Scientists working to optimize this technology have recently made a breakthrough that could greatly increase its efficiency.

Solar panels convert light waves into electricity.

What is a photovoltaic cell?

A solar panel is made up of many photovoltaic (PV) cells, which convert light waves into electrical current. Incoming light waves strike the semiconductor, usually silicon, and transfer energy to electrons. The electrons flow in one direction through the material, creating an electric current.

Limitations of Current Technology

Energy emitted by the Sun encompasses the entire electromagnetic spectrum. The silicon used in PV cells can absorb only a portion of these waves—from red to violet on the visible light spectrum. The remainder of the Sun's energy cannot be utilized by existing PV cells. As a result, PV cells are very inefficient. For example, most residential solar panels convert about 10 to 20 percent of the incoming energy to electricity, so solar panels need to be very large, especially in areas with cold and cloudy climates.

Hot Solar Cells

Scientists have developed a new solar thermo-photovoltaic (STPV) cell for converting solar energy to electricity. These STPV cells, called "hot solar cells," couple conventional PV cells with a light concentrator to utilize a greater percentage of the incoming energy from the Sun. The absorbing layer of carbon nanotubes turns energy from the Sun into thermal energy—with temperatures up to 1000°C! The emitting layer of nanophotonic crystals converts this thermal energy back into light that is specifically in the range of wavelengths that can be absorbed by the traditional PV cell. Initial results show that STPV cells create up to twice the amount of electrical energy compared to basic PV cells. This increased energy production can reduce the dependence on nonrenewable energy sources such as fossil fuels.

EVALUATE DESIGN SOLUTIONS

Using the Internet, gather information about the new STPV cell technology and evaluate this design solution. With a partner, discuss how the new technology might impact the cost, safety, reliability, or aesthetics of using solar energy to produce electricity. Summarize your discussion in a written paragraph.

MODULE 15
STUDY GUIDE

GO ONLINE to study with your Science Notebook.

Lesson 1 ILLUMINATION

- Light can be modeled as a ray that travels in a straight path until it encounters a boundary. Mediums can be characterized as being transparent, translucent, or opaque, depending on how light interacts with them.
- The luminous flux of a light source is the rate at which light is emitted. It is measured in lumens (lm). Illuminance is the luminous flux per unit area. Illuminance is measured in lux (lx), or lumens per square meter (lm/m^2). For a point source, illuminance follows an inverse-square relationship with distance and a direct relationship with luminous flux.

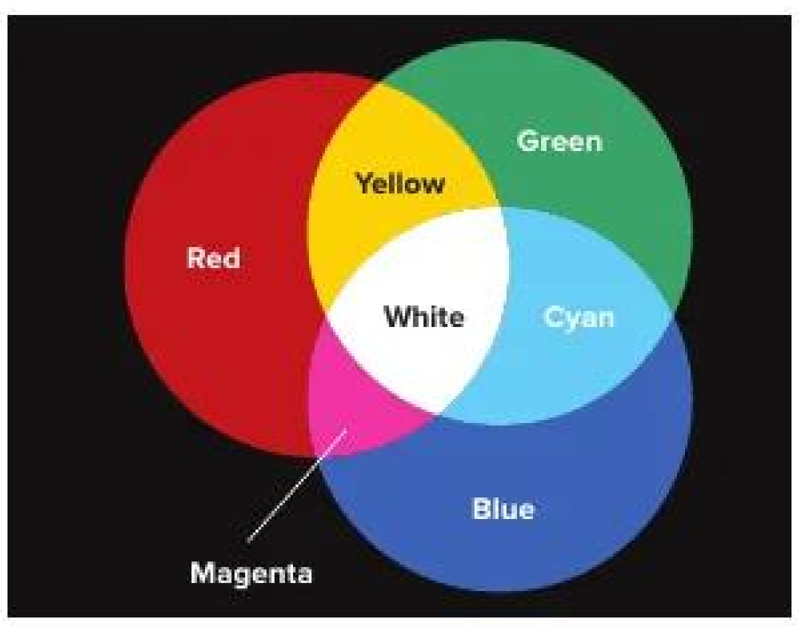
$$E = \frac{P}{4\pi r^2}$$

- Early measurements of the speed of light involved measurement of the time it takes for light to reach Earth from Jupiter's moon Io. Michelson used a land-based technique that involved the distance between two mountains and a set of rotating mirrors. In a vacuum, light has a constant speed of $c = 3.00\times10^8$ m/s.

- ray model of light
- luminous sources
- opaque
- translucent
- transparent
- luminous flux
- illuminance

Lesson 2 THE WAVE NATURE OF LIGHT

- In the wave model of light, all the points in a wavefront can be thought of as sources of smaller waves. As light travels past an edge, the wavefront is cut and each new wavelet generates a new circular wave.
- Visible light can have wavelengths between 400 and 700 nm. White light is a combination of the spectrum of colors, each color having a different wavelength. Combining the primary colors—red, blue, and green—forms white light. Combinations of two primary colors form the secondary colors, yellow, cyan, and magenta.



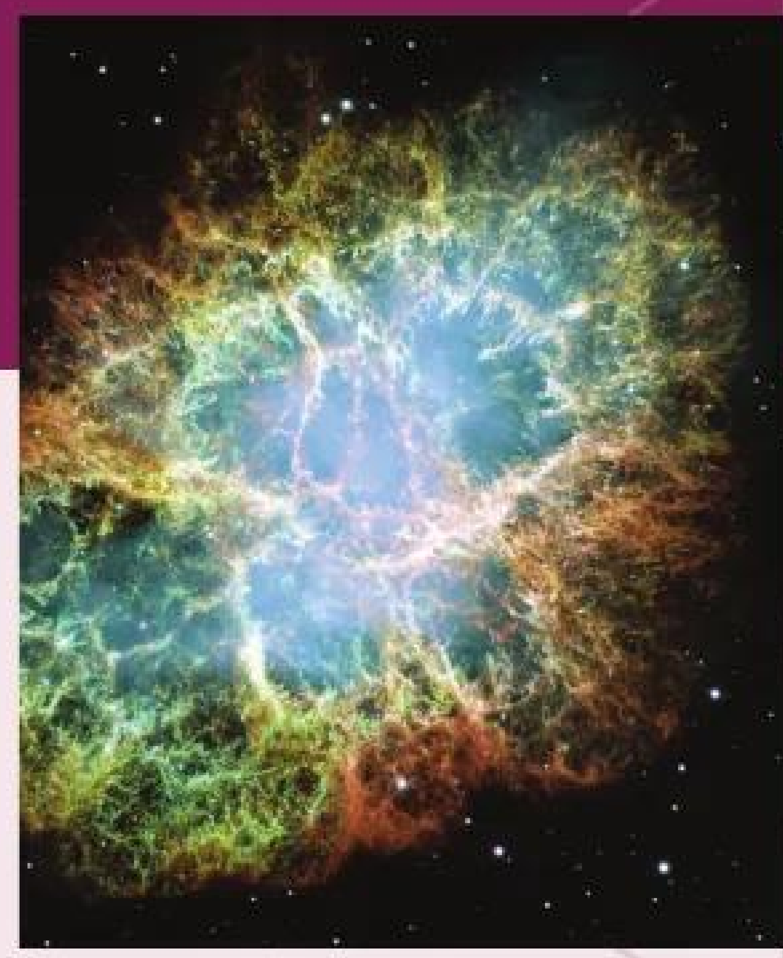
The primary pigments, cyan, magenta, and yellow, are used in combinations of two to produce the secondary pigments, red, blue, and green.

- Polarized light consists of waves whose electric fields oscillate with a specific pattern. Often, the oscillation is in a single plane. Light can be polarized with a polarizing filter or by reflection. Light waves traveling through a vacuum can be characterized in terms of frequency, wavelength, and the speed of light. Light waves are Doppler shifted based on the relative speed of the observer and light source along the axis of the observer and the light source.

- diffraction
- primary colors
- secondary color
- complementary colors
- primary pigment
- secondary pigment
- polarization
- Malus's law

THREE-DIMENSIONAL THINKING

Module Wrap-Up



REVISIT THE PHENOMENON

What does the light from a distant star or supernova tell us about it?

CER Claim, Evidence, Reasoning

Explain your Reasoning Revisit the claim you made when you encountered the phenomenon. Summarize the evidence you gathered from your investigations and research and finalize your Summary Table. Does your evidence support your claim? If not, revise your claim. Explain why your evidence supports your claim.

STEM UNIT PROJECT

Now that you've completed the module, revisit your STEM unit project. You will summarize your evidence and apply it to the project.

GO FURTHER

SEP Data Analysis Lab

Can a traffic light appear to change color?

Suppose you are a traffic officer and you stop a driver for going through a red light. Further suppose the driver draws you a picture and explains that the light looked green because of the Doppler effect when he drove through it. The wavelength for red light is 645 nm and it is 545 nm for a green light.

CER Analyze and Interpret Data

1. **Claim** Would you have given the driver a ticket for running the red light or accepted his explanation?
2. **Evidence and Reasoning** How would you explain your decision to the driver?

Credits

Student Notes