Interactive Student Edition

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Cover Images Each cover image features a major concept taught in physics. The runner and the colliding spheres represent motion. In addition, the spheres demonstrate the conservation of momentum. Fire represents thermodynamics—the study of thermal energy—and lightning, which is composed of negative electric charges, represents electricity and magnetism.

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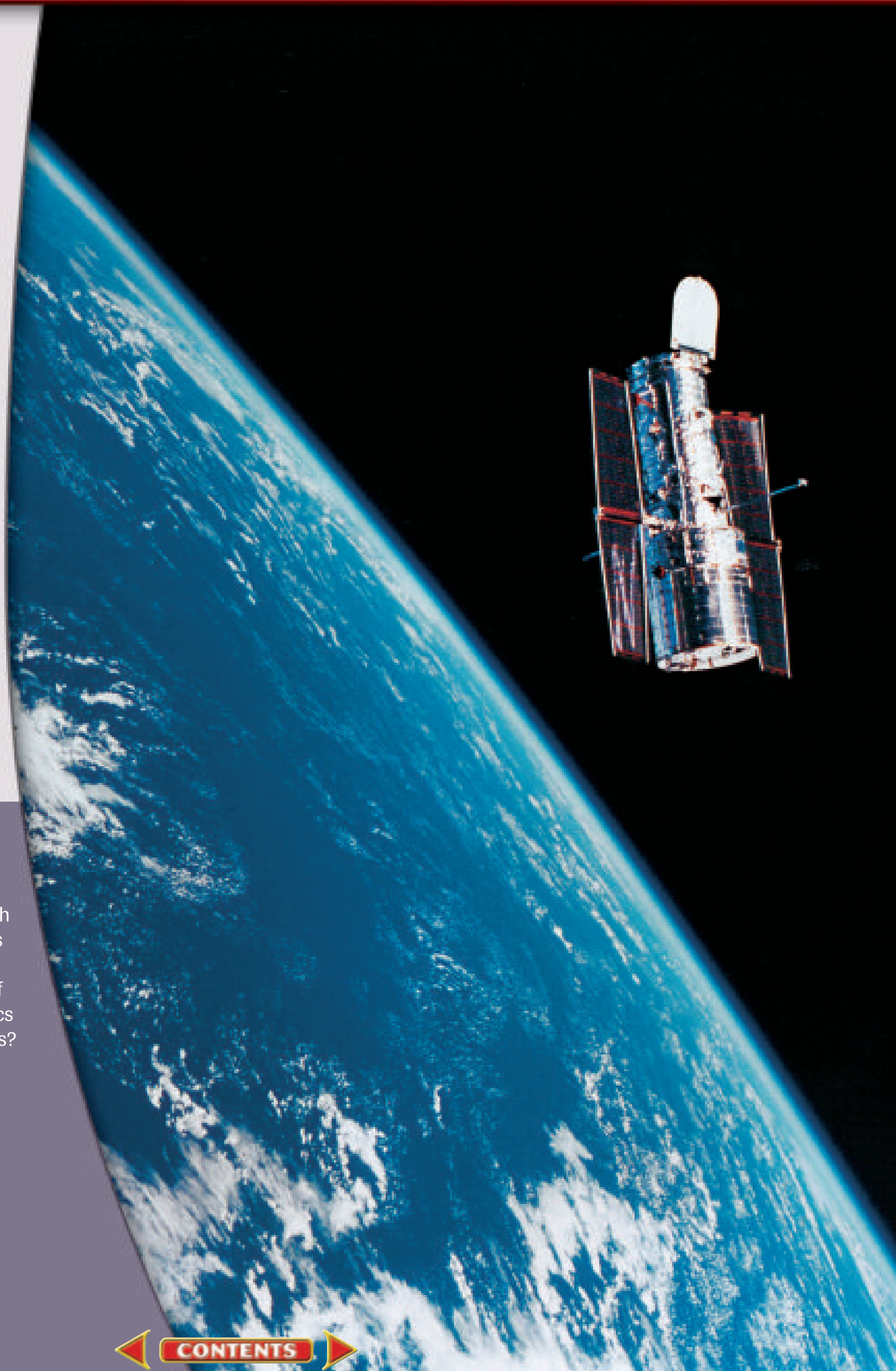
Chapter 1

A Physics Toolkit



What You'll Learn

- You will use mathematical tools to measure and predict.
- You will apply accuracy and precision when measuring.
- You will display and evaluate data graphically.

Why It's Important

The measurement and mathematics tools presented here will help you to analyze data and make predictions.

Satellites Accurate and precise measurements are important when constructing and launching a satellite—errors are not easy to correct later. Satellites, such as the *Hubble Space Telescope* shown here, have revolutionized scientific research, as well as communications.

Think About This ▶

Physics research has led to many new technologies, such as satellite-based telescopes and communications. What are some other examples of tools developed from physics research in the last 50 years?

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NASA

LAUNCH Lab

Do all objects fall at the same rate?

Question

How does weight affect the rate at which an object falls?

Procedure

The writings of the Greek philosopher Aristotle included works on physical science theories. These were a major influence in the late Middle Ages. Aristotle reasoned that weight is a factor governing the speed of fall of a dropped object, and that the rate of fall must increase in proportion to the weight of the object.

1. Tape four pennies together in a stack.
2. Place the stack of pennies on your hand and place a single penny beside them.
3. **Observe** Which is heaviest and pushes down on your hand the most?
4. **Observe** Drop the two at the same time and observe their motions.

Analysis

According to Aristotle, what should be the rate of fall of the single penny compared to the stack? What did you observe?

Critical Thinking Explain which of the following properties might affect the rate of fall of an object: size, mass, weight, color, shape.

1.1 Mathematics and Physics

Objectives

- **Demonstrate** scientific methods.
- **Use** the metric system.
- **Evaluate** answers using dimensional analysis.
- **Perform** arithmetic operations using scientific notation.

Vocabulary

physics
dimensional analysis
significant digits
scientific method
hypothesis
scientific law
scientific theory

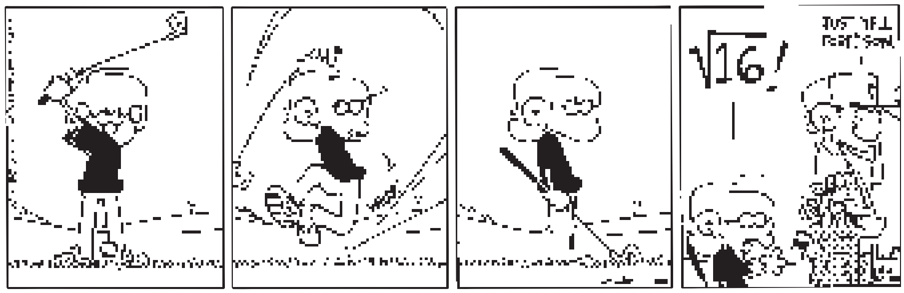
What do you think of when you see the word *physics?* Many people picture a chalkboard covered with formulas and mathematics: $E = mc^2$, $I = V/R$, $d = \frac{1}{2}at^2 + v_0t + d_0$. Perhaps you picture scientists in white lab coats, or well-known figures such as Marie Curie and Albert Einstein. Or, you might think of the many modern technologies created with physics, such as weather satellites, laptop computers, or lasers.

What is Physics?

Physics is a branch of science that involves the study of the physical world: energy, matter, and how they are related. Physicists investigate the motions of electrons and rockets, the energy in sound waves and electric circuits, the structure of the proton and of the universe. The goal of this course is to help you 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 astronomy, engineering, computer science, teaching, or medicine. Still others use the problem-solving skills of physics to work in business, finance, or other very different disciplines.

■ **Figure 1-1** Physicists use mathematics to represent many different phenomena—a trait sometimes spoofed in cartoons.



Mathematics in Physics

Physics uses mathematics as a powerful language. As illustrated in **Figure 1-1,** this use of mathematics often is spoofed in cartoons. In physics, equations are important tools for modeling observations and for making predictions. Physicists rely on theories and experiments with numerical results to support their conclusions. For example, think back to the Launch Lab. You can predict that if you drop a penny, it will fall. But how fast? Different models of falling objects give different answers to how the speed of the object changes, or on what the speed depends, or which objects will fall. 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.

▶ EXAMPLE Problem 1

Electric Current **The potential difference, or voltage, across a circuit equals the current multiplied by the resistance in the circuit. That is, V (volts) = I (amperes) × R (ohms). What is the resistance of a lightbulb that has a 0.75 amperes current when plugged into a 120-volt outlet?**

1 Analyze the Problem

- Rewrite the equation.
- Substitute values.

Known:	Unknown:
I = 0.75 amperes	R = ?
V = 120 volts	

2 Solve for the Unknown

Rewrite the equation so the unknown is alone on the left.

$$V = IR$$

$$IR = V \quad \text{Reflexive property of equality}$$

$$R = \frac{V}{I} \quad \text{Divide both sides by } I.$$

$$= \frac{120 \text{ volts}}{0.75 \text{ amperes}} \quad \text{Substitute 120 volts for } V\text{, 0.75 amperes for } I.$$

$$= 160 \text{ ohms} \quad \text{Resistance will be measured in ohms.}$$

Math Handbook
Isolating a Variable
page 845

3 Evaluate the Answer

- **Are the units correct?** 1 volt = 1 ampere-ohm, so the answer in volts/ampere is in ohms, as expected.
- **Does the answer make sense?** 120 is divided by a number a little less than 1, so the answer should be a little more than 120.

▶ PRACTICE Problems

Additional Problems, Appendix B

For each problem, give the rewritten equation you would use and the answer.

1. A lightbulb with a resistance of 50.0 ohms is used in a circuit with a 9.0-volt battery. What is the current through the bulb?
2. An object with uniform acceleration a, starting from rest, will reach a speed of v in time t according to the formula $v = at$. What is the acceleration of a bicyclist who accelerates from rest to 7 m/s in 4 s?
3. How long will it take a scooter accelerating at 0.400 m/s^2 to go from rest to a speed of 4.00 m/s?
4. The pressure on a surface is equal to the force divided by the area: $P = F/A$. A 53-kg woman exerts a force (weight) of 520 Newtons. If the pressure exerted on the floor is 32,500 N/m^2, what is the area of the soles of her shoes?

Does it make sense? Sometimes you will work with unfamiliar units, as in Example Problem 1, and you will need to use estimation to check that your answer makes sense mathematically. At other times you can check that an answer matches your experience, as shown in **Figure 1-2.** When you work with falling objects, for example, check that the time you calculate an object will take to fall matches your experience—a copper ball dropping 5 m in 0.002 s, or in 17 s, doesn't make sense.

The Math Handbook in the back of this book contains many useful explanations and examples. Refer to it as needed.

■ **Figure 1-2** What is a reasonable range of values for the speed of an automobile?

SI Units

To communicate results, it is helpful to use units that everyone understands. The worldwide scientific community and most countries currently use an adaptation of the metric system to state measurements. The Système International d'Unités, or SI, uses seven base quantities, which are shown in **Table 1-1.** These base quantities were originally defined in terms of direct measurements. Other units, called derived units, are created by combining the base units in various ways. For example, energy is measured in joules, where 1 joule equals one kilogram-meter squared per second squared, or 1 J = 1 kg·m^2/s^2. Electric charge is measured in coulombs, where 1 C = 1 A·s.

Table 1-1
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

■ **Figure 1-3** The standards for the kilogram and meter are shown. The International Prototype Meter originally was measured as the distance between two marks on a platinum-iridium bar, but as methods of measuring time became more precise than those for measuring length, the meter came to be defined as the distance traveled by light in a vacuum in 1/299 792 458 s.

Scientific institutions have been created to define and regulate measures. The SI system is regulated by the International Bureau of Weights and Measures in Sèvres, France. This bureau and the National Institute of Science and Technology (NIST) in Gaithersburg, Maryland keep the standards of length, time, and mass against which our metersticks, clocks, and balances are calibrated. Examples of two standards are shown in **Figure 1-3.** NIST works on many problems of measurement, including industrial and research applications.

You probably learned in math class that it is much easier to convert meters to kilometers than feet to miles. The ease of switching between units is another feature of the metric system. To convert between SI units, multiply or divide by the appropriate power of 10. Prefixes are used to change SI units by powers of 10, as shown in **Table 1-2.** You often will encounter these prefixes in daily life, as in, for example, milligrams, nanoseconds, and gigabytes.

Table 1-2
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)

Dimensional Analysis

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Dimensional Analysis
page 847

You can use units to check your work. You often will need to use different versions of a formula, or use a string of formulas, to solve a physics problem. To check that you have set up a problem correctly, write out the equation or set of equations you plan to use. Before performing calculations, check that the answer will be in the expected units, as shown in step 3 of Example Problem 1. For example, if you are finding a speed and you see that your answer will be measured in s/m or m/s^2, you know you have made an error in setting up the problem. This method of treating the units as algebraic quantities, which can be cancelled, is called **dimensional analysis.**

Dimensional analysis also is used in choosing conversion factors. A conversion factor is a multiplier equal to 1. For example, because 1 kg = 1000 g, you can construct the following conversion factors:

$$1 = \frac{1\ \text{kg}}{1000\ \text{g}} \qquad 1 = \frac{1000\ \text{g}}{1\ \text{kg}}$$

National Institute of Standards and Technology

Choose a conversion factor that will make the units cancel, leaving the answer in the correct units. For example, to convert 1.34 kg of iron ore to grams, do 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:

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

PRACTICE Problems **Additional Problems, Appendix B**

Use dimensional analysis to check your equation before multiplying.

5. How many megahertz is 750 kilohertz?

6. Convert 5021 centimeters to kilometers.

7. How many seconds are in a leap year?

8. Convert the speed 5.30 m/s to km/h.

Significant Digits

Suppose you use a meterstick to measure a pen, and you find that the end of the pen is just past 14.3 cm. This measurement has three valid digits: two you are sure of, and one you estimated. The valid digits in a measurement are called **significant digits.** 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 digits. This ambiguity is one reason to use scientific notation: it is clear that the measurement 1.7200×10^5 m has five significant digits.

Math Handbook
Significant Digits
pages 833–836

Arithmetic with significant digits When you perform any arithmetic operation, it is important to remember that the result never can be more precise than the least-precise measurement.

To add or subtract measurements, first perform 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 because the least-precise measure is to one-tenth of a meter.

To multiply or divide measurements, perform the calculation and then round to the same number of significant digits as the least-precise measurement. For example, 409.2 km/11.4 L = 35.9 km/L, because the least-precise measure has three significant digits.

Some calculators display several additional digits, as shown in **Figure 1-4,** while others round at different points. Be sure to record your answers with the correct number of digits. Note that significant digits are considered only when calculating with measurements. There is no uncertainty associated with counting (4 washers) or exact conversion factors (24 hours in 1 day).

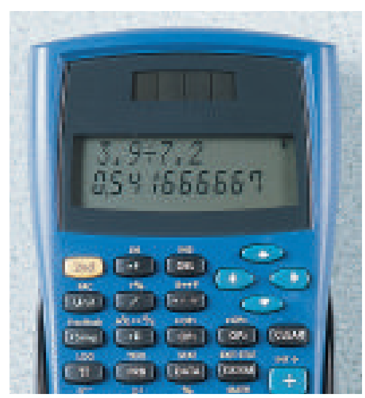


Figure 1-4 This answer to 3.9 ÷ 7.2 should be rounded to two significant digits.

Horizons Companies

PRACTICE Problems

Additional Problems, Appendix B

Solve the following problems.

9. a. 6.201 cm + 7.4 cm + 0.68 cm + 12.0 cm

b. 1.6 km + 1.62 m + 1200 cm

10. a. 10.8 g − 8.264 g

b. 4.75 m − 0.4168 m

11. a. 139 cm × 2.3 cm

b. 3.2145 km × 4.23 km

12. a. 13.78 g ÷ 11.3 mL

b. 18.21 g ÷ 4.4 cm^3

MINI LAB

Measuring Change

Collect five identical washers and a spring that will stretch measurably when one washer is suspended from it.

1. Measure the length of the spring with zero, one, two, and three washers suspended from it.

2. Graph the length of the spring versus the mass.

3. Predict the length of the spring with four and five washers.

4. Test your prediction.

Analyze and Conclude

5. Describe the shape of the graph. How did you use it to predict the two new lengths?

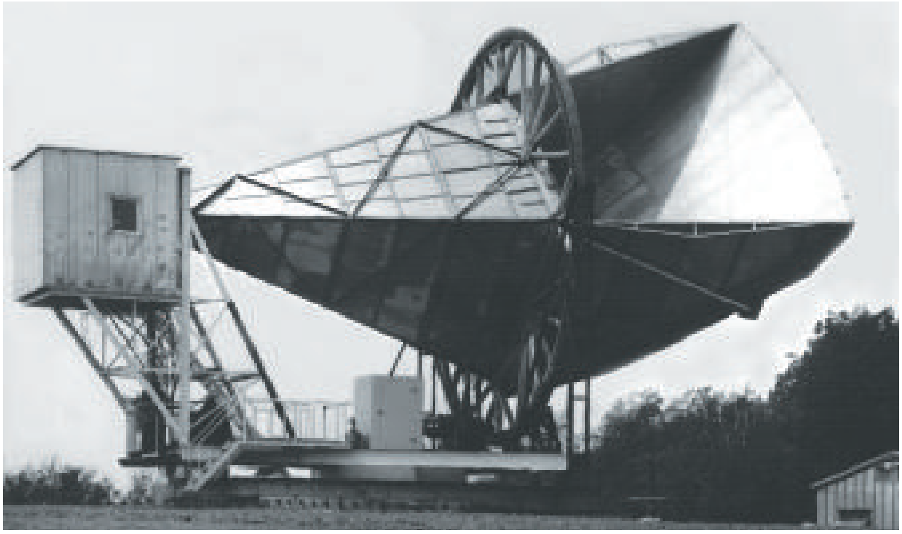
Scientific Methods

In physics class, you will make observations, do experiments, and create models or theories to try to explain your results or predict new answers, as shown in **Figure 1-5.** This is the essence of a **scientific method.** All scientists, including physicists, obtain data, make predictions, and create compelling explanations that quantitatively describe many different phenomena. The experiments and results must be reproducible; that is, other scientists must be able to recreate the experiment and obtain similar data. Written, oral, and mathematical communication skills are vital to every scientist.

A scientist often works with an idea that can be worded as a **hypothesis,** which is an educated guess about how variables are related. How can the hypothesis be tested? Scientists conduct experiments, take measurements, and identify what variables are important and how they are related. For example, you might find that the speed of sound depends on the medium through which sound travels, but not on the loudness of the sound. You can then predict the speed of sound in a new medium and test your results.

■ **Figure 1-5** These students are conducting an experiment to determine how much power they produce climbing the stairs **(a).** They use their data to predict how long it would take an engine with the same power to lift a different load **(b).**

Laura Sifferlin



■ **Figure 1-6** In the mid-1960s, Arno Penzias and Robert Wilson were trying to eliminate the constant background noise in an antenna to be used for radio astronomy. They tested systems, duct-taped seams, and cleared out pigeon manure, but the noise persisted. This noise is now understood to be the cosmic microwave background radiation, and is experimental support for the Big Bang theory.

Models, laws, and theories An idea, equation, structure, or system can model the phenomenon you are trying to explain. Scientific models are based on experimentation. Recall from chemistry class the different models of the atom that were in use over time—new models were developed to explain new observations and measurements.

If new data do not fit a model, both are re-examined. **Figure 1-6** shows a historical example. If a very well-established model is questioned, physicists might first look at the new data: can anyone reproduce the results? Were there other variables at work? If the new data are born out by subsequent experiments, the theories have to change to reflect the new findings. For example, in the nineteenth century it was believed that linear markings on Mars showed channels, as shown in **Figure 1-7a.** As telescopes improved, scientists realized that there were no such markings, as shown in **Figure 1-7b.** In recent times, again with better instruments, scientists have found features that suggest Mars once had running and standing water on its surface, as shown in **Figure 1-7c.** Each new discovery has raised new questions and areas for exploration.

A **scientific law** is a rule of nature that sums up related observations to describe a pattern in nature. For example, the law of conservation of charge states that in the various changes matter can undergo, the electric charge before and after stays the same. The law of reflection states that the angle of incidence for a light beam on a reflective surface equals the angle of reflection. Notice that the laws do not explain why these phenomena happen, they simply describe them.

■ **Figure 1-7** Drawings of early telescope observations **(a)** showed channels on Mars; recent photos taken with improved telescopes do not **(b).** In this photo of Mars' surface from the *Mars Global Surveyor* spacecraft **(c),** these layered sedimentary rocks suggest that sedimentary deposits might have formed in standing water.

(t)Tom Pantages, (bc)NASA, (others)Photo Researchers

Figure 1-8 Theories are changed and modified as new experiments provide insight and new observations are made. The theory of falling objects has undergone many revisions.

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 it falls, not on its mass.

↓ **Revision**

Galileo's statement is true, but Newton revised the reason 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**

Galileo's and Newton's statements still hold true. However, Einstein suggested that the force of attraction between two objects is due to mass causing the space around it to curve.

A **scientific theory** is an explanation based on many observations supported by experimental results. Theories may serve as explanations for laws. A theory is the best available explanation of why things work as they do. For example, the theory of universal gravitation states that all the mass in the universe is attracted to other mass. Laws and theories may be revised or discarded over time, as shown in **Figure 1-8.** Notice that this use of the word *theory* is different from the common use, as in "I have a theory about why it takes longer to get to school on Fridays." In scientific use, only a very well-supported explanation is called a theory.

1.1 Section Review

13. Math Why are concepts in physics described with formulas?

14. Magnetism The force of a magnetic field on a charged, moving particle is given by $F = Bqv$, where F is the force in kg·m/s^2, q is the charge in A·s, and v is the speed in m/s. B is the strength of the magnetic field, measured in teslas, T. What is 1 tesla described in base units?

15. Magnetism A proton with charge 1.60×10^{-19} A·s is moving at 2.4×10^{5} m/s through a magnetic field of 4.5 T. You want to find the force on the proton.

a. Substitute the values into the equation you will use. Are the units correct?

b. The values are written in scientific notation, $m\times10^{n}$. Calculate the 10^{n} part of the equation to estimate the size of the answer.

c. Calculate your answer. Check it against your estimate from part b.

d. Justify the number of significant digits in your answer.

16. Magnetism Rewrite $F = Bqv$ to find v in terms of F, q, and B.

17. Critical Thinking An accepted value for the acceleration due to gravity is 9.801 m/s^2. In an experiment with pendulums, you calculate that the value is 9.4 m/s^2. Should the accepted value be tossed out to accommodate your new finding? Explain.

Physics Online physicspp.com/self_check_quiz

CONTENTS

1.2 Measurement

When you visit the doctor for a checkup, many measurements are taken: your height, weight, blood pressure, and heart rate. Even your vision is measured and assigned a number. Blood might be drawn so measurements can be made of lead or cholesterol levels. Measurements quantify our observations: a person's blood pressure isn't just "pretty good," it's 110/60, the low end of the good range.

What is a 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. In the Mini Lab in Section 1.1, the length of the spring was the unknown and the centimeter was the standard.

▶ **Objectives**

- **Distinguish** between accuracy and precision.
- **Determine** the precision of measured quantities.

▶ **Vocabulary**

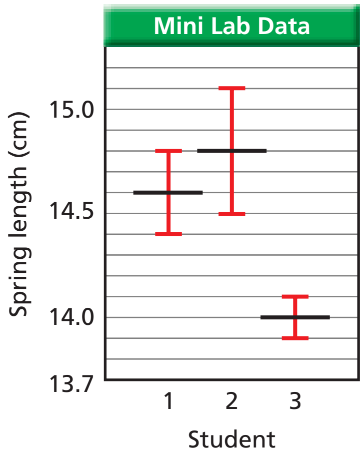
measurement
precision
accuracy

Comparing Results

As you learned in Section 1.1, scientists share their results. Before new data are fully accepted, other scientists examine the experiment, looking 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 confirms the old measurement.

For example, archaeologists use radiocarbon dating to find the age of cave paintings, such as those from the Lascaux cave, in **Figure 1-9,** and the Chauvet cave. Radiocarbon dates are reported with an uncertainty. Three radiocarbon ages from a panel in the Chauvet cave are 30,940 $\pm$ 610 years, 30,790 $\pm$ 600 years, and 30,230 $\pm$ 530 years. While none of the measurements exactly match, the uncertainties in all three overlap, and the measurements confirm each other.

■ **Figure 1-9** Drawings of animals from the Lascaux cave in France. By dating organic material in the cave, such as pigments and torch marks, scientists are able to suggest dates at which these cave paintings were made. Each date is reported with an uncertainty to show how precise the measurement is.



■ **Figure 1-10** Three students took multiple measurements. Are the measurements in agreement? Is student 1's result reproducible?

Suppose three students performed the Mini Lab from Section 1.1 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 1-10.** 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.

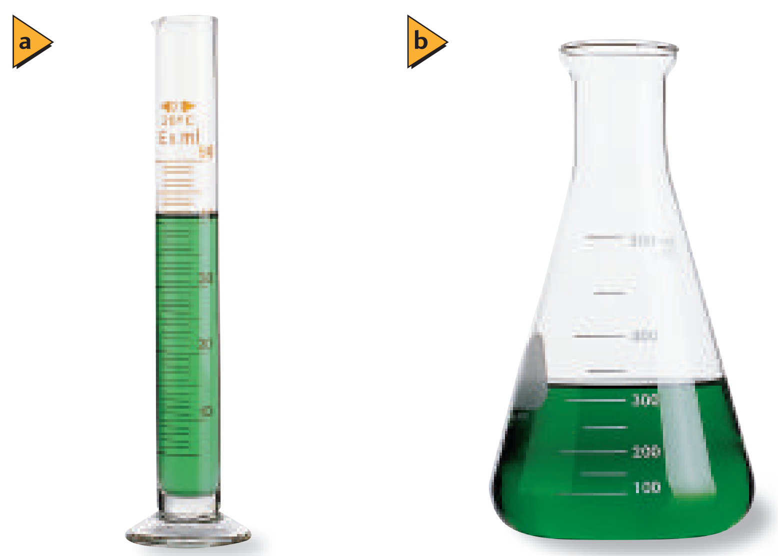
Could you conclude that the three measurements are in agreement? Is student 1's result reproducible? The results of students 1 and 2 overlap; that is, they have the lengths 14.5 cm to 14.8 cm in common. However, there is no overlap and, therefore, no agreement, between their results and the result of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

Precision Versus Accuracy

Both precision and accuracy are characteristics of measured values. How precise and accurate are the measurements of the three students? The degree of exactness of a measurement is called its **precision.** Student 3's measurements are the most precise, within ± 0.1 cm. The measurements of the other two students are less precise because they have a larger uncertainty.

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, the graduated cylinder in **Figure 1-11a** has divisions of 1 mL. You can measure an object to within 0.5 mL with this device. However, the smallest division on the beaker in **Figure 1-11b** is 50 mL. How precise were your measurements in the MiniLab?

The significant digits in an answer show its precision. A measure of 67.100 g is precise to the nearest thousandth of a gram. Recall from Section 1.1 the rules for performing operations with measurements given to different levels of precision. If 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 100 times that.



■ **Figure 1-11** The graduated cylinder contains 41 ± 0.5 mL **(a).** The flask contains 325 mL ± 25 mL **(b)**.

Horizons Companies

Accuracy describes how well the results of a measurement agree with the "real" value; that is, the accepted value as measured by competent experimenters. If the length of the spring that the three students measured had been 14.8 cm, then student 2 would have been most accurate and student 3 least accurate. How accurate do you think your measurements in the Mini Lab on page 8 were? 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? Second, does it give the correct reading when it is measuring an accepted standard, as shown in **Figure 1-12?** Regular checks for accuracy are performed on critical measuring instruments, such as the radiation output of the machines used to treat cancer.

Figure 1-12 Accuracy is checked by measuring a known value.

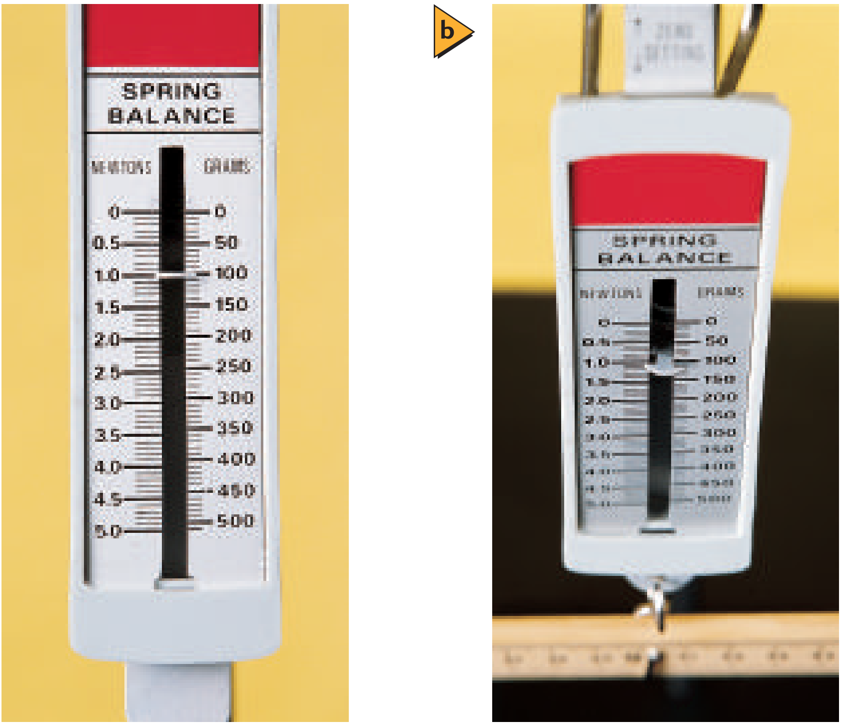
Techniques of Good Measurement

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 above the measure, as shown in **Figure 1-13a.** If the scale is read from an angle, as shown in **Figure 1-13b,** you will get a different, and less accurate, value. 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 1-13 By positioning the scale head on **(a),** your results will be more accurate than if you read your measurements at an angle **(b).** How far did parallax shift the measurement in b?

a

b



APPLYING PHYSICS

Distance to the Moon For over 25 years, scientists have been accurately measuring the distance to the Moon by shining lasers through telescopes. The laser beam reflects off reflectors placed on the surface of the Moon by Apollo astronauts. They have determined that the average distance between the centers of Earth and the Moon is 385,000 km, and it is known with an accuracy of better than one part in 10 billion. Using this laser technique, scientists also have discovered that the Moon is receding from Earth at about 3.8 cm/yr.

■ **Figure 1-14** A series of expeditions succeeded in placing a GPS receiver on top of Mount Everest. This improved the accuracy of the altitude measurement: Everest's peak is 8850 m, not 8848 m, above sea level.

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 numerous 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, as in **Figure 1-14,** can measure movements of millimeters in Earth's crust.

The GPS was developed by the United States Department of Defense. It uses atomic clocks, 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.

1.2 Section Review

18. 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?

19. Tools You find a micrometer (a tool used to measure objects to the nearest 0.01 mm) that has been badly bent. How would it compare to a new, high-quality meterstick in terms of its precision? Its accuracy?

20. Parallax Does parallax affect the precision of a measurement that you make? Explain.

21. Error Your friend tells you that his height is 182 cm. In your own words, explain the range of heights implied by this statement.

22. Precision A box has a length of 18.1 cm and a width of 19.2 cm, and it is 20.3 cm tall.

a. What is its volume?

b. How precise is the measure of length? Of volume?

c. How tall is a stack of 12 of these boxes?

d. How precise is the measure of the height of one box? of 12 boxes?

23. Critical Thinking Your friend states in a report that the average time required to circle a 1.5-mi 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.

Physics Online physicspp.com/self_check_quiz

1.3 Graphing Data

A well-designed graph can convey information quickly and simply. Patterns that are not immediately evident in a list of numbers take shape when the data are graphed. In this section, you will develop graphing techniques that will enable you to display, analyze, and model data.

▶ **Objectives**

- **Graph** the relationship between independent and dependent variables.
- **Interpret** graphs.
- **Recognize** common relationships in graphs.

▶ **Vocabulary**

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

Identifying Variables

When you perform an experiment, it is important to change only one factor at a time. For example, **Table 1-3** gives the length of a spring with different masses attached, as measured in the Mini Lab. 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 to the different springs.

Table 1-3

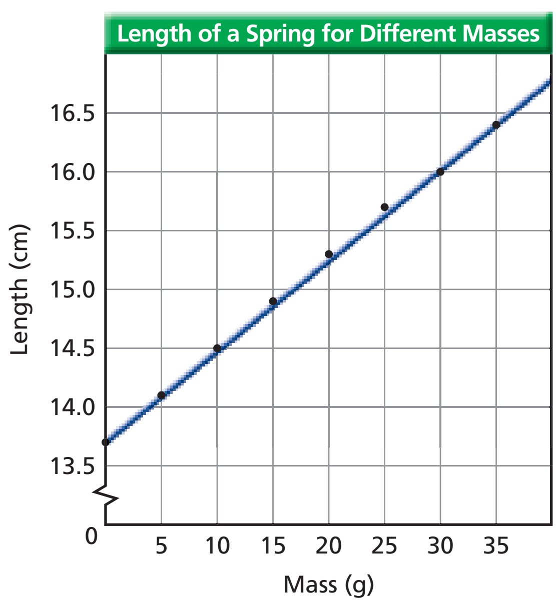
Length of a Spring for Different Masses

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

A *variable* is any factor that might affect the behavior of an experimental setup. The **independent variable** is the factor that is changed or manipulated during the experiment. In this experiment, the mass was the independent variable. The **dependent variable** is the factor that depends on the independent variable. In this experiment, the amount that the spring stretched depended on the mass. An experiment might look at how radioactivity varies with time, how friction changes with weight, or how the strength of a magnetic field depends on the distance from a magnet.

One way to analyze data is to make a line graph. This shows how the dependent variable changes with the independent variable. The data from Table 1-3 are graphed in black in **Figure 1-15.** 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 that helps determine the line. The problem-solving strategy on the next page gives detailed instructions for graphing data and sketching a line of best fit.

■ **Figure 1-15** The independent variable, mass, is on the horizontal axis. The graph shows that the length of the spring increases as the mass suspended from the spring increases.



PROBLEM-SOLVING **Strategies**

Plotting Line Graphs

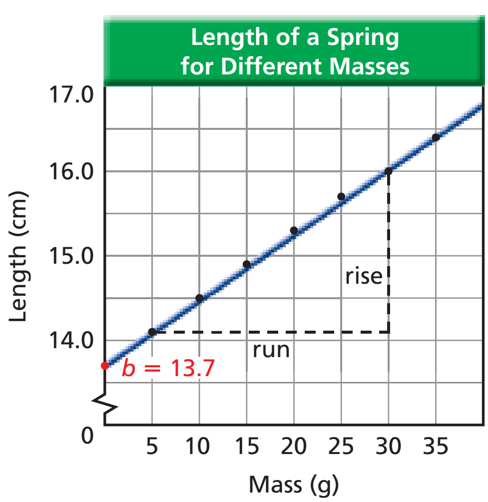
Connecting **Math to Physics**

Use the following steps to plot line graphs from data tables.

1. Identify the independent and dependent variables in your data. 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.
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 units, such as *Mass (grams).*
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.

Math Handbook
Graphs of Relations
pages 848–852

Figure 1-16 To find an equation of the line of best fit for a linear relationship, find the slope and *y*-intercept.



Linear Relationships

Scatter plots of data may take many different shapes, suggesting different relationships. (The line of best fit may be called a curve of best fit for nonlinear graphs.) Three of the most common relationships will be shown in this section. You probably are familiar with them from math class.

When the line of best fit is a straight line, as in Figure 1-15, the dependent variable varies linearly with the independent variable. There is a **linear relationship** between the two variables. The relationship can be written as an equation.

Linear Relationship Between Two Variables $y = mx + b$

Find the *y*-intercept, *b*, and the slope, *m*, as illustrated in **Figure 1-16.** Use points on the line—they may or may not be data points.

The slope is the ratio of the vertical change to the horizontal change. To find the slope, select two points, A and B, far apart on the line. The vertical change, or rise, Δy, is the difference between the vertical values of A and B. The horizontal change, or run, Δx, is the difference between the horizontal values of A and B.

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

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

$$\text{In Figure 1-16: } m = \frac{(16.0 \text{ cm} - 14.1 \text{ cm})}{(30 \text{ g} - 5 \text{ g})} = 0.08 \text{ cm/g}$$

If y gets smaller as x gets larger, then $\Delta y/\Delta x$ is negative, and the line slopes downward.

The y-intercept, b, is the point at which the line crosses the y-axis, and it is the y-value when the value of x is zero. In this example, $b = 13.7$ cm. When $b = 0$, or $y = mx$, the quantity y is said to vary directly with x.

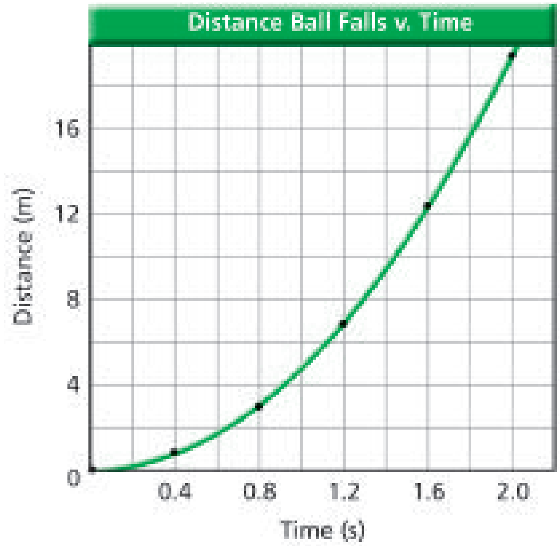


Figure 1-17 This graph indicates a quadratic, or parabolic, relationship.

Nonlinear Relationships

Figure 1-17 shows 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 the quadratic and inverse relationships. The graph in Figure 1-17 is a **quadratic relationship,** represented by the following equation.

Quadratic Relationship Between Two Variables

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

A quadratic relationship exists when one variable depends on the square of another.

Math Handbook

Quadratic Graphs page 852
Quadratic Equations page 846

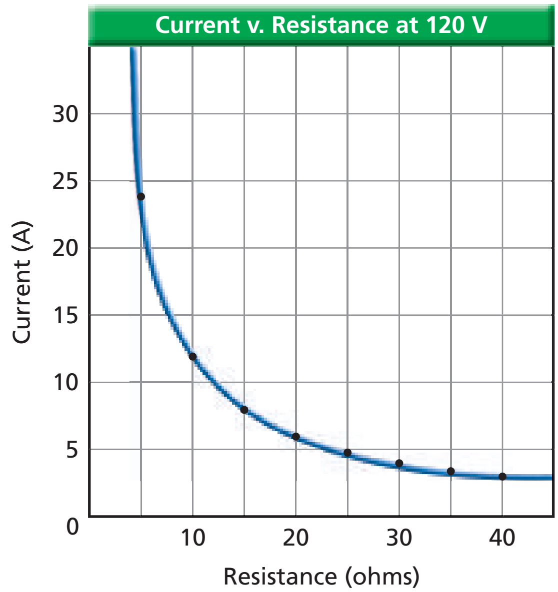
A computer program or graphing calculator easily can find the values of the constants a, b, and c in this equation. In this case, the equation is $d = 5t^2$. See the Math Handbook in the back of the book for more on making and using line graphs.

CHALLENGE PROBLEM

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. Is the origin 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 1-18 This graph shows the inverse relationship between resistance and current. As resistance increases, current decreases.



The graph in **Figure 1-18** shows how the current in an electric circuit varies as the resistance is increased. This is an example of an **inverse relationship,** represented by the following equation.

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

A hyperbola results when one variable depends on the inverse of the other.

The three relationships you have learned about are a sample of the simple relations you will most likely try to derive 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.

PRACTICE Problems

Additional Problems, Appendix B

24. The mass values of specified volumes of pure gold nuggets are given in **Table 1-4.**

a. Plot mass versus volume from the values given in the table and draw the curve that best fits all points.

b. Describe the resulting curve.

c. According to the graph, what type of relationship exists between the mass of the pure gold nuggets and their volume?

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

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

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

Table 1-4
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

■ **Figure 1-19** Computer animators use mathematical models of the real world to create a convincing fictional world. They need to accurately portray how beings of different sizes move, how hair or clothing move with a character, and how light and shadows fall, among other physics topics.

Predicting Values

When scientists discover relations like the ones shown in the graphs in this section, they use them to make predictions. For example, the equation for the linear graph in **Figure 1-16** is as follows:

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

Relations, 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 1-3 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, 49 kg is a value far outside the ones measured, 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, how changes to a circuit will change the performance of a device, or how electromagnetic fields will affect a medical instrument. People in all walks of life use models in many ways. One example is shown in **Figure 1-19.** With the tools you have learned in this chapter, you can answer questions and produce models for the physics questions you will encounter in the rest of this textbook.

1.3 Section Review

25. 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

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

27. Predict Use the relation illustrated in Figure 1-16 to determine the mass required to stretch the spring 15 cm.

28. Predict Use the relation in Figure 1-18 to predict the current when the resistance is 16 ohms.

29. Critical Thinking In your own words, explain the meaning of a shallower line, or a smaller slope than the one in Figure 1-16, in the graph of stretch versus total mass for a different spring.

PHYSICS LAB • Internet

Exploring Objects in Motion

Physics is a science that is based upon experimental observations. Many of the basic principles used to describe and understand mechanical systems, such as objects in linear motion, can be applied later to describe more complex natural phenomena. How can you measure the speed of the vehicles in a video clip?

Benjamin Coifman

QUESTION

What types of measurements could be made to find the speed of a vehicle?

Objectives

- **Observe** the motion of the vehicles seen in the video.
- **Describe** the motion of the vehicles.
- **Collect and organize data** on the vehicle's motion.
- **Calculate** a vehicle's speed.

Safety Precautions

Materials

Internet access is required.
watch or other timer

Procedure

1. Visit physicspp.com/internet_lab to view the Chapter 1 lab video clip.
2. The video footage was taken in the midwestern United States at approximately noon. Along the right shoulder of the road are large, white, painted rectangles. These types of markings are used in many states for aerial observation of traffic. They are placed at 0.322-km (0.2-mi) intervals.
3. **Observe** What type of measurements might be taken? Prepare a data table, such as the one shown on the next page. Record your observations of the surroundings, other vehicles, and markings. On what color vehicle is the camera located, and what color is the pickup truck in the lane to the left?
4. **Measure and Estimate** View the video again and look for more details. Is the road smooth? In what direction are the vehicles heading? How long does it take each vehicle to travel two intervals marked by the white blocks? Record your observations and data.

Data Table			
Marker	Distance (km)	White Vehicle Time (s)	Gray Pickup Time (s)

Analyze

1. Summarize your qualitative observations.
2. Summarize your quantitative observations.
3. **Make and Use Graphs** Graph both sets of data on one pair of axes.
4. **Estimate** What is the speed of the vehicles in km/s and km/h?
5. **Predict** How far will each vehicle travel in 5 min?

Conclude and Apply

1. **Measure** What is the precision of the distance and time measurements?
2. **Measure** What is the precision of your speed measurement? On what does it depend?
3. **Use Variables, Constants, and Controls** Describe the independent and the dependent variables in this experiment.
4. **Compare and Contrast** Which vehicle's graph has a steeper slope? What is the slope equal to?
5. **Infer** What would a horizontal line mean on the graph? A line with a steeper slope?

Going Further

Speed is distance traveled divided by the amount of time to travel that distance. Explain how you could design your own experiment to measure speed in the classroom using remote-controlled cars. What would you use for markers? How precisely could you measure distance and time? Would the angle at which you measured the cars passing the markers affect the results? How much? How could you improve your measurements? What units make sense for speed? How far into the future could you predict the cars' positions? If possible, carry out the experiment and summarize your results.

Real-World Physics

When the speedometer is observed by a front-seat passenger, the driver, and a passenger in the rear driver's-side seat, readings of 90 km/h, 100 km/h, and 110 km/h, respectively, are observed. Explain the differences.

ShareYourData

Design an Experiment Visit **physicspp.com/internet_lab** to post your experiment for measuring speed in the classroom using remote-controlled cars. Include your list of materials, your procedure, and your predictions for the accuracy of your lab. If you actually perform your lab, post your data and results as well.

Physics Online

To find out more about measurement, visit the Web site: **physicspp.com**

Future Technology

Computer History and Growth

Each pixel of the animations or movies you watch, and each letter of the instant messages you send presents your computer with several hundred equations. Each equation must be solved in a few billionths of a second—if it takes a bit longer, you might complain that your computer is slow.

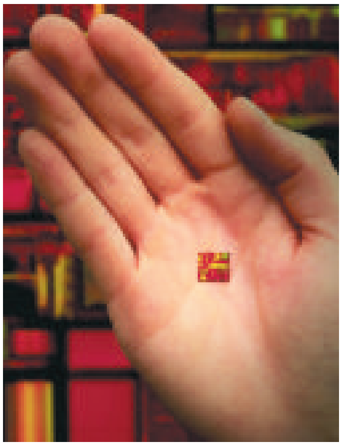
Early Computers The earliest computers could solve very complex arrays of equations, just as yours can, but it took them a lot longer to do so. There were several reasons for this. First, the mathematics of algorithms (problem-solving strategies) still was new. Computer scientists were only beginning to learn how to arrange a particular problem, such as the conversion of a picture into an easily-transmittable form, so that it could be solved by a machine.

UNIVAC 1, an early computer, filled an entire room.

Machine Size Second, the machines were physically large. Computers work by switching patterns of electric currents that represent binary numbers. A 16-bit machine works with binary numbers that are 16 bits long. If a 64-bit number must be dealt with, the machine must repeat the same operation four times. A 32-bit machine would have to repeat the operation only twice, thus making it that much faster. But a 32-bit machine is four times the size of a 16-bit machine; that is, it has four times as many wires and transistor switches, and even 8-bit machines were the size of the old UNIVAC shown above.

Moreover, current travels along wires at speeds no greater than about two-thirds the speed of light. This is a long time if the computer wires are 15 m long and must move information in less than 10^{-9} s.

Memory Third, electronic memories were extremely expensive. You may know that a larger memory lets your computer work faster. When one byte of memory required eight circuit boards, 1024 bytes (or 1 K) of memory was enormous. Because memory was so precious, computer programs had to be written with great cleverness. Astronants got to the Moon with 64 K of memory in *Apollo's* on-board computers.



Processor chips used in today's computers are tiny compared to the old computer systems.

When Gordon Moore and others invented the integrated circuit around 1960, the size and cost of computer circuitry dropped drastically. Physically smaller, and thus faster, machines could be built and very large memories became possible. Today, the transistors on a chip are now smaller than bacteria.

The cost and size of computers have dropped so much that your cell phone has far more computing power than most big office machines of the 1970s.

Going Further

1. **Research** A compression protocol makes a computer file smaller and less prone to transmission errors. Look up the terms *.jpg*, *.mp3*, *.mpeg*, and *.midi* and see how they apply to the activities you do on your computer.
2. **Calculate** Using the example here, how long does it take for a binary number to travel 15 m? How many such operations could there be each second?

CORBIS

Chapter 1

Study Guide

1.1 Mathematics and Physics

Vocabulary
- physics (p. 3)
- dimensional analysis (p. 6)
- significant digits (p. 7)
- scientific method (p. 8)
- hypothesis (p. 8)
- scientific law (p. 9)
- scientific theory (p. 10)

Key Concepts
- Physics is the study of matter and energy and their relationships.
- Dimensional analysis is used to check that an answer will be in the correct units.
- The result of any mathematical operation with measurements never can be more precise than the least-precise measurement involved in the operation.
- The scientific method is a systematic method of observing, experimenting, and analyzing to answer questions about the natural world.
- Scientific ideas change in response to new data.
- Scientific laws and theories are well-established descriptions and explanations of nature.

1.2 Measurement

Vocabulary
- measurement (p. 11)
- precision (p. 12)
- accuracy (p. 13)

Key Concepts
- New scientific findings must be reproducible; that is, others must be able to measure and find the same results.
- All measurements are subject to some uncertainty.
- Precision is the degree of exactness with which a quantity is measured. Scientific notation shows how precise a measurement is.
- Accuracy is the extent to which a measurement matches the true value.

1.3 Graphing Data

Vocabulary
- independent variable (p. 15)
- dependent variable (p. 15)
- line of best fit (p. 15)
- linear relationship (p. 16)
- quadratic relationship (p. 17)
- inverse relationship (p. 18)

Key Concepts
- Data are plotted in graphical form to show the relationship between two variables.
- The line that best passes through or near graphed data is called the line of best fit. It is used to describe the data and to predict where new data would lie on the graph.
- A graph in which data points lie on a straight line is a graph of a linear relationship. In the equation, m and b are constants.

$$y = mx + b$$

- The slope of a straight-line graph is the vertical change (rise) divided by the horizontal change (run) and often has a physical meaning.

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

- The graph of a quadratic relationship is a parabolic curve. It is represented by the equation below. The constants a, b, and c can be found with a computer or a graphing calculator; simpler ones can be found using algebra.

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

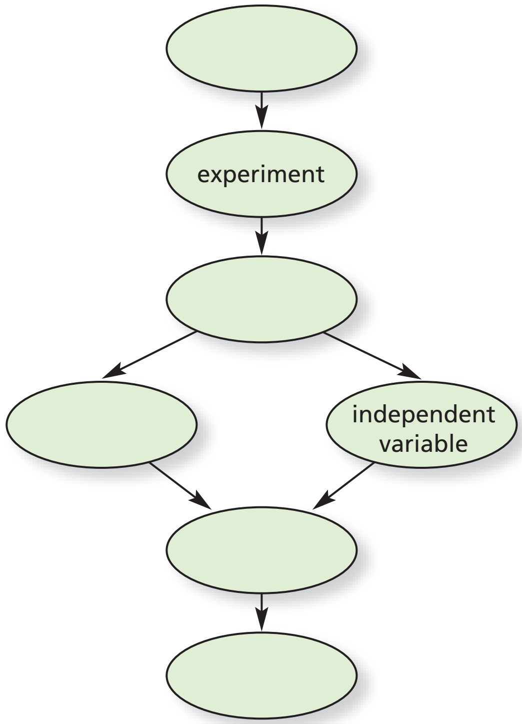
- The graph of an inverse relationship between x and y is a hyperbolic curve. It is represented by the equation below, where a is a constant.

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

Assessment

Concept Mapping

30. Complete the following concept map using the following terms: *hypothesis, graph, mathematical model, dependent variable, measurement.*



Mastering Concepts

31. Describe a scientific method. (1.1)

32. Why is mathematics important to science? (1.1)

33. What is the SI system? (1.1)

34. How are base units and derived units related? (1.1)

35. Suppose your lab partner recorded a measurement as 100 g. (1.1)

a. Why is it difficult to tell the number of significant digits in this measurement?

b. How can the number of significant digits in such a number be made clear?

36. Give the name for each of the following multiples of the meter. (1.1)

a. $\frac{1}{100}$ m **b.** $\frac{1}{1000}$ m **c.** 1000 m

37. To convert 1.8 h to minutes, by what conversion factor should you multiply? (1.1)

38. Solve each problem. Give the correct number of significant digits in the answers. (1.1)

a. 4.667×10^4 g + 3.02×10^5 g

b. $(1.70\times10^2$ J$) \div (5.922\times10^{-4}$ cm$^3)$

39. What determines the precision of a measurement? (1.2)

40. How does the last digit differ from the other digits in a measurement? (1.2)

41. A car's odometer measures the distance from home to school as 3.9 km. Using string on a map, you find the distance to be 4.2 km. Which answer do you think is more accurate? What does *accurate* mean? (1.2)

42. How do you find the slope of a linear graph? (1.3)

43. For a driver, the time between seeing a stoplight and stepping on the brakes is called reaction time. The distance traveled during this time is the reaction distance. Reaction distance for a given driver and vehicle depends linearly on speed. (1.3)

a. Would the graph of reaction distance versus speed have a positive or a negative slope?

b. A driver who is distracted has a longer reaction time than a driver who is not. Would the graph of reaction distance versus speed for a distracted driver have a larger or smaller slope than for a normal driver? Explain.

44. During a laboratory experiment, the temperature of the gas in a balloon is varied and the volume of the balloon is measured. Which quantity is the independent variable? Which quantity is the dependent variable? (1.3)

45. What type of relationship is shown in **Figure 1-20?** Give the general equation for this type of relation. (1.3)

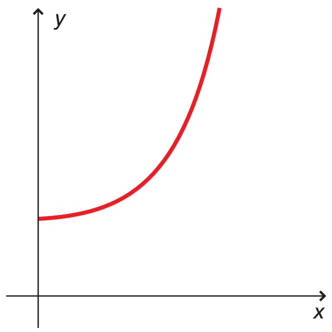


Figure 1-20

46. Given the equation $F = mv^2/R$, what relationship exists between each of the following? (1.3)

a. F and R

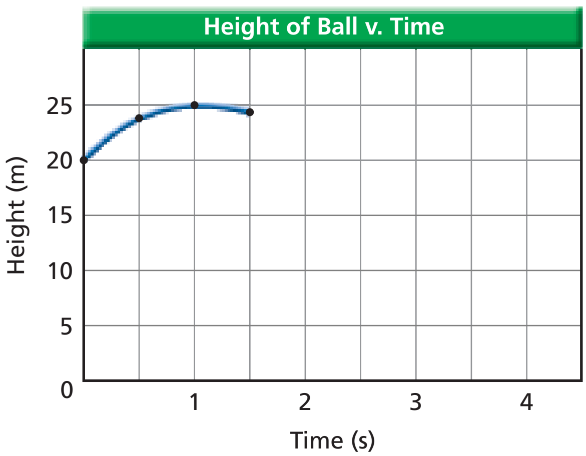
b. F and m

c. F and v

For more problems, go to Additional Problems, Appendix B.

Applying Concepts

47. **Figure 1-21** gives the height above the ground of a ball that is thrown upward from the roof of a building, for the first 1.5 s of its trajectory. What is the ball's height at $t = 0$? Predict the ball's height at $t = 2$ s and at $t = 5$ s.



■ **Figure 1-21**

48. Is a scientific method one set of clearly defined steps? Support your answer.

49. Explain the difference between a scientific theory and a scientific law.

50. **Density** The density of a substance is its mass per unit volume.
a. Give a possible metric unit for density.
b. Is the unit for density a base unit or a derived unit?

51. What metric unit would you use to measure each of the following?
a. the width of your hand
b. the thickness of a book cover
c. the height of your classroom
d. the distance from your home to your classroom

52. **Size** Make a chart of sizes of objects. Lengths should range from less than 1 mm to several kilometers. Samples might include the size of a cell, the distance light travels in 1 s, and the height of a room.

53. **Time** Make a chart of time intervals. Sample intervals might include the time between heartbeats, the time between presidential elections, the average lifetime of a human, and the age of the United States. Find as many very short and very long examples as you can.

54. **Speed of Light** Two students measure the speed of light. One obtains $(3.001 \pm 0.001)\times10^8$ m/s; the other obtains $(2.999 \pm 0.006)\times10^8$ m/s.
a. Which is more precise?
b. Which is more accurate? (You can find the speed of light in the back of this textbook.)

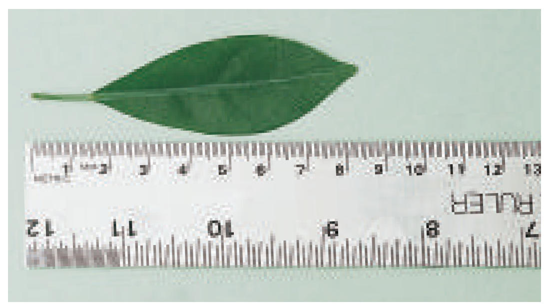
55. You measure the dimensions of a desk as 132 cm, 83 cm, and 76 cm. The sum of these measures is 291 cm, while the product is 8.3×10^5 cm^3. Explain how the significant digits were determined in each case.

56. **Money** Suppose you receive \$5.00 at the beginning of a week and spend \$1.00 each day for lunch. You prepare a graph of the amount you have left at the end of each day for one week. Would the slope of this graph be positive, zero, or negative? Why?

57. Data are plotted on a graph, and the value on the y-axis is the same for each value of the independent variable. What is the slope? Why? How does y depend on x?

58. **Driving** The graph of braking distance versus car speed is part of a parabola. Thus, the equation is written $d = av^2 + bv + c$. The distance, d, has units in meters, and velocity, v, has units in meters/second. How could you find the units of a, b, and c? What would they be?

59. How long is the leaf in **Figure 1-22?** Include the uncertainty in your measurement.



■ **Figure 1-22**

60. The masses of two metal blocks are measured. Block A has a mass of 8.45 g and block B has a mass of 45.87 g.
a. How many significant digits are expressed in these measurements?
b. What is the total mass of block A plus block B?
c. What is the number of significant digits for the total mass?
d. Why is the number of significant digits different for the total mass and the individual masses?

61. **History** Aristotle said that the speed of a falling object varies inversely with the density of the medium through which it falls.
a. According to Aristotle, would a rock fall faster in water (density 1000 kg/m^3), or in air (density 1 kg/m^3)?
b. How fast would a rock fall in a vacuum? Based on this, why would Aristotle say that there could be no such thing as a vacuum?

62. Explain the difference between a hypothesis and a scientific theory.

63. Give an example of a scientific law.

64. What reason might the ancient Greeks have had not to question the hypothesis that heavier objects fall faster than lighter objects? *Hint: Did you ever question which falls faster?*

65. **Mars** Explain what observations led to changes in scientists' ideas about the surface of Mars.

66. A graduated cylinder is marked every mL. How precise a measurement can you make with this instrument?

Mastering Problems

1.1 Mathematics and Physics

67. Convert each of the following measurements to meters.
   a. 42.3 cm
   b. 6.2 pm
   c. 21 km
   d. 0.023 mm
   e. 214 μm
   f. 57 nm

68. Add or subtract as indicated.
   a. 5.80×10^{9} s + 3.20×10^{8} s
   b. 4.87×10^{-6} m − 1.93×10^{-6} m
   c. 3.14×10^{-5} kg + 9.36×10^{-5} kg
   d. 8.12×10^{7} g − 6.20×10^{6} g

69. Rank the following mass measurements from least to greatest: 11.6 mg, 1021 μg, 0.000006 kg, 0.31 mg.

70. State the number of significant digits in each of the following measurements.
   a. 0.00003 m
   b. 64.01 fm
   c. 80.001 m
   d. 0.720 μg
   e. 2.40×10^{6} kg
   f. 6×10^{8} kg
   g. 4.07×10^{16} m

71. Add or subtract as indicated.
   a. 16.2 m + 5.008 m + 13.48 m
   b. 5.006 m + 12.0077 m + 8.0084 m
   c. 78.05 cm^2 − 32.046 cm^2
   d. 15.07 kg − 12.0 kg

72. Multiply or divide as indicated.
   a. $(6.2\times10^{18}\text{ m})(4.7\times10^{-10}\text{ m})$
   b. $(5.6\times10^{-7}\text{ m})/(2.8\times10^{-12}\text{ s})$
   c. $(8.1\times10^{-4}\text{ km})(1.6\times10^{-3}\text{ km})$
   d. $(6.5\times10^{5}\text{ kg})/(3.4\times10^{3}\text{ m}^3)$

73. **Gravity** The force due to gravity is $F = mg$ where $g = 9.80$ m/s^2.
   a. Find the force due to gravity on a 41.63-kg object.
   b. The force due to gravity on an object is 632 kg·m/s^2. What is its mass?

74. **Dimensional Analysis** Pressure is measured in pascals, where 1 Pa = 1 kg/m·s^2. Will the following expression give a pressure in the correct units?

$$\frac{(0.55\text{ kg})(2.1\text{ m/s})}{9.8\text{ m/s}^2}$$

1.2 Measurement

75. A water tank has a mass of 3.64 kg when it is empty and a mass of 51.8 kg when it is filled to a certain level. What is the mass of the water in the tank?

76. The length of a room is 16.40 m, its width is 4.5 m, and its height is 3.26 m. What volume does the room enclose?

77. The sides of a quadrangular plot of land are 132.68 m, 48.3 m, 132.736 m, and 48.37 m. What is the perimeter of the plot?

78. How precise a measurement could you make with the scale shown in **Figure 1-23?**

Figure 1-23

79. Give the measure shown on the meter in **Figure 1-24** as precisely as you can. Include the uncertainty in your answer.

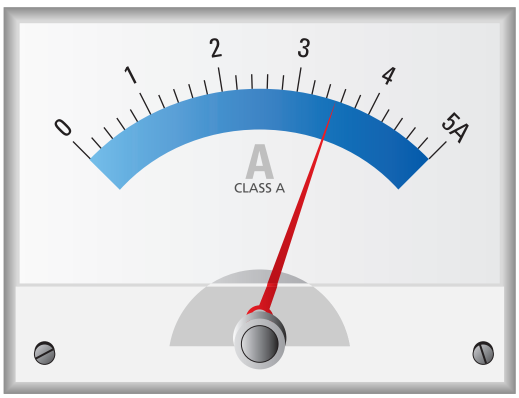


Figure 1-24

 For more problems, go to Additional Problems, Appendix B.

80. Estimate the height of the nearest door frame in centimeters. Then measure it. How accurate was your estimate? How precise was your estimate? How precise was your measurement? Why are the two precisions different?

81. **Base Units** Give six examples of quantities you might measure in a physics lab. Include the units you would use.

82. **Temperature** The temperature drops from 24°C to 10°C in 12 hours.
 a. Find the average temperature change per hour.
 b. Predict the temperature in 2 more hours if the trend continues.
 c. Could you accurately predict the temperature in 24 hours?

1.3 Graphing Data

83. **Figure 1-25** shows the masses of three substances for volumes between 0 and 60 cm^3.
 a. What is the mass of 30 cm^3 of each substance?
 b. If you had 100 g of each substance, what would be their volumes?
 c. In one or two sentences, describe the meaning of the slopes of the lines in this graph.
 d. What is the *y*-intercept of each line? What does it mean?

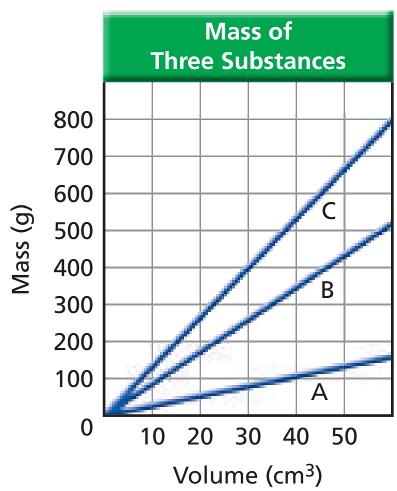


Figure 1-25

84. During a class demonstration, a physics instructor placed a mass on a horizontal table that was nearly frictionless. The instructor then applied various horizontal forces to the mass and measured the distance it traveled in 5 seconds for each force applied. The results of the experiment are shown in **Table 1-5.**

Table 1-5
Distance Traveled with Different Forces

Force (N)	Distance (cm)
5.0	24
10.0	49
15.0	75
20.0	99
25.0	120
30.0	145

 a. Plot the values given in the table and draw the curve that best fits all points.
 b. Describe the resulting curve.
 c. Use the graph to write an equation relating the distance to the force.
 d. What is the constant in the equation? Find its units.
 e. Predict the distance traveled when a 22.0-N force is exerted on the object for 5 s.

85. The physics instructor from the previous problem changed the procedure. The mass was varied while the force was kept constant. Time and distance were measured, and the acceleration of each mass was calculated. The results of the experiment are shown in **Table 1-6.**

Table 1-6
Acceleration of Different Masses

Mass (kg)	Acceleration (m/s^2)
1.0	12.0
2.0	5.9
3.0	4.1
4.0	3.0
5.0	2.5
6.0	2.0

 a. Plot the values given in the table and draw the curve that best fits all points.
 b. Describe the resulting curve.
 c. According to the graph, what is the relationship between mass and the acceleration produced by a constant force?
 d. Write the equation relating acceleration to mass given by the data in the graph.
 e. Find the units of the constant in the equation.
 f. Predict the acceleration of an 8.0-kg mass.

86. During an experiment, a student measured the mass of 10.0 cm^3 of alcohol. The student then measured the mass of 20.0 cm^3 of alcohol. In this way, the data in **Table 1-7** were collected.

Table 1-7
The Mass Values of Specific Volumes of Alcohol

Volume (cm^3)	Mass (g)
10.0	7.9
20.0	15.8
30.0	23.7
40.0	31.6
50.0	39.6

a. Plot the values given in the table and draw the curve that best fits all the points.
b. Describe the resulting curve.
c. Use the graph to write an equation relating the volume to the mass of the alcohol.
d. Find the units of the slope of the graph. What is the name given to this quantity?
e. What is the mass of 32.5 cm^3 of alcohol?

Mixed Review

87. Arrange the following numbers from most precise to least precise

0.0034 m 45.6 m 1234 m

88. **Figure 1-26** shows the toroidal (doughnut-shaped) interior of the now-dismantled Tokamak Fusion Test Reactor. Explain why a width of 80 m would be an unreasonable value for the width of the toroid. What would be a reasonable value?

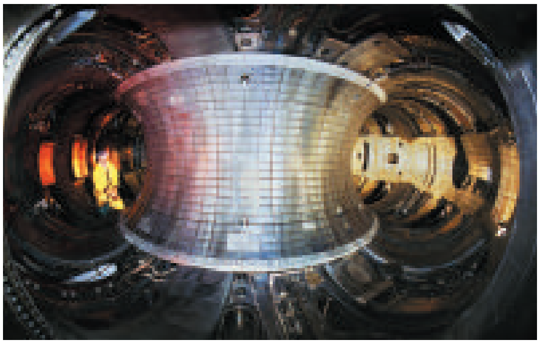


Figure 1-26

89. You are cracking a code and have discovered the following conversion factors: 1.23 longs = 23.0 mediums, and 74.5 mediums = 645 shorts. How many shorts are equal to one long?

90. You are given the following measurements of a rectangular bar: length = 2.347 m, thickness = 3.452 cm, height = 2.31 mm, mass = 1659 g. Determine the volume, in cubic meters, and density, in g/cm^3, of the beam. Express your results in proper form.

91. A drop of water contains 1.7×10^{21} molecules. If the water evaporated at the rate of one million molecules per second, how many years would it take for the drop to completely evaporate?

92. A 17.6-gram sample of metal is placed in a graduated cylinder containing 10.0 cm^3 of water. If the water level rises to 12.20 cm^3, what is the density of the metal?

Thinking Critically

93. **Apply Concepts** It has been said that fools can ask more questions than the wise can answer. In science, it is frequently the case that one wise person is needed to ask the right question rather than to answer it. Explain.

94. **Apply Concepts** Find the approximate mass of water in kilograms needed to fill a container that is 1.40 m long and 0.600 m wide to a depth of 34.0 cm. Report your result to one significant digit. (Use a reference source to find the density of water.)

95. **Analyze and Conclude** A container of gas with a pressure of 101 kPa has a volume of 324 cm^3 and a mass of 4.00 g. If the pressure is increased to 404 kPa, what is the density of the gas? Pressure and volume are inversely proportional.

96. **Design an Experiment** How high can you throw a ball? What variables might affect the answer to this question?

97. **Calculate** If the Sun suddenly ceased to shine, how long would it take Earth to become dark? (You will have to look up the speed of light in a vacuum and the distance from the Sun to Earth.) How long would it take the surface of Jupiter to become dark?

Writing in Physics

98. Research and describe a topic in the history of physics. Explain how ideas about the topic changed over time. Be sure to include the contributions of scientists and to evaluate the impact of their contributions on scientific thought and the world outside the laboratory.

99. Explain how improved precision in measuring time would have led to more accurate predictions about how an object falls.

 For more problems, go to Additional Problems, Appendix B.

Standardized Test Practice

Multiple Choice

1. Two laboratories use radiocarbon dating to measure the age of two wooden spear handles found in the same grave. Lab A finds an age of 2250 ± 40 years for the first object; lab B finds an age of 2215 ± 50 years for the second object. Which of the following is true?

- (A) Lab A's reading is more accurate than lab B's.
- (B) Lab A's reading is less accurate than lab B's.
- (C) Lab A's reading is more precise than lab B's.
- (D) Lab A's reading is less precise than lab B's.

2. Which of the following is equal to 86.2 cm?

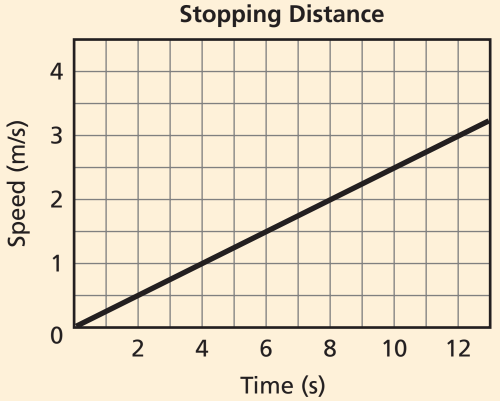
- (A) 8.62 m
- (C) 8.62×10^{-4} km
- (B) 0.862 mm
- (D) 862 dm

3. Jario has a problem to do involving time, distance, and velocity, but he has forgotten the formula. The question asks him for a measurement in seconds, and the numbers that are given have units of m/s and km. What could Jario do to get the answer in seconds?

- (A) Multiply the km by the m/s, then multiply by 1000.
- (B) Divide the km by the m/s, then multiply by 1000.
- (C) Divide the km by the m/s, then divide by 1000.
- (D) Multiply the km by the m/s, then divide by 1000.

4. What is the slope of the graph?

- (A) 0.25 m/s^2
- (C) 2.5 m/s^2
- (B) 0.4 m/s^2
- (D) 4.0 m/s^2



5. Which formula is equivalent to $D = \frac{m}{V}$?

- (A) $V = \frac{m}{D}$
- (C) $V = \frac{mD}{V}$
- (B) $V = Dm$
- (D) $V = \frac{D}{m}$

Extended Answer

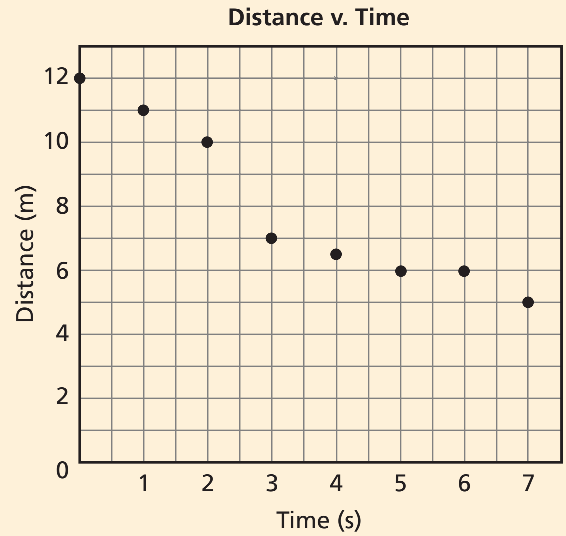
6. You want to calculate an acceleration, in units of m/s^2, given a force, in N, and the mass, in g, on which the force acts. ($1\ N = 1\ kg{\cdot}m/s^2$)

a. Rewrite the equation $F = ma$ so a is in terms of m and F.

b. What conversion factor will you need to multiply by to convert grams to kilograms?

c. A force of 2.7 N acts on a 350-g mass. Write the equation you will use, including the conversion factor, to find the acceleration.

7. Find an equation for a line of best fit for the data shown below.



✓ Test-Taking TIP

Skip Around if You Can

You may want to skip over difficult questions and come back to them later, after you've answered the easier questions. This will guarantee more points toward your final score. In fact, other questions may help you answer the ones you skipped. Just be sure you fill in the correct ovals on your answer sheet.

Chapter 2

Representing Motion

What You'll Learn

- You will represent motion through the use of words, motion diagrams, and graphs.
- You will use the terms *position, distance, displacement,* and *time interval* in a scientific manner to describe motion.

Why It's Important

Without ways to describe and analyze motion, travel by plane, train, or bus would be chaotic at best. Times and speeds determine the winners of races as well as transportation schedules.

Running a Marathon As one runner passes another, the speed of the overtaking runner is greater than the speed of the other runner.

Think About This ▶

How can you represent the motion of two runners?

Physics Online

physicspp.com

AFP/Corbis

LAUNCH Lab

Which car is faster?

Question

In a race between two toy cars, can you explain which car is faster?

Procedure

1. Obtain two toy cars, either friction cars or windup cars. Place the cars on your lab table or other surface recommended by your teacher.
2. Decide on a starting line for the race.
3. Release both cars from the same starting line at the same time. Note that if you are using windup cars, you will need to wind them up before you release them. Be sure to pull the cars back before release if they are friction cars.
4. **Observe** Watch the two cars closely as they move and determine which car is moving faster.
5. Repeat steps 1–3, but this time collect one type of data to support your conclusion about which car is faster.

Analysis

What data did you collect to show which car was moving faster? What other data could you collect to determine which car is faster?

Critical Thinking Write an operational definition of average speed.

2.1 Picturing Motion

Objectives

- **Draw** motion diagrams to describe motion.
- **Develop** a particle model to represent a moving object.

Vocabulary

motion diagram
particle model

In the previous chapter, you learned about the scientific processes that will be useful in your study of physics. In this chapter, you will begin to use these tools to analyze motion. In subsequent chapters, you will apply them to all kinds of movement using sketches, diagrams, graphs, and equations. These concepts will help you to determine how fast and how far an object will move, whether the object is speeding up or slowing down, and whether it is standing still or moving at a constant speed. Perceiving motion is instinctive—your eyes naturally pay more attention to moving objects than to stationary ones. Movement is all around you—from fast trains and speedy skiers to slow breezes and lazy clouds. Movements travel in many directions, such as the straight-line path of a bowling ball in a lane's gutter, the curved path of a tether ball, the spiral of a falling kite, and the swirls of water circling a drain.

Horizons Companies

All Kinds of Motion

■ **Figure 2-1** An object in motion changes its position as it moves. In this photo, the camera was focused on the rider, so the blurry background indicates that the rider's position has changed.

What comes to your mind when you hear the word *motion?* A speeding automobile? A spinning ride at an amusement park? A baseball soaring over a fence for a home run? Or a child swinging back and forth in a regular rhythm? When an object is in motion, as shown in **Figure 2-1,** its position changes. Its position can change along the path of a straight line, a circle, an arc, or a back-and-forth vibration.

Some of the types of motion described above appear to be more complicated than others. When beginning a new area of study, it is generally a good idea to begin with what appears to be 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.

Movement along a straight line Suppose that you are reading this textbook at home. At the beginning of Chapter 2, you glance over at your pet hamster and see that he is sitting in a corner of his cage. Sometime later, you look over again, and you see that he now is sitting by the food dish in the opposite corner of the cage. You can infer that he has moved from one place to another in the time in between your observations. Thus, a description of motion relates to place and time. You must be able to answer the questions of where and when an object is positioned to describe its motion. Next, you will look at some tools that are useful in determining when an object is at a particular place.

Motion Diagrams

Consider an example of straight-line motion: a runner is jogging along a straight path. One way of representing the motion of the runner is to create a series of images showing the positions of the runner at equal time intervals. This can be done by photographing the runner in motion to obtain a series of images.

Suppose you point a camera in a direction perpendicular to the direction of motion, and hold it still while the motion is occurring. Then you take a series of photographs of the runner at equal time intervals. **Figure 2-2** 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 ground, only the runner is in motion. What is another way of representing the runner's motion?

■ **Figure 2-2** If you relate the position of the runner to the background in each image over equal time intervals, you will conclude that she is in motion.

(t)Getty Images, (others)Hutchings Photography

Suppose that you stacked the images from Figure 2-2, one on top of the other. **Figure 2-3** shows what such a stacked image might look like. You will see more than one image of the moving runner, but only a single image of the motionless objects in the background. A series of images showing the positions of a moving object at equal time intervals is called a **motion diagram.**

Figure 2-3 Stacking a series of images taken at regular time intervals and combining them into one image creates a motion diagram for the runner for one portion of her run. Reducing the runner's motion to a series of single points results in a particle model of her motion.

The Particle Model

Keeping track of the motion of the runner is easier if you disregard the movement of the arms and legs, and instead concentrate on a single point at the center of her body. In effect, you can disregard the fact that she has some size and imagine that she is a very small object located precisely at that central point. A **particle model** is a simplified version of a motion diagram in which the object in motion is replaced by a series of single points. To use the particle model, the size of the object must be much less than the distance it moves. The internal motions of the object, such as the waving of the runner's arms are ignored in the particle model. In the photographic motion diagram, you could identify one central point on the runner, such as a dot centered at her waistline, and take measurements of the position of the dot. The bottom part of Figure 2-3 shows the particle model for the runner's motion. You can see that applying the particle model produces a simplified version of the motion diagram. In the next section, you will learn how to create and use a motion diagram that shows how far an object moved and how much time it took to move that far.

2.1 Section Review

1. **Motion Diagram of a Runner** Use the particle model to draw a motion diagram for a bike rider riding at a constant pace.

2. **Motion Diagram of a Bird** Use the particle model to draw a simplified motion diagram corresponding to the motion diagram in **Figure 2-4** for a flying bird. What point on the bird did you choose to represent it?

Figure 2-4

3. **Motion Diagram of a Car** Use the particle model to draw a simplified motion diagram corresponding to the motion diagram in **Figure 2-5** for a car coming to a stop at a stop sign. What point on the car did you use to represent it?

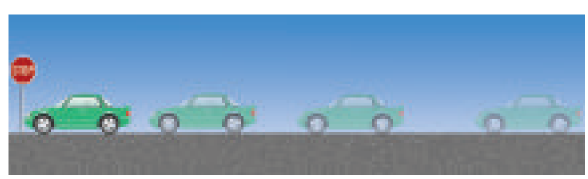


Figure 2-5

4. **Critical Thinking** Use the particle model to draw motion diagrams for two runners in a race, when the first runner crosses the finish line as the other runner is three-fourths of the way to the finish line.

Physics Online physicspp.com/self_check_quiz

Hutchings Photography

CONTENTS

2.2 Where and When?

▶ **Objectives**

- **Define** coordinate systems for motion problems.
- **Recognize** that the chosen coordinate system affects the sign of objects' positions.
- **Define** displacement.
- **Determine** a time interval.
- **Use** a motion diagram to answer questions about an object's position or displacement.

▶ **Vocabulary**

coordinate system
origin
position
distance
magnitude
vectors
scalars
resultant
time interval
displacement

Would it be possible to take measurements of distance and time from a motion diagram, such as the motion diagram of the runner? Before taking the photographs, you could place a meterstick or a measuring tape on the ground along the path of the runner. The measuring tape would tell you where the runner was in each image. A stopwatch or clock within the view of the camera could tell the time. But where should you place the end of the measuring tape? When should you start the stopwatch?

Coordinate Systems

When you decide where to place the measuring tape and when to start the stopwatch, you are defining a **coordinate system,** which tells you the location of the zero point of the variable you are studying and the direction in which the values of the variable increase. The **origin** is the point at which both variables have the value zero. In the example of the runner, the origin, represented by the zero end of the measuring tape, could be placed 6 m to the left of the tree. The motion is in a straight line; thus, your measuring tape should lie along that straight line. The straight line is an axis of the coordinate system. You probably would place the tape so that the meter scale increases to the right of the zero, but putting it in the opposite direction is equally correct. In **Figure 2-6a,** the origin of the coordinate system is on the left.

You can indicate how far away the runner is from the origin at a particular time on the simplified motion diagram by drawing an arrow from the origin to the point representing the runner, as shown in **Figure 2-6b.** This arrow represents the runner's **position,** the separation between an object and the origin. The length of the arrow indicates how far the object is from the origin, or the object's **distance** from the origin. The arrow points from the origin to the location of the moving object at a particular time.

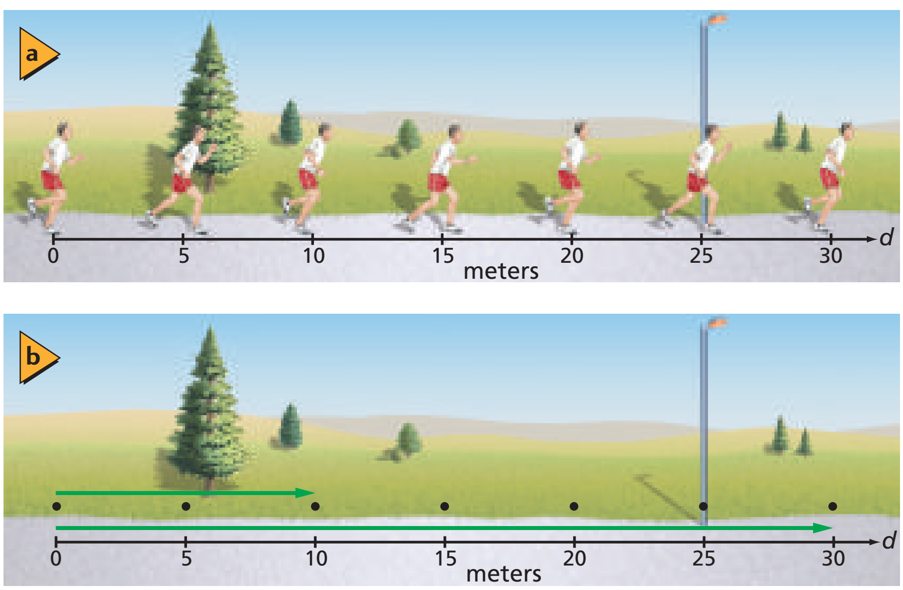
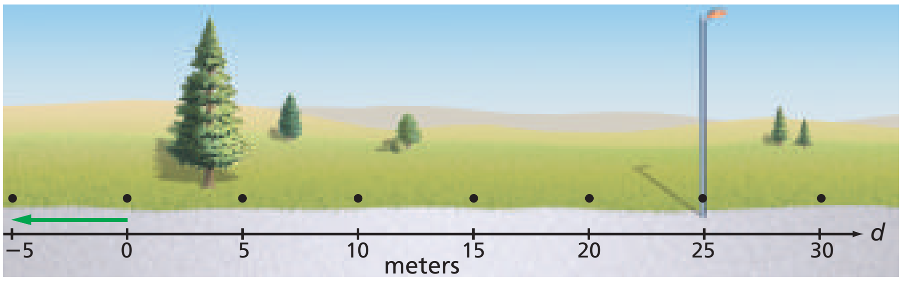


Figure 2-6 In these motion diagrams, the origin is at the left **(a),** and the positive values of distance extend horizontally to the right. The two arrows, drawn from the origin to points representing the runner, locate his position at two different times **(b).**

Is there such a thing as a negative position? Suppose you chose the coordinate system just described, placing the origin 4 m left of the tree with the *d*-axis extending in a positive direction to the right. A position 9 m to the left of the tree, 5 m left of the origin, would be a negative position, as shown in **Figure 2-7.** In the same way, you could discuss a time before the stopwatch was started.

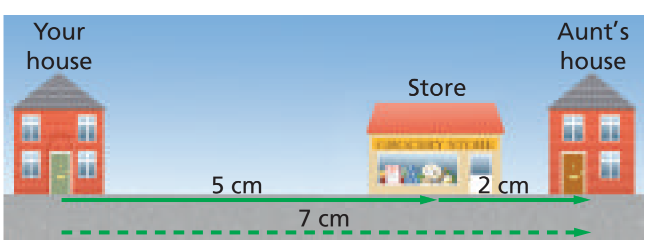


■ **Figure 2-7** The arrow drawn on this motion diagram indicates a negative position.

Vectors and scalars Quantities that have both size, also called **magnitude,** and direction, are called **vectors,** and can be represented by arrows. Quantities that are just numbers without any direction, such as distance, time, or temperature, are called **scalars.** This textbook will use boldface letters to represent vector quantities and regular letters to represent scalars.

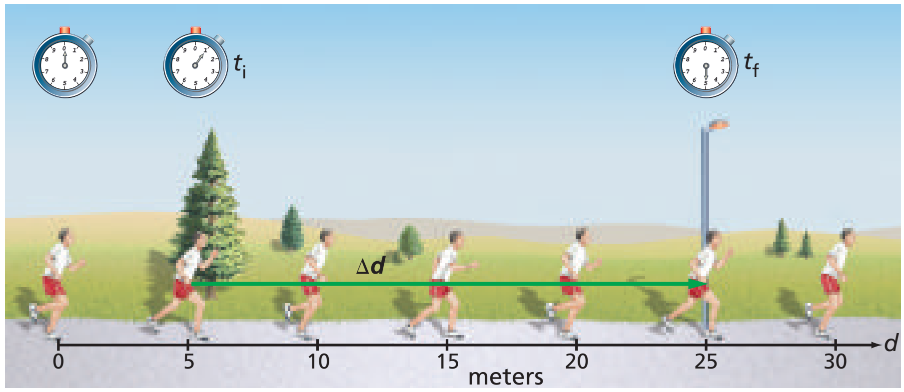
You already know how to add scalars; for example, 0.6 + 0.2 = 0.8. How do you add vectors? Think about how you would solve the following problem. Your aunt asks you to get her some cold medicine at the store nearby. You walk 0.5 km east from your house to the store, buy the cold medicine, and then walk another 0.2 km east to your aunt's house. How far from the origin are you at the end of your trip? The answer, of course, is 0.5 km east + 0.2 km east = 0.7 km east. You also could solve this problem graphically, using the following method.

Using a ruler, measure and draw each vector. The length of a vector should be proportional to the magnitude of the quantity being represented, so you must decide on a scale for your drawing. For example, you might let 1 cm on paper represent 0.1 km. The important thing is to choose a scale that produces a diagram of reasonable size with a vector that is about 5–10 cm long. The vectors representing the two segments that made up your trip to your aunt's house are shown in **Figure 2-8,** drawn to a scale of 1 cm, which represents 0.1 km. The vector that represents the total of these two, shown here with a dotted line, is 7 cm long. According to the established scale, you were 0.7 km from the origin at the end of your trip. The vector that represents the sum of the other two vectors is called the **resultant.** The resultant always points from the tail of the first vector to the tip of the last vector.



■ **Figure 2-8** Add two vectors by placing them tip to tail. The resultant points from the tail of the first vector to the tip of the last vector.

■ **Figure 2-9** You can see that it took the runner 4.0 s to run from the tree to the lamppost. The initial position of the runner is used as a reference point. The vector from position 1 to position 2 indicates both the direction and amount of displacement during this time interval.



Time Intervals and Displacements

When analyzing the runner's motion, you might want to know how long it took the runner to travel from the tree to the lamppost. This value is obtained by finding the difference in the stopwatch readings at each position. Assign the symbol t_i to the time when the runner was at the tree and the symbol t_f to the time when he was at the lamppost. 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. The time interval is defined mathematically as follows.

Color Convention

- Displacement vectors are shown in **green.**

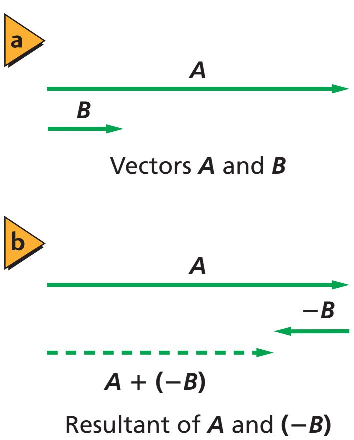
Time Interval $\Delta t = t_f - t_i$

The time interval is equal to the final time minus the initial time.

Although i and f are used to represent the initial and final times, 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 him to go from the tree to the lamppost is $t_f - t_i = 5.0\ \text{s} - 1.0\ \text{s} = 4.0\ \text{s}$. How did the runner's position change when he ran from the tree to the lamppost, as shown in **Figure 2-9?** The symbol $\boldsymbol{d}$ may be used to represent position. In common speech, a position refers to a place; but in physics, a position is a vector with its tail at the origin of a coordinate system and its tip at the place.

Figure 2-9 shows $\Delta \boldsymbol{d}$, an arrow drawn from the runner's position at the tree to his position at the lamppost. This vector represents his change in position, or **displacement,** during the time interval between t_i and t_f. The length of the arrow represents the distance the runner moved, while the direction the arrow points indicates the direction of the displacement. Displacement is mathematically defined as follows.

■ **Figure 2-10** Start with two vectors, ***A*** and ***B*** **(a).** To subtract vector ***B*** from vector ***A,*** first reverse vector ***B,*** then add them together to obtain the resultant, ***R*** **(b).**



Displacement $\Delta \boldsymbol{d} = \boldsymbol{d}_f - \boldsymbol{d}_i$

Displacement is equal to the final position minus the initial position.

Again, the initial and final positions are the beginning and end of any interval you choose. Also, while position can be considered a vector, it is common practice when doing calculations to drop the boldface, and use signs and magnitudes. This is because position usually is measured from the origin, and direction typically is included with the position indication.

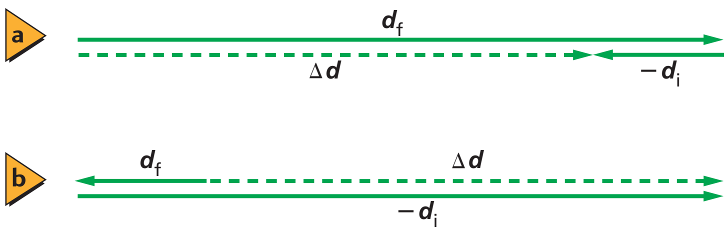


Figure 2-11 The displacement of the runner during the 4.0-s time interval is found by subtracting $\boldsymbol{d}_f$ from $\boldsymbol{d}_i$. In **(a)** the origin is at the left, and in **(b)** it is at the right. Regardless of your choice of coordinate system, $\Delta\boldsymbol{d}$ is the same.

How do you subtract vectors? Reverse the subtracted vector and add. This is because $\boldsymbol{A} - \boldsymbol{B} = \boldsymbol{A} + (-\boldsymbol{B})$. **Figure 2-10a** shows two vectors, $\boldsymbol{A}$, 4 cm long pointing east, and $\boldsymbol{B}$, 1 cm long also pointing east. **Figure 2-10b** shows $-\boldsymbol{B}$, which is 1 cm long pointing west. Figure 2-10b shows the resultant of $\boldsymbol{A}$ and $-\boldsymbol{B}$. It is 3 cm long pointing east.

To determine the length and direction of the displacement vector, $\Delta\boldsymbol{d} = \boldsymbol{d}_f - \boldsymbol{d}_i$, draw $-\boldsymbol{d}_i$, which is $\boldsymbol{d}_i$ reversed. Then draw $\boldsymbol{d}_f$ and copy $-\boldsymbol{d}_i$ with its tail at $\boldsymbol{d}_f$'s tip. Add $\boldsymbol{d}_f$ and $-\boldsymbol{d}_i$. In the example of the runner, his displacement is $\boldsymbol{d}_f - \boldsymbol{d}_i = 25.0\text{ m} - 5.0\text{ m} = 20.0\text{ m}$. He moved to the right of the tree. To completely describe an object's displacement, you must indicate the distance it traveled and the direction it moved. Thus, displacement, a vector, is not identical to distance, a scalar; it is distance and direction.

What would happen if you chose a different coordinate system; that is, if you measured the position of the runner from another location? Look at Figure 2-9, and suppose you change the right side of the *d*-axis to be zero. While the vectors drawn to represent each position change, the length and direction of the displacement vector does not, as shown in **Figures 2-11a** and **b.** The displacement, $\Delta\boldsymbol{d}$, in the time interval from 1.0 s to 5.0 s does not change. Because displacement is the same in any coordinate system, you frequently will use displacement when studying the motion of an object. The displacement vector is always drawn with its flat end, or tail, at the earlier position, and its point, or tip, at the later position.

2.2 Section Review

5. Displacement The particle model for a car traveling on an interstate highway is shown below. The starting point is shown.

Here • • • • • • There

Make a copy of the particle model, and draw a vector to represent the displacement of the car from the starting time to the end of the third time interval.

6. Displacement The particle model for a boy walking to school is shown below.

Home • • • • • • • • • • School

Make a copy of the particle model, and draw vectors to represent the displacement between each pair of dots.

7. Position Two students compared the position vectors they each had drawn on a motion diagram to show the position of a moving object at the same time. They found that their vectors did not point in the same direction. Explain.

8. Critical Thinking A car travels straight along the street from the grocery store to the post office. To represent its motion you use a coordinate system with its origin at the grocery store and the direction the car is moving in as the positive direction. Your friend uses a coordinate system with its origin at the post office and the opposite direction as the positive direction. Would the two of you agree on the car's position? Displacement? Distance? The time interval the trip took? Explain.

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2.3 Position-Time Graphs

▶ **Objectives**

- **Develop** position-time graphs for moving objects.
- **Use** a position-time graph to interpret an object's position or displacement.
- **Make** motion diagrams, pictorial representations, and position-time graphs that are equivalent representations describing an object's motion.

▶ **Vocabulary**

position-time graph
instantaneous position

When analyzing motion, particularly when it is more complex than the examples considered so far, it often is useful to represent the motion of an object in a variety of ways. As you have seen, a motion diagram contains useful information about an object's position at various times and can be helpful in determining the displacement of an object during time intervals. Graphs of the object's position and time also contain this information.

Review Figure 2-9, the motion diagram for the runner with a location to the left of the tree chosen as the origin. From this motion diagram, you can organize the times and corresponding positions of the runner, as in **Table 2-1.**

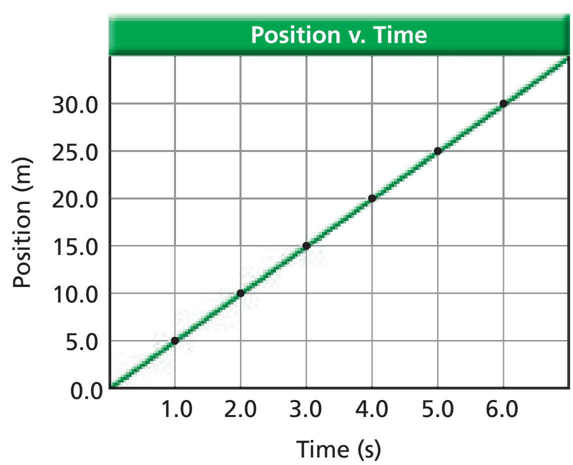
Using a Graph to Find Out Where and When

The data from **Table 2-1** can be presented by plotting the time data on a horizontal axis and the position data on a vertical axis, which is called a **position-time graph.** The graph of the runner's motion is shown in **Figure 2-12.** To draw this graph, first plot the runner's recorded positions. Then, draw a line that best fits the recorded points. Notice that this graph is not a picture of the path taken by the runner as he was moving—the graphed line is sloped, but the path that he ran was flat. The line represents the most likely positions of the runner at the times between the recorded data points. (Recall from Chapter 1 that this line often is referred to as a best-fit line.) This means that even though there is no data point to tell you exactly when the runner was 30.0 m beyond his starting point or where he was at $t = 4.5$ s, you can use the graph to estimate his position. The following example problem shows how. Note that before estimating the runner's position, the questions first are restated in the language of physics in terms of positions and times.

Table 2-1
Position v. Time

Time t (s)	Position d (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
6.0	30.0

■ **Figure 2-12** A position-time graph for the runner can be created by plotting his known position at each of several times. After these points are plotted, the line that best fits them is drawn. The best-fit line indicates the runner's most likely positions at the times between the data points.



EXAMPLE Problem 1

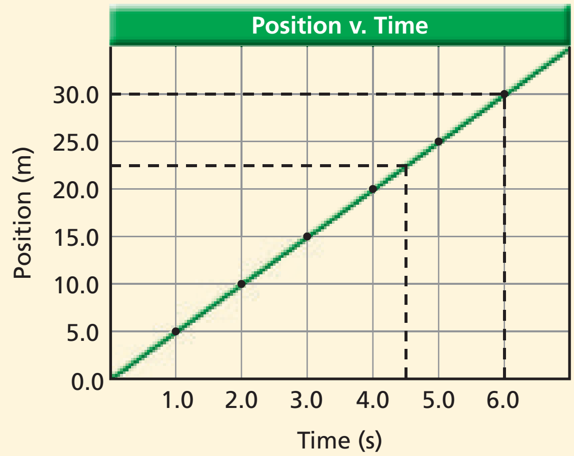
When did the runner whose motion is described in Figure 2-12 reach 30.0 m beyond the starting point? Where was he after 4.5 s?

1 Analyze the Problem

- Restate the questions.

  Question 1: At what time was the position of the object equal to 30.0 m?

  Question 2: What was the position of the object at 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 30.0-m mark. Next, find where a vertical line from that point crosses the time axis. The value of t there is 6.0 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 d is approximately 22.5 m.

The two intersections are shown on the graph above.

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PRACTICE Problems

Additional Problems, Appendix B

*For problems 9–11, refer to **Figure 2-13.***

9. Describe the motion of the car shown by the graph.

10. Draw a motion diagram that corresponds to the graph.

11. Answer the following questions about the car's motion. Assume that the positive d-direction is east and the negative d-direction is west.

   a. When was the car 25.0 m east of the origin?

   b. Where was the car at 1.0 s?

12. Describe, in words, the motion of the two pedestrians shown by the lines in **Figure 2-14.** Assume that the positive direction is east on Broad Street and the origin is the intersection of Broad and High Streets.

13. Odina 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 her position every 2.0 s, noting that she moved 2.6 m every 2.0 s. When was Odina in the following positions?

   a. 25.0 m from the cafeteria

   b. 25.0 m from the band room

   c. Create a graph showing Odina's motion.

Figure 2-13

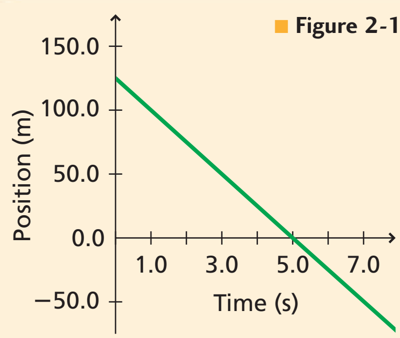
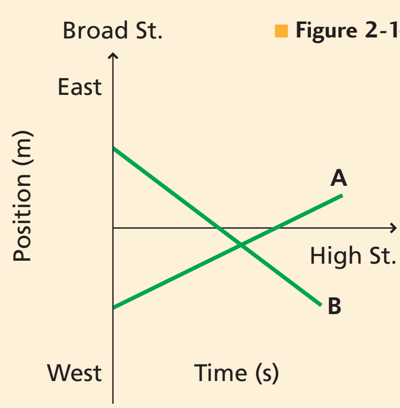
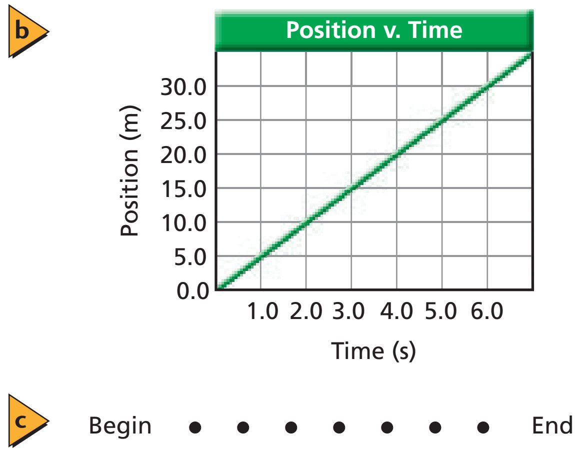


Figure 2-14



a

Table 2-1	
Position v. Time	
Time *t* **(s)**	**Position** *d* **(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
6.0	30.0



■ **Figure 2-15** The data table **(a),** position-time graph **(b),** and particle model **(c)** all represent the same moving object.

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 he would not have been moving. However, as he was moving, an instant is not a finite period of time. This means that an instant of time lasts zero seconds. The symbol ***d*** represents the **instantaneous position** of the runner—the position at a particular instant.

Equivalent representations As shown in **Figure 2-15,** you now have several different ways to describe motion: words, pictures (or pictorial representations), motion diagrams, data tables, and position-time graphs. All of these representations are equivalent. That is, they can all contain the same information about the runner's motion. However, depending on what you want to find out about an object's motion, some of the representations will be more useful than others. In the pages that follow, you will get some practice constructing these equivalent representations and learning which ones are the easiest to use in solving different kinds of problems.

Considering the motion of multiple objects A position-time graph for two different runners in a race is shown in Example Problem 2. When and where does one runner pass the other? First, you need to restate this question in physics terms: At what time do the two objects have the same position? You can evaluate this question by identifying the point on the position-time graph at which the lines representing the two objects intersect.

CHALLENGE PROBLEM

Niram, Oliver, and Phil all enjoy exercising and often go to a path along the river for this purpose. Niram bicycles at a very consistent 40.25 km/h, Oliver runs south at a constant speed of 16.0 km/h, and Phil walks south at a brisk 6.5 km/h. Niram starts biking north at noon from the waterfalls. Oliver 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 within the smallest distance interval?
3. What is the length of that distance interval?

EXAMPLE Problem 2

When and where does runner B pass runner A?

1 Analyze the Problem

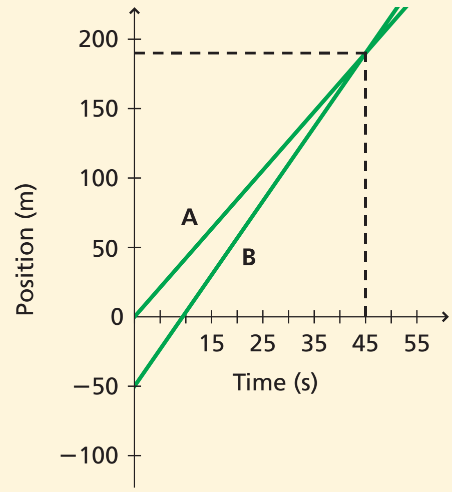
- Restate the question.
  At what time do A and B have the same position?

2 Solve for the Unknown

In the figure at right, examine the graph to find the intersection of the line representing the motion of A with the line representing the motion of B.

These lines intersect at 45 s and at about 190 m.

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



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PRACTICE Problems

Additional Problems, Appendix B

For problems 14–17, refer to the figure in Example Problem 2.

14. What event occurred at t = 0.0 s?

15. Which runner was ahead at t = 48.0 s?

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

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

18. Juanita goes for a walk. Sometime later, her friend Heather starts to walk after her. Their motions are represented by the position-time graphs in **Figure 2-16.**

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

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

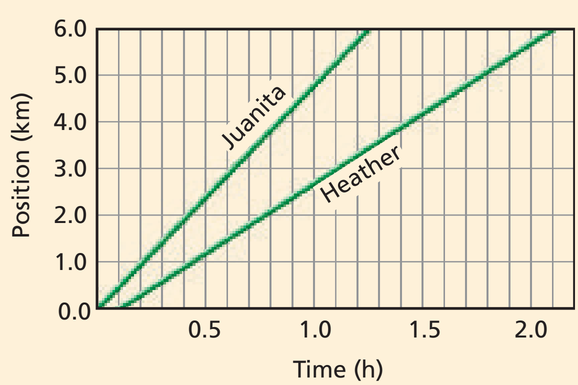


Figure 2-16

As you have seen, you can represent the motion of more than one object on a position-time graph. The intersection of two lines tells you when the two objects have the same position. 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. Later in this textbook, you will learn to represent motion in two dimensions.

Is there anything else that you can learn from a position-time graph? Do you know what the slope of a line means? In the next section, you will use the slope of a line on a position-time graph to determine the velocity of an object. What about the area under a plotted line? In Chapter 3, you will draw other graphs and learn to interpret the areas under the plotted lines. In later chapters you will continue to refine your skills with creating and interpreting graphs.

2.3 Section Review

19. Position-Time Graph From the particle model in **Figure 2-17** of a baby crawling across a kitchen floor, plot a position-time graph to represent his motion. The time interval between successive dots is 1 s.

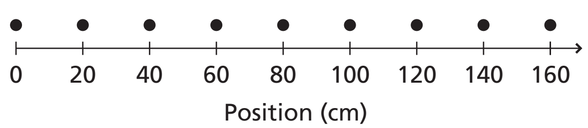


Figure 2-17

20. Motion Diagram Create a particle model from the position-time graph of a hockey puck gliding across a frozen pond in **Figure 2-18.**

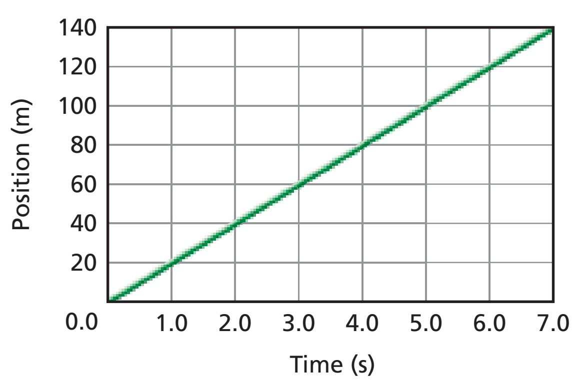


Figure 2-18

For problems 21–23, refer to Figure 2-18.

21. Time Use the position-time graph of the hockey puck to determine when it was 10.0 m beyond the origin.

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

23. Time Interval Use the position-time graph for the hockey puck to determine how much time it took for the puck to go from 40 m beyond the origin to 80 m beyond the origin.

24. Critical Thinking Look at the particle model and position-time graph shown in **Figure 2-19.** Do they describe the same motion? How do you know? Do not confuse the position coordinate system in the partical model with the horizontal axis in the position-time graph. The time intervals in the partical model are 2 s.

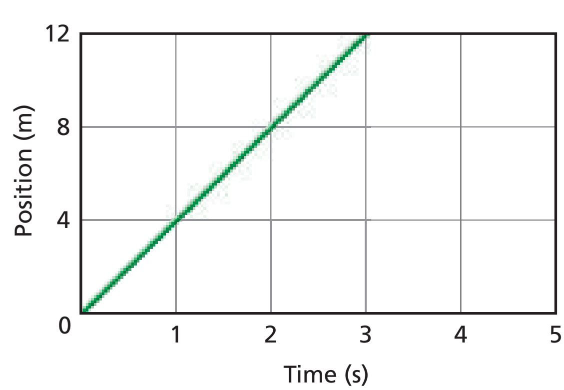


Figure 2-19

2.4 How Fast?

You have learned how to use a motion diagram to show an object's movement. How can you measure how fast it is moving? With devices such as a meterstick and a stopwatch, you can measure position and time. Can this information be used to describe the rate of motion?

▶ **Objectives**

- **Define** velocity.
- **Differentiate** between speed and velocity.
- **Create** pictorial, physical, and mathematical models of motion problems.

▶ **Vocabulary**

average velocity
average speed
instantaneous velocity

Velocity

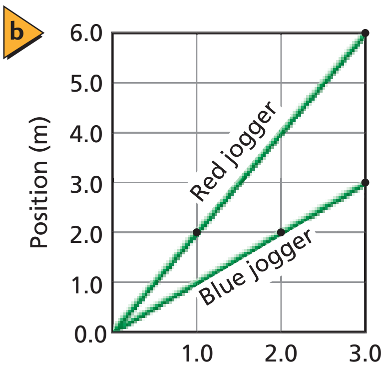
Suppose you recorded two joggers on one motion diagram, as shown in **Figure 2-20a.** From one frame to the next you can see that the position of the jogger in red shorts changes more than that of the one wearing blue. In other words, for a fixed time interval, the displacement, $\Delta \boldsymbol{d}$, is greater for the jogger in red because she is moving faster. She covers a larger distance than the jogger in blue does in the same amount of time. Now, suppose that each jogger travels 100.0 m. The time interval, Δt, would be smaller for the jogger in red than for the one in blue.

Average velocity From the example of the joggers, you can see that both the displacement, $\Delta \boldsymbol{d}$, and time interval, Δt, might be needed to create the quantity that tells how fast an object is moving. How might they be combined? Compare the lines representing the red and blue joggers in the position-time graphs in **Figure 2-20b.** The slope of the red jogger's line is steeper than the slope of the blue jogger's line. A steeper slope indicates a greater change in displacement during each time interval.

Recall from Chapter 1 that to find the slope, you first choose two points on the line. Next, you subtract the vertical coordinate (d 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. Finally, you divide the rise by the run to obtain the slope. The slopes of the two lines shown in Figure 2-20b are found as follows:

$$\text{Red slope} = \frac{d_f - d_i}{t_f - t_i} = \frac{6.0\text{ m} - 2.0\text{ m}}{3.0\text{ s} - 1.0\text{ s}} = 2.0\text{ m/s}$$

$$\text{Blue slope} = \frac{d_f - d_i}{t_f - t_i} = \frac{3.0\text{ m} - 2.0\text{ m}}{3.0\text{ s} - 2.0\text{ s}} = 1.0\text{ m/s}$$



■ **Figure 2-20** The red jogger's displacement is greater than the displacement of the blue jogger in each time interval because the jogger in red is moving faster than the jogger in blue **(a).** The position-time graph represents the motion of the red and blue joggers. The points used to calculate the slope of each line are shown **(b).**

Hutchings Photography

APPLYING PHYSICS

Speed Records The world record for the men's 100-m dash is 9.78 s, established in 2002 by Tim Montgomery. The world record for the women's 100-m dash is 10.65 s, established in 1998 by Marion Jones. These sprinters often are referred to as the world's fastest man and woman.

There are some important things to notice about this comparison. First, the slope of the faster runner is a greater number, so it is reasonable to assume that this number might be connected with the runner's speed. Second, look at the units of the slope, meters per second. In other words, the slope tells how many meters the runner moved in 1 s. These units are similar to miles per hour, which also measure speed. Looking at how the slope is calculated, you can see that slope is the change in position, divided by the time interval during which that change took place, or $(d_f - d_i) / (t_f - t_i)$, or $\Delta \boldsymbol{d}/\Delta t$. When $\Delta \boldsymbol{d}$ gets larger, the slope gets larger; when Δt gets larger, the slope gets smaller. This agrees with the interpretation above of the movements of the red and blue joggers. The slope of a position-time graph for an object is the object's **average velocity** and is represented by the ratio of the change of position to the time interval during which the change occurred.

Average Velocity $$\bar{\boldsymbol{v}} \equiv \frac{\Delta \boldsymbol{d}}{\Delta t} = \frac{\boldsymbol{d}_f - \boldsymbol{d}_i}{t_f - t_i}$$

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

Color Convention

- Velocity vectors are **red.**
- Displacement vectors are **green.**

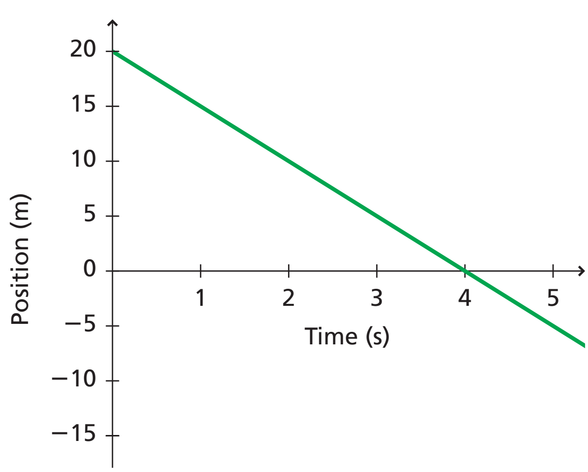
The symbol $\equiv$ means that the left-hand side of the equation is defined by the right-hand side.

It is a common misconception to say that the slope of a position-time graph gives the speed of the object. Consider the slope of the position-time graph shown in **Figure 2-21.** The slope of this position-time graph is −5.0 m/s. As you can see the slope indicates both the magnitude and direction. Recall that average velocity is a quantity that has both magnitude and direction. The slope of a position-time graph indicates the average velocity of the object and not its speed. Take another look at Figure 2-21. The slope of the graph is −5.0 m/s and thus, the object has a velocity of −5.0 m/s. The object starts out at a positive position and moves toward the origin. It moves in the negative direction at a rate of 5.0 m/s.

Average speed The absolute value of the slope of a position-time graph tells you the **average speed** of the object; that is, how fast the object is moving. The sign of the slope tells you in what direction the object is moving. The combination of an object's average speed, $\bar{v}$, and the direction in which it is moving is the average velocity, $\bar{\boldsymbol{v}}$. Thus, for the object represented in Figure 2-21, the average velocity is −5.0 m/s, or 5.0 m/s in the negative direction. Its average speed is 5.0 m/s. Remember that if an object moves in the negative direction, then its displacement is negative. This means that the object's velocity always will have the same sign as the object's displacement.

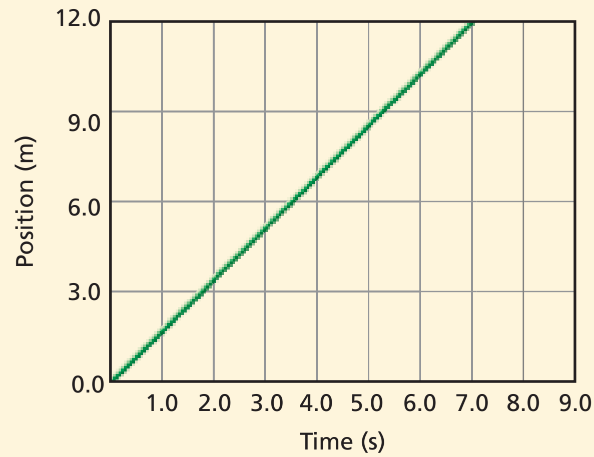
As you consider other types of motion to analyze in future chapters, sometimes the velocity will be the important quantity to consider, while at other times, the speed will be the important quantity. Therefore, it is a good idea to make sure that you understand the differences between velocity and speed so that you will be sure to use the right one later.

Figure 2-21 The object whose motion is represented here is moving in the negative direction at a rate of 5.0 m/s.



▶ EXAMPLE Problem 3

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



1 Analyze and Sketch the Problem

- Identify the coordinate system of the graph.

2 Solve for the Unknown

Unknown:

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

Find the average velocity using two points on the line.

$$\bar{\boldsymbol{v}} = \frac{\Delta d}{\Delta t}$$

Use magnitudes with signs indicating directions.

$$= \frac{d_2 - d_1}{t_2 - t_1}$$

$$= \frac{12.0\text{ m} - 6.0\text{ m}}{8.0\text{ s} - 4.0\text{ s}}$$

Substitute d_2 = 12.0 m, d_1 = 6.0 m, t_2 = 8.0 s, t_1 = 4.0 s.

$\bar{\boldsymbol{v}}$ = 1.5 m/s in the positive direction

The average speed, $\bar{v}$, is the absolute value of the average velocity, or 1.5 m/s.

Math Handbook
Slope
page 850

3 Evaluate the Answer

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

▶ PRACTICE Problems

Additional Problems, Appendix B

25. The graph in **Figure 2-22** describes the motion of a cruise ship during its voyage through calm waters. The positive *d*-direction is defined to be south.

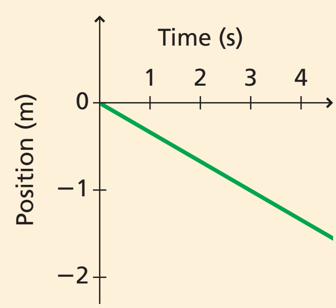
a. What is the ship's average speed?

b. What is its average velocity?

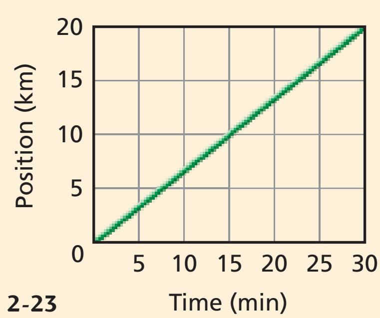
26. Describe, in words, the motion of the cruise ship in the previous problem.

27. The graph in **Figure 2-23** represents the motion of a bicycle. Determine the bicycle's average speed and average velocity, and describe its motion in words.

28. When Marilyn takes her pet dog for a walk, the dog walks at a very consistent pace of 0.55 m/s. Draw a motion diagram and position-time graph to represent Marilyn's dog walking the 19.8-m distance from in front of her house to the nearest fire hydrant.



■ **Figure 2-22**



■ **Figure 2-23**

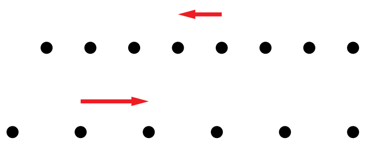


Figure 2-24 Average velocity vectors have the same direction as their corresponding displacement vectors. Their lengths are different, but proportional, and they have different units because they are obtained by dividing the displacement by the time interval.

Instantaneous Velocity

Why is the quantity $\Delta \boldsymbol{d}/\Delta t$ called average velocity? Why isn't it called velocity? Think about how a motion diagram is constructed. 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 speed of the object could have remained the same, increased, or decreased. The object may have stopped or even changed direction. All that can be determined from the motion diagram is an average velocity, which is found by dividing the total displacement by the time interval in which it took place. The speed and 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 $\boldsymbol{v}$.

Average Velocity on Motion Diagrams

How can you show average velocity on a motion diagram? Although the average velocity is in the same direction as displacement, the two quantities are not measured using the same units. Nevertheless, they are proportional—when displacement is greater during a given time interval, so is average velocity. A motion diagram is not a precise graph of average velocity, but you can indicate the direction and magnitude of the average velocity on it. Imagine two cars driving down the road at different speeds. A video camera records their motions at the rate of one frame every second. Imagine that each car has a paintbrush attached to it that automatically descends and paints a 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 made by the paintbrushes on the ground below the cars. Red is used to indicate velocity vectors on motion diagrams. **Figure 2-24** shows the particle models, complete with velocity vectors, for two cars: one moving to the right and the other moving more slowly to the left.

Using equations Any time you graph a straight line, you can find an equation to describe it. There will be many cases for which it will be more efficient to use such an equation instead of a graph to solve problems. Take another look at the graph in Figure 2-21 on page 44 for the object moving with a constant velocity of -5.0 m/s. Recall from Chapter 1 that any straight line can be represented by the formula: $y = mx + b$ where y is the quantity plotted on the vertical axis, m is the slope of the line, x is the quantity plotted on the horizontal axis, and b is the y-intercept of the line.

For the graph in Figure 2-21, the quantity plotted on the vertical axis is position, and the variable used to represent position is $\boldsymbol{d}$. The slope of the line 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? By inspecting the graph and thinking about how the object moves, you can figure out 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 is designated $\boldsymbol{d}_i$. **Table 2-2** summarizes how the general variables in the straight-line formula are changed to the specific variables you have been using to describe motion. It also shows the numerical values for the two constants in this equation.

MINI LAB

Instantaneous Velocity Vectors

1. Attach a 1-m-long string to your hooked mass.
2. Hold the string in one hand with the mass suspended.
3. Carefully pull the mass to one side and release it.
4. **Observe** the motion, the speed, and direction of the mass for several swings.
5. Stop the mass from swinging.
6. Draw a diagram showing instantaneous velocity vectors at the following points: top of the swing, midpoint between top and bottom, bottom of the swing, midpoint between bottom and top, and back to the top of the swing.

Analyze and Conclude

7. Where was the velocity greatest?
8. Where was the velocity least?
9. **Explain** how the average speed can be determined using your vector diagram.

Based on the information shown in Table 2-2, the equation $y = mx + b$ becomes $\boldsymbol{d} = \bar{\boldsymbol{v}}t + \boldsymbol{d}_i$, or, by inserting the values of the constants, $d = (-5.0\ \text{m/s})t + 20.0\ \text{m}$. This equation describes the motion that is represented in Figure 2-21. You can check this by plugging a value of t into the equation and seeing that you obtain the same value of $\boldsymbol{d}$ as when you read it directly from the graph. To conduct an extra check to be sure the equation makes sense, take a look at the units. You cannot set two items with different units equal to each other in an equation. In this equation, the left-hand side is a position, so its units are meters. The first term on the right-hand side multiplies meters per second times seconds, so its units are also meters. The last term is in meters, too, so the units on this equation are valid.

Connecting Math to Physics

Table 2-2

Comparison of Straight Lines with Position-Time Graphs

General Variable	Specific Motion Variable	Value in Figure 2-21
y	$\boldsymbol{d}$	
m	$\bar{\boldsymbol{v}}$	−5.0 m/s
x	$\boldsymbol{t}$	
b	$\boldsymbol{d}_i$	20.0 m

Equation of Motion for Average Velocity $\quad \boldsymbol{d} = \bar{\boldsymbol{v}}t + \boldsymbol{d}_i$

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

This equation gives you another way to represent the motion of an object. Note that once a coordinate system is chosen, the direction of $\boldsymbol{d}$ is specified by positive and negative values, and the boldface notation can be dispensed with, as in "d-axis." However, the boldface notation for velocity will be retained to avoid confusing it with speed.

Your toolbox of representations now includes words, motion diagrams, pictures, data tables, position-time graphs, and an equation. You should be able to use any one of these representations to generate at least the characteristics of the others. You will get more practice with this in the rest of this chapter and also in Chapter 3 as you apply these representations to help you solve problems.

2.4 Section Review

*For problems 29–31, refer to **Figure 2-25.***

29. Average Speed Rank the position-time graphs according to the average speed of the object, from greatest average speed to least average speed. Specifically indicate any ties.

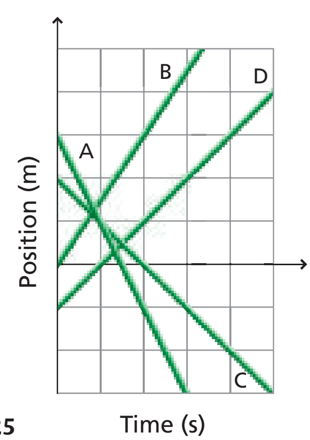


Figure 2-25

30. Average Velocity Rank the graphs according to average velocity, from greatest average velocity to least average velocity. Specifically indicate any ties.

31. Initial Position Rank the graphs according to the object's initial position, from most positive position to most negative position. Specifically indicate any ties. Would your ranking be different if you had been asked to do the ranking according to initial distance from the origin?

32. Average Speed and Average Velocity Explain how average speed and average velocity are related to each other.

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

PHYSICS LAB

Creating Motion Diagrams

Alternate CBL instructions can be found on the Web site.
physicspp.com

In this activity you will construct motion diagrams for two toy cars. A motion diagram consists of a series of images showing the positions of a moving object at equal time intervals. Motion diagrams help describe the motion of an object. By looking at a motion diagram you can determine whether an object is speeding up, slowing down, or moving at constant speed.

Horizons Companies

QUESTION

How do the motion diagrams of a fast toy car and a slow toy car differ?

Objectives

- **Measure in SI** the location of a moving object.
- **Recognize spatial relationships** of moving objects.
- **Describe** the motion of a fast and slow object.

Safety Precautions

Materials

video camera
two toy windup cars
meterstick
foam board

Procedure

1. Mark a starting line on the lab table or the surface recommended by your teacher.
2. Place both toy cars at the starting line and release them at the same time. Be sure to wind them up before releasing them.
3. Observe both toy cars and determine which one is faster.
4. Place the slower toy car at the starting line.
5. Place a meterstick parallel to the path the toy car will take.
6. Have one of the members of your group get ready to operate the video camera.
7. Release the slower toy car from the starting line. Be sure to wind up the toy car before releasing it.
8. Use the video camera to record the slower toy car's motion parallel to the meterstick.
9. Set the recorder to play the tape frame by frame. Replay the video tape for 0.5 s, pressing the pause button every 0.1 s (3 frames).
10. Determine the toy car's position for each time interval by reading the meterstick on the video tape and record it in the data table.
11. Repeat steps 5–10 with the faster car.
12. Place a piece of foam board at an angle of approximately 30° to form a ramp.
13. Place the meterstick on the ramp so that it is parallel to the path the toy car will take.
14. Place the slower toy car at the top of the ramp and repeat steps 6–10.

CONTENTS

Data Table 1

Time (s)	Position of the Slower Toy Car (cm)
0.0	
0.1	
0.2	
0.3	
0.4	
0.5	

Data Table 2

Time (s)	Position of the Faster Toy Car (cm)
0.0	
0.1	
0.2	
0.3	
0.4	
0.5	

Data Table 3

Time (s)	Position of the Slower Toy Car on the Ramp (cm)
0.0	
0.1	
0.2	
0.3	
0.4	
0.5	

Analyze

1. Draw a motion diagram for the slower toy car using the data you collected.
2. Draw a motion diagram for the faster toy car using the data you collected.
3. Using the data you collected, draw a motion diagram for the slower toy car rolling down the ramp.

Conclude and Apply

How is the motion diagram of the faster toy car different from the motion diagram of the slower toy car?

Going Further

1. Draw a motion diagram for a car moving at a constant speed.
2. What appears to be the relationship between the distances between points in the motion diagram of a car moving at a constant speed?
3. Draw a motion diagram for a car that starts moving fast and then begins to slow down.
4. What happens to the distance between points in the motion diagram in the previous question as the car slows down?
5. Draw a motion diagram for a car that starts moving slowly and then begins to speed up.
6. What happens to the distance between points in the motion diagram in the previous question as the car speeds up?

Real-World Physics

Suppose a car screeches to a halt to avoid an accident. If that car has antilock brakes that pump on and off automatically every fraction of a second, what might the tread marks on the road look like? Include a drawing along with your explanation of what the pattern of tread marks on the road might look like.

Physics Online

To find out more about representing motion, visit the Web site: **physicspp.com**

eXtreme physics

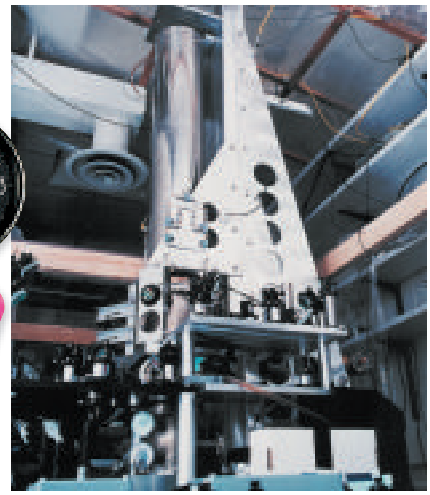
Accurate Time

What time is it really? You might use a clock to find out what time it is at any moment. A clock is a device that counts regularly recurring events in order to measure time. Suppose the clock in your classroom reads 9:00. Your watch, however, reads 8:55, and your friend's watch reads 9:02. So what time is it, really? Which clock or watch is accurate?

Many automated processes are controlled by clocks. For example, an automated bell that signals the end of a class period is controlled by a clock. Thus, if you wanted to be on time for a class you would have to synchronize your watch to the one controlling the bell. Other processes, such as GPS navigation, space travel, internet synchronization, transportation, and communication, rely on clocks with extreme precision and accuracy. A reliable standard clock that can measure when exactly one second has elapsed is needed.

The Standard Cesium Clock Atomic clocks, such as cesium clocks, address this need. Atomic clocks measure the number of times the atom used in the clock switches its energy state. Such oscillations in an atom's energy occur very quickly and regularly. The National Institute of Standards and Technology (NIST) currently uses the oscillations of the cesium atom to determine the standard 1-s interval. One second is defined as the duration of 9,192,631,770 oscillations of the cesium atom.

The cesium atom has a single electron in its outermost energy level. This outer electron spins and behaves like a miniature magnet. The cesium nucleus also spins and acts like a miniature magnet. The nucleus and electron may spin in such a manner that their north magnetic poles are aligned. The nucleus and electron also may spin in a way that causes opposite poles to be aligned. If the poles are aligned, the cesium atom is in one energy state. If they are oppositely aligned, the atom is in another energy state. A microwave with a particular frequency can strike a cesium atom and cause the outside spinning electron to switch its magnetic pole orientation and change the atom's energy state. As a result, the atom emits light. This occurs at cesium's natural frequency of 9,192,631,770 cycles/s. This principle was used to design the cesium clock.



The cesium clock, *NIST-F1*, located at the NIST laboratories in Boulder, Colorado is among the most accurate clocks in the world.

How Does the Cesium Clock Work? The cesium clock consists of cesium atoms and a quartz crystal oscillator, which produces microwaves. When the oscillator's microwave signal precisely equals cesium's natural frequency, a large number of cesium atoms will change their energy state. Cesium's natural frequency is equal to 9,192,631,770 microwave cycles. Thus, there are 9,192,631,770 cesium energy level changes in 1 s. Cesium clocks are so accurate that a modern cesium clock is off by less than 1 s in 20 million years.

Going Further

1. **Research** What processes require the precise measurement of time?
2. **Analyze and Conclude** Why is the precise measurement of time essential to space navigation?

National Institute of Standards and Technology

Study Guide

2.1 Picturing Motion

Vocabulary

- motion diagram (p. 33)
- particle model (p. 33)

Key Concepts

- A motion diagram shows the position of an object at successive times.
- In the particle model, the object in the motion diagram is replaced by a series of single points.

2.2 Where and When?

Vocabulary

- coordinate system (p. 34)
- origin (p. 34)
- position (p. 34)
- distance (p. 34)
- magnitude (p. 35)
- vectors (p. 35)
- scalars (p. 35)
- resultant (p. 35)
- time interval (p. 36)
- displacement (p. 36)

Key Concepts

- You can define any coordinate system you wish in describing motion, but some are more useful than others.
- A time interval is the difference between two times.

$$\Delta t = t_f - t_i$$

- A vector drawn from the origin of the coordinate system to the object indicates the object's position.
- Change in position is displacement, which has both magnitude and direction.

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

- The length of the displacement vector represents how far the object was displaced, and the vector points in the direction of the displacement.

2.3 Position-Time Graphs

Vocabulary

- position-time graph (p. 38)
- instantaneous position (p. 40)

Key Concepts

- Position-time graphs can be used to find the velocity and position of an object, as well as where and when two objects meet.
- Any motion can be described using words, motion diagrams, data tables, and graphs.

2.4 How Fast?

Vocabulary

- average velocity (p. 44)
- average speed (p. 44)
- instantaneous velocity (p. 46)

Key Concepts

- The slope of an object's position-time graph is the average velocity of the object's motion.

$$\bar{\boldsymbol{v}} = \frac{\Delta \boldsymbol{d}}{\Delta t} = \frac{\boldsymbol{d}_f - \boldsymbol{d}_i}{t_f - t_i}$$

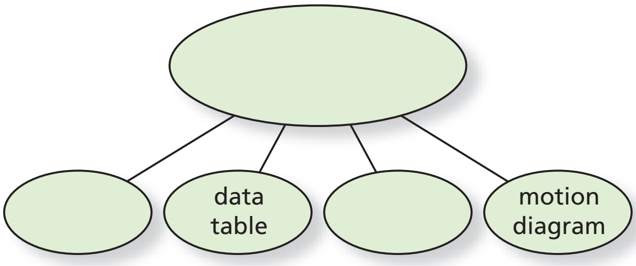
- The average speed is the absolute value of the average velocity.
- An object's velocity is how fast it is moving and in what direction it is moving.
- An object's initial position, $\boldsymbol{d}_i$, its constant average velocity, $\bar{\boldsymbol{v}}$, its position, $\boldsymbol{d}$, and the time, t, since the object was at its initial position are related by a simple equation.

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

Assessment

Concept Mapping

34. Complete the concept map below using the following terms: *words, equivalent representations, position-time graph.*



Mastering Concepts

35. What is the purpose of drawing a motion diagram? (2.1)

36. Under what circumstances is it legitimate to treat an object as a point particle? (2.1)

37. The following quantities describe location or its change: position, distance, and displacement. Briefly describe the differences among them. (2.2)

38. How can you use a clock to find a time interval? (2.2)

39. In-line Skating How can you use the position-time graphs for two in-line skaters to determine if and when one in-line skater will pass the other one? (2.3)

40. Walking Versus Running A walker and a runner leave your front door at the same time. They move in the same direction at different constant velocities. Describe the position-time graphs of each. (2.4)

41. What does the slope of a position-time graph measure? (2.4)

42. If you know the positions of a moving object at two points along its path, and you also know the time it took for the object to get from one point to the other, can you determine the particle's instantaneous velocity? Its average velocity? Explain. (2.4)

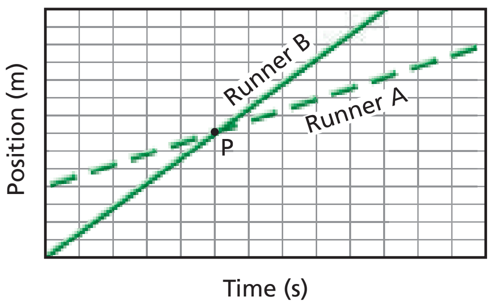
Applying Concepts

43. Test the following combinations and explain why each does not have the properties needed to describe the concept of velocity: $\Delta d + \Delta t$, $\Delta d - \Delta t$, $\Delta d \times \Delta t$, $\Delta t/\Delta d$.

44. Football When can a football be considered a point particle?

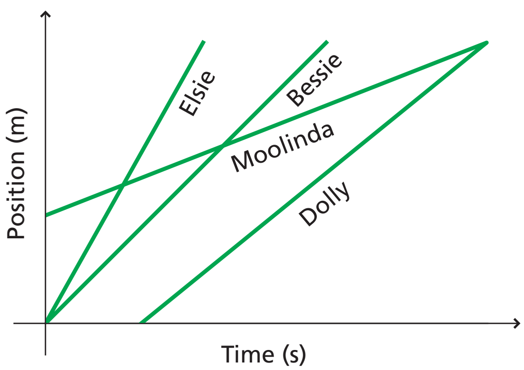
45. When can a football player be treated as a point particle?

46. Figure 2-26 is a graph of two people running.
- **a.** Describe the position of runner A relative to runner B at the *y*-intercept.
- **b.** Which runner is faster?
- **c.** What occurs at point P and beyond?



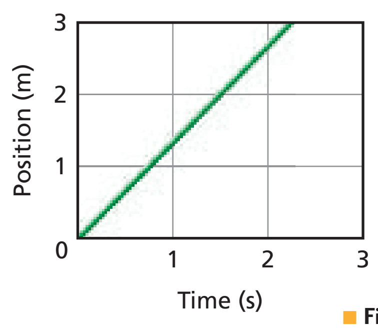
■ **Figure 2-26**

47. The position-time graph in **Figure 2-27** shows the motion of four cows walking from the pasture back to the barn. Rank the cows according to their average velocity, from slowest to fastest.



■ **Figure 2-27**

48. Figure 2-28 is a position-time graph for a rabbit running away from a dog.
- **a.** Describe how this graph would be different if the rabbit ran twice as fast.
- **b.** Describe how this graph would be different if the rabbit ran in the opposite direction.



■ **Figure 2-28**

 For more problems, go to Additional Problems, Appendix B.

Mastering Problems

2.4 How Fast?

49. A bike travels at a constant speed of 4.0 m/s for 5.0 s. How far does it go?

50. **Astronomy** Light from the Sun reaches Earth in 8.3 min. The speed of light is 3.00×10^8 m/s. How far is Earth from the Sun?

51. A car is moving down a street at 55 km/h. A child suddenly runs into the street. If it takes the driver 0.75 s to react and apply the brakes, how many meters will the car have moved before it begins to slow down?

52. Nora jogs several times a week and always keeps track of how much time she runs each time she goes out. One day she forgets to take her stopwatch with her and wonders if there's a way she can still have some idea of her time. As she passes a particular bank, she remembers that it is 4.3 km from her house. She knows from her previous training that she has a consistent pace of 4.0 m/s. How long has Nora been jogging when she reaches the bank?

53. **Driving** You and a friend each drive 50.0 km. You travel at 90.0 km/h; your friend travels at 95.0 km/h. How long will your friend have to wait for you at the end of the trip?

Mixed Review

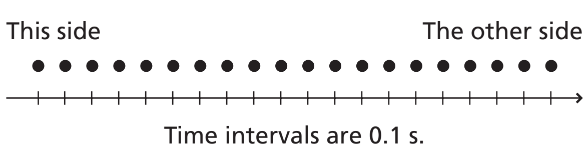
54. **Cycling** A cyclist maintains a constant velocity of +5.0 m/s. At time t = 0.0 s, the cyclist is +250 m from point A.

a. Plot a position-time graph of the cyclist's location from point A at 10.0-s intervals for 60.0 s.

b. What is the cyclist's position from point A at 60.0 s?

c. What is the displacement from the starting position at 60.0 s?

55. **Figure 2-29** is a particle model for a chicken casually walking across the road. Time intervals are every 0.1 s. Draw the corresponding position-time graph and equation to describe the chicken's motion.



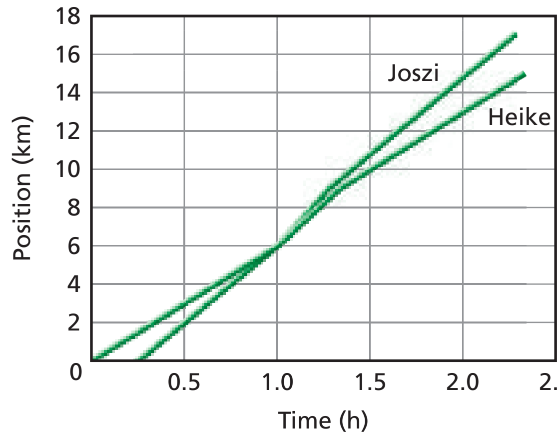
■ **Figure 2-29**

56. **Figure 2-30** shows position-time graphs for Joszi and Heike paddling canoes in a local river.

a. At what time(s) are Joszi and Heike in the same place?

b. How much time does Joszi spend on the river before he passes Heike?

c. Where on the river does it appear that there might be a swift current?



■ **Figure 2-30**

57. **Driving** Both car A and car B leave school when a stopwatch reads zero. Car A travels at a constant 75 km/h, and car B travels at a constant 85 km/h.

a. Draw a position-time graph showing the motion of both cars. How far are the two cars from school when the stopwatch reads 2.0 h? Calculate the distances and show them on your graph.

b. Both cars passed a gas station 120 km from the school. When did each car pass the gas station? Calculate the times and show them on your graph.

58. Draw a position-time graph for two cars traveling to the beach, which is 50 km from school. At noon, Car A leaves a store that is 10 km closer to the beach than the school is and moves at 40 km/h. Car B starts from school at 12:30 P.M. and moves at 100 km/h. When does each car get to the beach?

59. Two cars travel along a straight road. When a stopwatch reads t = 0.00 h, car A is at d_A = 48.0 km moving at a constant 36.0 km/h. Later, when the watch reads t = 0.50 h, car B is at d_B = 0.00 km moving at 48.0 km/h. Answer the following questions, first, graphically by creating a position-time graph, and second, algebraically by writing equations for the positions d_A and d_B as a function of the stopwatch time, t.

a. What will the watch read when car B passes car A?

b. At what position will car B pass car A?

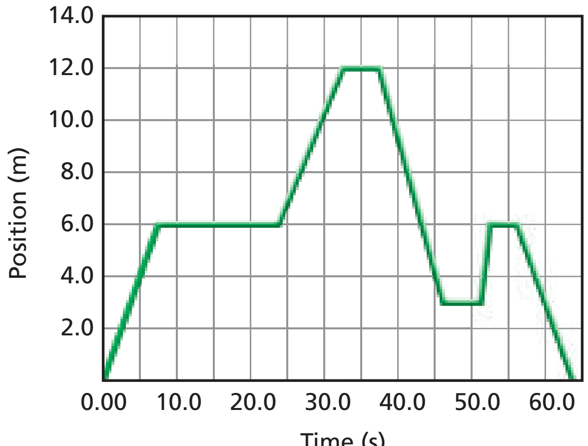
c. When the cars pass, how long will it have been since car A was at the reference point?

60. **Figure 2-31** shows the position-time graph depicting Jim's movement up and down the aisle at a store. The origin is at one end of the aisle.

a. Write a story describing Jim's movements at the store that would correspond to the motion represented by the graph.

b. When does Jim have a position of 6.0 m?

c. How much time passes between when Jim enters the aisle and when he gets to a position of 12.0 m? What is Jim's average velocity between 37.0 s and 46.0 s?



■ Figure 2-31

Thinking Critically

61. **Apply Calculators** Members of a physics class stood 25 m apart and used stopwatches to measure the time at which a car traveling on the highway passed each person. Their data are shown in **Table 2-3.**

Table 2-3
Position v. Time

Time	Position (m)
0.0	0.0
1.3	25.0
2.7	50.0
3.6	75.0
5.1	100.0
5.9	125.0
7.0	150.0
8.6	175.0
10.3	200.0

Use a graphing calculator to fit a line to a position-time graph of the data and to plot this line. Be sure to set the display range of the graph so that all the data fit on it. Find the slope of the line. What was the speed of the car?

62. **Apply Concepts** You plan a car trip for which you want to average 90 km/h. You cover the first half of the distance at an average speed of only 48 km/h. What must your average speed be in the second half of the trip to meet your goal? Is this reasonable? Note that the velocities are based on half the distance, not half the time.

63. **Design an Experiment** Every time a particular red motorcycle is driven past your friend's home, his father becomes angry because he thinks the motorcycle is going too fast for the posted 25 mph (40 km/h) speed limit. Describe a simple experiment you could do to determine whether or not the motorcycle is speeding the next time it is driven past your friend's house.

64. **Interpret Graphs** Is it possible for an object's position-time graph to be a horizontal line? A vertical line? If you answer yes to either situation, describe the associated motion in words.

Writing in Physics

65. Physicists have determined that the speed of light is 3.00×10^8 m/s. How did they arrive at this number? Read about some of the series of experiments that were done to determine light's speed. Describe how the experimental techniques improved to make the results of the experiments more accurate.

66. Some species of animals have good endurance, while others have the ability to move very quickly, but for only a short amount of time. Use reference sources to find two examples of each quality and describe how it is helpful to that animal.

Cumulative Review

67. Convert each of the following time measurements to its equivalent in seconds. (Chapter 1)

a. 58 ns
b. 0.046 Gs
c. 9270 ms
d. 12.3 ks

68. State the number of significant digits in the following measurements. (Chapter 1)

a. 3218 kg
b. 60.080 kg
c. 801 kg
d. 0.000534 kg

69. Using a calculator, Chris obtained the following results. Rewrite the answer to each operation using the correct number of significant digits. (Chapter 1)

a. 5.32 mm + 2.1 mm = 7.4200000 mm

b. 13.597 m × 3.65 m = 49.62905 m^2

c. 83.2 kg − 12.804 kg = 70.3960000 kg

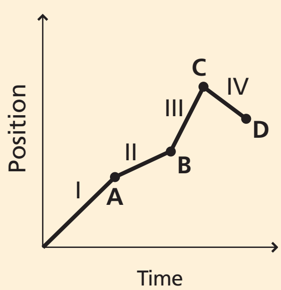
Standardized Test Practice

Multiple Choice

1. Which of the following statements would be true about the particle model motion diagram for an airplane taking off from an airport?
   - (A) The dots would form an evenly spaced pattern.
   - (B) The dots would be far apart at the beginning, but get closer together as the plane accelerated.
   - (C) The dots would be close together to start with, and get farther apart as the plane accelerated.
   - (D) The dots would be close together to start, get farther apart, and become close together again as the airplane leveled off at cruising speed.

2. Which of the following statements about drawing vectors is false?
   - (A) A vector diagram is needed to solve all physics problems properly.
   - (B) The length of the vector should be proportional to the data.
   - (C) Vectors can be added by measuring the length of each vector and then adding them together.
   - (D) Vectors can be added in straight lines or in triangle formations.

Use this graph for problems 3–5.



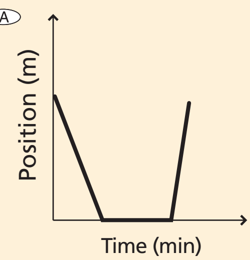
3. The graph shows the motion of a person on a bicycle. When does the person have the greatest velocity?
   - (A) section I
   - (B) section III
   - (C) point D
   - (D) point B

4. When is the person on the bicycle farthest away from the starting point?
   - (A) point A
   - (B) point B
   - (C) point C
   - (D) point D

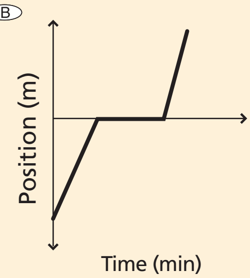
5. Over what interval does the person on the bicycle travel the greatest distance?
   - (A) section I
   - (B) section II
   - (C) section III
   - (D) point IV

6. A squirrel descends an 8-m tree at a constant speed in 1.5 min. It remains still at the base of the tree for 2.3 min, and then walks toward an acorn on the ground for 0.7 min. A loud noise causes the squirrel to scamper back up the tree in 0.1 min to the exact position on the branch from which it started. Which of the following graphs would accurately represent the squirrel's vertical displacement from the base of the tree?

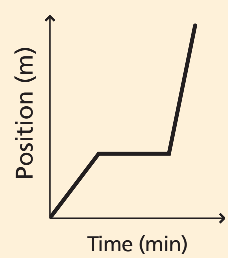
   (A)



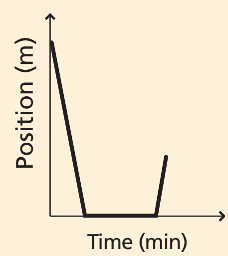
   (B)



   (C)



   (D)



Extended Answer

7. Find a rat's total displacement at the exit if it takes the following path in a maze: start, 1.0 m north, 0.3 m east, 0.8 m south, 0.4 m east, finish.

✓ Test-Taking TIP

Stock up on Supplies

Bring all your test-taking tools: number two pencils, black and blue pens, erasers, correction fluid, a sharpener, a ruler, a calculator, and a protractor.

Chapter 3

Accelerated Motion

What You'll Learn

- You will develop descriptions of accelerated motion.
- You will use graphs and equations to solve problems involving moving objects.
- You will describe the motion of objects in free fall.

Why It's Important

Objects do not always move at constant velocities. Understanding accelerated motion will help you better decribe the motion of many objects.

Acceleration Cars, planes, subways, elevators, and other common forms of transportation often begin their journeys by speeding up quickly, and end by stopping rapidly.

Think About This ▶

The driver of a dragster on the starting line waits for the green light to signal the start of the race. At the signal, the driver will step on the gas pedal and try to speed up as quickly as possible. As the car speeds up, how will its position change?

Physics Online

physicspp.com

Rob Tringali/SportsChrome

LAUNCH Lab

Do all types of motion look the same when graphed?

Question

How does a graph showing constant speed compare to a graph of a vehicle speeding up?

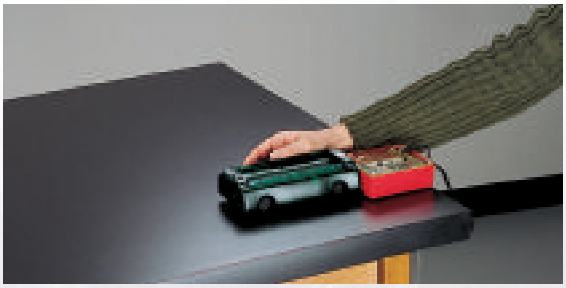
Procedure

1. Clamp a spark timer to the back edge of a lab table.
2. Cut a piece of timer tape approximately 50 cm in length, insert it into the timer, and tape it to vehicle 1.
3. Turn on the timer and release the vehicle. Label the tape with the vehicle number.
4. Raise one end of the lab table 8–10 cm by placing a couple of bricks under the back legs. ***CAUTION: Make sure the lab table remains stable.***
5. Repeat steps 2–4 with vehicle 2, but hold the vehicle in place next to the timer and release it after the timer has been turned on. Catch the vehicle before it falls.
6. **Construct and Organize Data** Mark the first dark dot where the timer began as *zero.* Measure the distance to each dot from the zero dot for 10 intervals and record your data.
7. **Make and Use Graphs** Make a graph of total distance versus interval number. Place data for both vehicles on the same plot and label each graph.

Analysis

Which vehicle moved with constant speed? Which one sped up? Explain how you determined this by looking at the timer tape.

Critical Thinking Describe the shape of each graph. How does the shape of the graph relate to the type of motion observed?



3.1 Acceleration

Uniform motion is one of the simplest kinds of motion. You learned in Chapter 2 that an object in uniform motion moves along a straight line with an unchanging velocity. From your own experiences, you know, however, that few objects move in this manner all of the time. In this chapter, you will expand your knowledge of motion by considering a slightly more complicated type of motion. You will be presented with situations in which the velocity of an object changes, while the object's motion is still along a straight line. Examples of objects and situations you will encounter in this chapter include automobiles that are speeding up, drivers applying brakes, falling objects, and objects thrown straight upward. In Chapter 6, you will continue to add to your knowledge of motion by analyzing some common types of motion that are not confined to a straight line. These include motion along a circular path and the motion of thrown objects, such as baseballs.

▶ Objectives

- **Define** acceleration.
- **Relate** velocity and acceleration to the motion of an object.
- **Create** velocity-time graphs.

▶ Vocabulary

velocity-time graph
acceleration
average acceleration
instantaneous acceleration

MINI LAB

A Steel Ball Race

If two steel balls are released at the same instant, will the steel balls get closer or farther apart as they roll down a ramp?

1. Assemble an inclined ramp from a piece of U-channel or two metersticks taped together.

2. Measure 40 cm from the top of the ramp and place a mark there. Place another mark 80 cm from the top.

3. Predict whether the steel balls will get closer or farther apart as they roll down the ramp.

4. At the same time, release one steel ball from the top of the ramp and the other steel ball from the 40-cm mark.

5. Next, release one steel ball from the top of the ramp. As soon as it reaches the 40-cm mark, release the other steel ball from the top of the ramp.

Analyze and Conclude

6. Explain your observations in terms of velocities.

7. Do the steel balls have the same velocity as they roll down the ramp? Explain.

8. Do they have the same acceleration? Explain.

Changing Velocity

You can feel a difference between uniform and nonuniform motion. Uniform motion feels smooth. You could close your eyes and it would feel as though you were not moving at all. In contrast, when you move along a curve or up and down a roller coaster, you feel pushed or pulled.

Consider the motion diagrams shown in **Figure 3-1.** How would you describe the motion of the person in each case? In one diagram, the person is motionless. In another, she is moving at a constant speed. In a third, she is speeding up, and in a fourth, she is slowing down. How do you know which one is which? What information do the motion diagrams contain that could be used to make these distinctions?

The most important thing to notice in these motion diagrams is the distance between successive positions. You learned in Chapter 2 that motionless objects in the background of motion diagrams do not change positions. Therefore, because there is only one image of the person in **Figure 3-1a,** you can conclude that she is not moving; she is at rest. **Figure 3-1b** is like the constant-velocity motion diagrams in Chapter 2. The distances between images are the same, so the jogger is moving at a constant speed. The distance between successive positions changes in the two remaining diagrams. If the change in position gets larger, the jogger is speeding up, as shown in **Figure 3-1c.** If the change in position gets smaller, as in **Figure 3-1d,** the jogger is slowing down.

What does a particle-model motion diagram look like for an object with changing velocity? **Figure 3-2** shows the particle-model motion diagrams below the motion diagrams of the jogger 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. If the object slows down, each vector is shorter than the previous one. Both types of motion diagrams give an idea of how an object's velocity is changing.

Velocity-Time Graphs

Just as it was useful to graph a changing position versus time, it also is useful to plot an object's velocity versus time, which is called a **velocity-time,** or ***v-t* graph. Table 3-1** on the next page shows the data for a car that starts at rest and speeds up along a straight stretch of road.

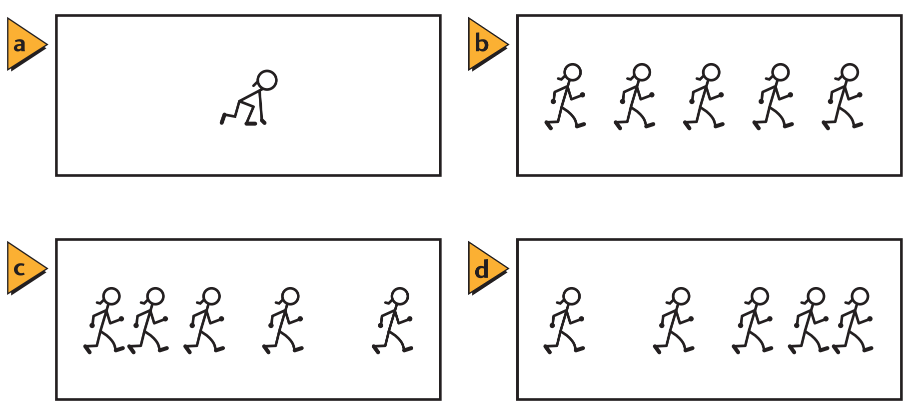
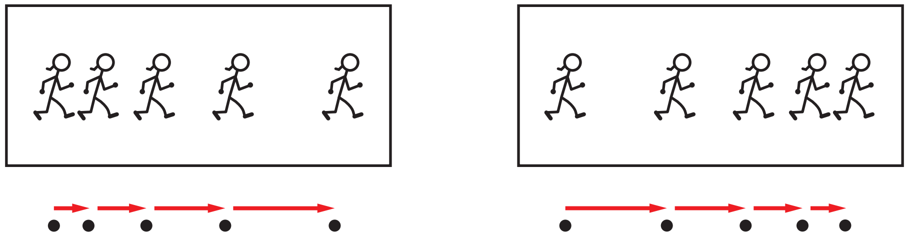


Figure 3-1 By noting the distance the jogger moves in equal time intervals, you can determine that the jogger is standing still **(a),** moving at a constant speed **(b),** speeding up **(c),** and slowing down **(d).**



■ **Figure 3-2** The particle-model version of the motion diagram indicates the runner's changing velocity not only by the change in spacing of the position dots, but also by the change in length of the velocity vectors.

The velocity-time graph obtained by plotting these data points is shown in **Figure 3-3.** The positive direction has been chosen to be the same as that of the motion of the car. Notice that this graph is a straight line, which means that the car was speeding up at a constant rate. The rate at which the car's velocity is changing can be found by calculating the slope of the velocity-time graph.

The graph shows that the slope is (10.0 m/s)/(2.00 s), or 5.00 m/s^2. This means that every second, the velocity of the car increased by 5.00 m/s. Consider a pair of data points that are separated by 1 s, such as 4.00 s and 5.00 s. At 4.00 s, the car was moving at a velocity of 20.0 m/s. At 5.00 s, the car was traveling at 25.0 m/s. Thus, the car's velocity increased by 5.00 m/s in 1.00 s. The rate at which an object's velocity changes is called the **acceleration** of the object. When the velocity of an object changes at a constant rate, it has a constant acceleration.

Average and Instantaneous Acceleration

The **average acceleration** of an object is the change in velocity during some measurable time interval divided by that time interval. Average acceleration is measured in m/s^2. The change in velocity at an instant of time is called **instantaneous acceleration.** The instantaneous acceleration of an object can be found by drawing a tangent line on the velocity-time graph at the point of time in which you are interested. The slope of this line is equal to the instantaneous acceleration. Most of the situations considered in this textbook involve motion with acceleration in which the average and instantaneous accelerations are equal.

■ **Figure 3-3** The slope of a velocity-time graph is the acceleration of the object represented.

Table 3-1
Velocity v. Time

Time (s)	Velocity (m/s)
0.00	0.00
1.00	5.00
2.00	10.0
3.00	15.0
4.00	20.0
5.00	25.0

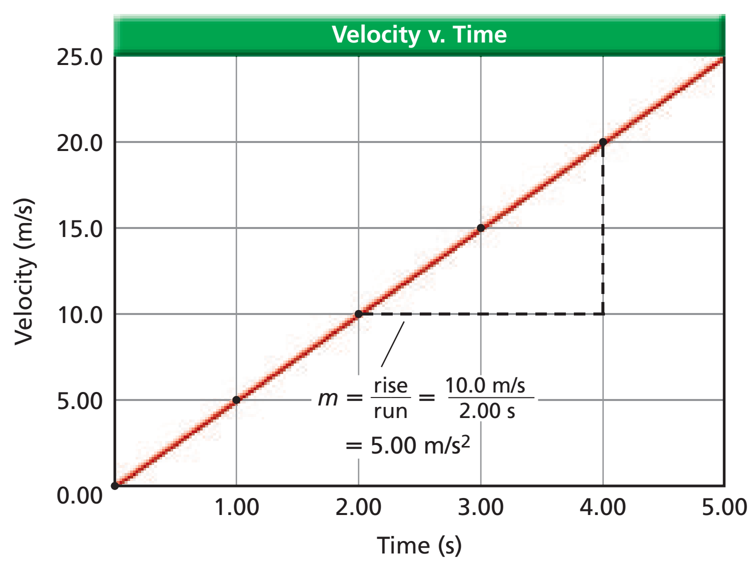
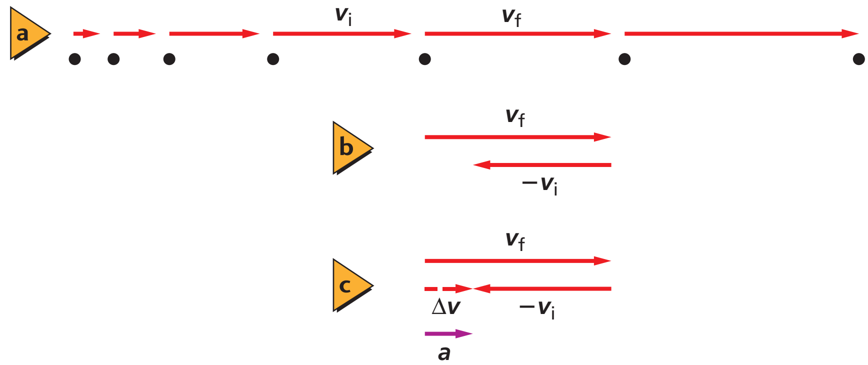


Figure 3-4 Looking at two consecutive velocity vectors and finding the difference between them yields the average acceleration vector for that time interval.



Color Convention

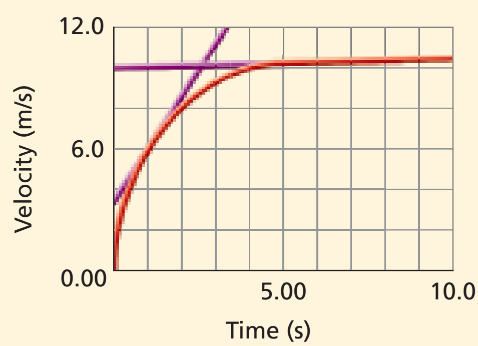
- Acceleration vectors are **violet.**
- Velocity vectors are **red.**
- Displacement vectors are **green.**

Displaying Acceleration on a Motion Diagram

For a motion diagram to give a full picture of an object's movement, it also should contain information about acceleration. This can be done by including average acceleration vectors. These vectors will indicate how the velocity is changing. To determine the length and direction of an average acceleration vector, subtract two consecutive velocity vectors, as shown in **Figures 3-4a** and **b.** That is, $\Delta \boldsymbol{v} = \boldsymbol{v}_f - \boldsymbol{v}_i = \boldsymbol{v}_f + (-\boldsymbol{v}_i)$. Then divide by the time interval, Δt. In Figures 3-4a and b, the time interval, Δt, is 1 s. This vector, $(\boldsymbol{v}_f - \boldsymbol{v}_i)/1$ s, shown in violet in **Figure 3-4c,** is the average acceleration during that time interval. The velocities $\boldsymbol{v}_i$ and $\boldsymbol{v}_f$ refer to the velocities at the beginning and end of a chosen time interval.

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 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: v = varies

Unknown: a = ?

2 Solve for the Unknown

Draw a tangent to the curve at $t = 1.0$ s and $t = 5.0$ s.

Solve for acceleration at 1.0 s:

$$a = \frac{\text{rise}}{\text{run}}$$

The slope of the line at 1.0 s is equal to the acceleration at that time.

$$= \frac{11.0\ \text{m/s} - 2.8\ \text{m/s}}{2.4\ \text{s} - 0.00\ \text{s}}$$

$$= 3.4\ \text{m/s}^2$$

Solve for acceleration at 5.0 s:

$$a = \frac{\text{rise}}{\text{run}}$$

The slope of the line at 5.0 s is equal to the acceleration at that time.

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

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

The acceleration is not constant because it changes from 3.4 m/s^2 to 0.03 m/s^2 at 5.0 s. The acceleration is in the direction chosen to be positive because both values are positive.

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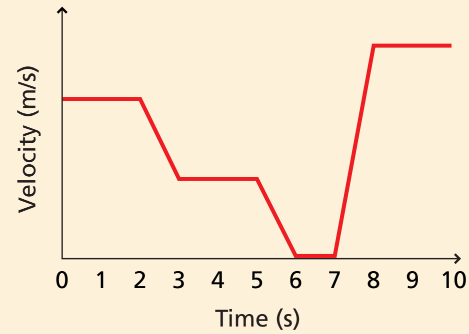
3 Evaluate the Answer

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

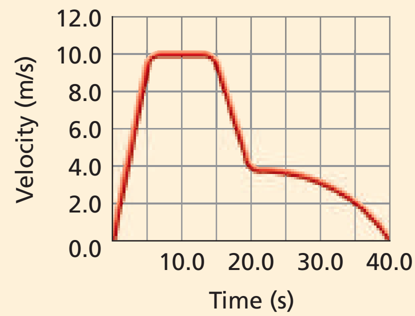
▶ PRACTICE Problems

Additional Problems, Appendix B

1. A dog runs into a room and sees a cat at the other end of the room. The dog instantly stops running but slides along the wood floor until he stops, by slowing down with a constant acceleration. Sketch a motion diagram for this situation, and use the velocity vectors to find the acceleration vector.
2. **Figure 3-5** is a *v-t* graph for Steven as he walks along the midway at the state fair. Sketch the corresponding motion diagram, complete with velocity vectors.
3. Refer to the *v-t* graph of the toy train in **Figure 3-6** to answer the following 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?
4. Refer to Figure 3-6 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
5. 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 experiences a constant downward acceleration of 0.25 m/s^2 for 4.0 s as it reaches the third floor.



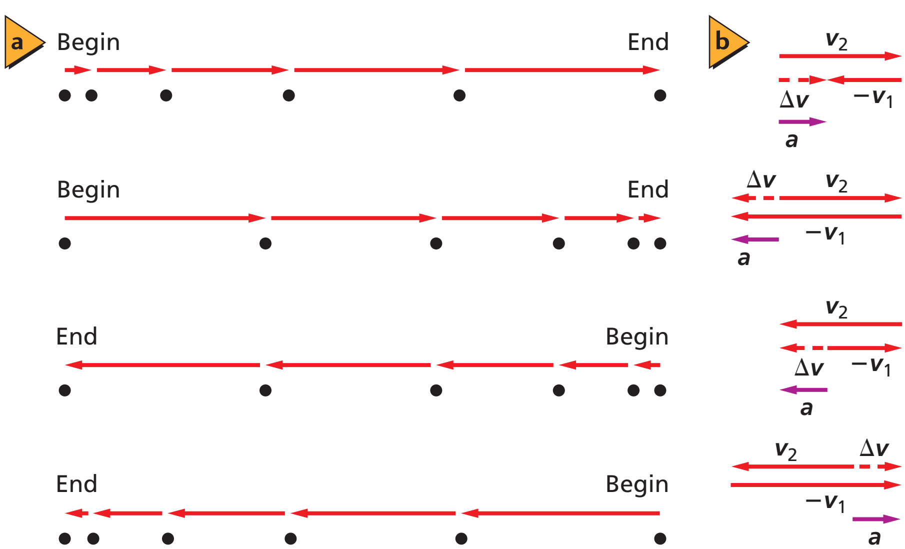
■ **Figure 3-5**



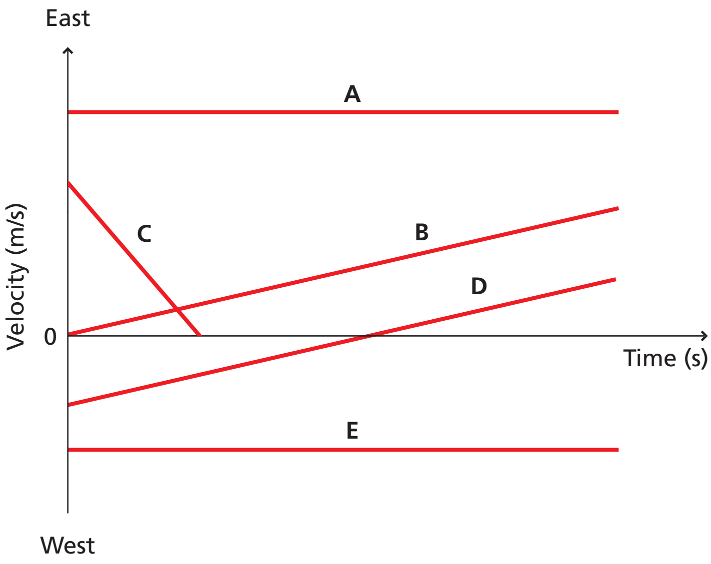
■ **Figure 3-6**

Positive and Negative Acceleration

Consider the four situations shown in **Figure 3-7a.** The first motion diagram shows an object moving in the positive direction and speeding up. The second motion diagram shows the object moving in the positive direction and slowing down. The third shows the object speeding up in the negative direction, and the fourth shows the object slowing down as it moves in the negative direction. **Figure 3-7b** shows the velocity vectors for the second time interval of each diagram, along with the corresponding acceleration vectors. Note Δt is equal to 1 s.



■ **Figure 3-7** These four motion diagrams represent the four different possible ways to move along a straight line with constant acceleration **(a).** When the velocity vectors of the motion diagram and acceleration vectors point in the same direction, an object's speed increases. When they point in opposite directions, the object slows down **(b).**



■ **Figure 3-8** Graphs A and E show motion with constant velocity in opposite directions. Graph B shows both positive velocity and positive acceleration. Graph C shows positive velocity and negative acceleration. Graph D shows motion with constant positive acceleration that slows down while velocity is negative and speeds up when velocity is positive.

In the first and third situations when the object is speeding up, the velocity and acceleration vectors point in the same direction in each case, as shown in Figure 3-7b. In the other two situations in which the acceleration vector is in the opposite direction from the velocity vectors, the object is slowing down. In other words, when the object's acceleration is in the same direction as its velocity, the object's speed increases. When they are in opposite directions, the speed 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. The sign of acceleration does not indicate whether the object is speeding up or slowing down.

Determining Acceleration from a *v-t* Graph

Velocity and acceleration information also is contained in velocity-time graphs. Graphs A, B, C, D, and E, shown in **Figure 3-8,** represent the motions of five different runners. Assume that the positive direction has been chosen to be east. The slopes of Graphs A and E are zero. Thus, the accelerations are zero. Both Graphs A and E 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. The slope of this graph indicates a constant, positive acceleration. You also can infer from Graph B that the speed increased because it shows positive velocity and acceleration. Graph C has a negative slope. Graph C shows motion that begins with a positive velocity, slows down, and then stops. This means that the acceleration and velocity are in opposite directions. The point at which Graphs C and B cross shows that the runners' velocities are equal at that point. It does not, however, give any information about the runners' positions.

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

Calculating acceleration How can you describe acceleration mathematically? The following equation expresses average acceleration as the slope of the velocity-time graph.

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

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

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

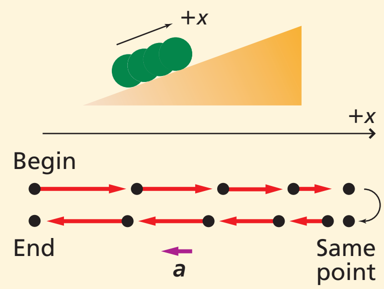
$$\bar{a} \equiv \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}$$

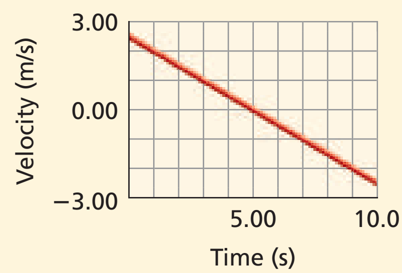
$$= \frac{(-4.0 \text{ m/s}) - (4.0 \text{ m/s})}{10.0 \text{ s}} = \frac{-8.0 \text{ m/s}}{10.0 \text{ s}} = -0.80 \text{ m/s}^2$$

The negative sign indicates that the direction of acceleration is away from the wall. The velocity changes when the direction of motion changes, because velocity includes the direction of motion. A change in velocity results in acceleration. Thus, acceleration also is associated with a change in the direction of motion.

▶ EXAMPLE Problem 2

Acceleration Describe the motion of a ball as it rolls up a slanted driveway. The ball starts at 2.50 m/s, slows down for 5.00 s, stops for an instant, and then rolls back down at an increasing speed. The positive direction is chosen to be up the driveway, and the origin is at the place where the motion begins. What is the sign of the ball's acceleration as it rolls up the driveway? What is 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:
$v_i = +2.5$ m/s
$v_f = 0.00$ m/s at $t = 5.00$ s

Unknown:
$a = ?$

2 Solve for the Unknown

Find the magnitude of the acceleration from the slope of the graph.

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

$\Delta v = v_f - v_i$
$= 0.00 \text{ m/s} - 2.50 \text{ m/s}$ — **Substitute $v_f = 0.00$ m/s at $t_f = 5.00$ s, $v_i = 2.50$ m/s at $t_i = 0.00$ s**
$= -2.50$ m/s

$\Delta t = t_f - t_i$
$= 5.00 \text{ s} - 0.00 \text{ s}$ — **Substitute $t_f = 5.00$ s, $t_i = 0.00$ s**
$= 5.00$ s

Solve for the acceleration.

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

$$= \frac{-2.50 \text{ m/s}}{5.00 \text{ s}}$$ — **Substitute $\Delta v = -2.50$ m/s, $\Delta t = 5.00$ s**

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

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3 Evaluate the Answer

- **Are the units correct?** Acceleration is measured in m/s^2.
- **Do the directions make sense?** In the first 5.00 s, the direction of the acceleration is opposite to that of the velocity, and the ball slows down.

PRACTICE Problems

Additional Problems, Appendix B

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

7. 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?

8. A car is coasting backwards 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. A bus is moving 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?**

10. Rohith has been jogging to the bus stop for 2.0 min 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?

11. 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?

There are several parallels between acceleration and velocity. Both are rates of change: acceleration is the time rate of change of velocity, and velocity is the time rate of change of position. Both acceleration and velocity have average and instantaneous forms. You will learn later in this chapter that the area under a velocity-time graph is equal to the object's displacement and that the area under an acceleration-time graph is equal to the object's velocity.

3.1 Section Review

12. Velocity-Time Graph What information can you obtain from a velocity-time graph?

13. Position-Time and Velocity-Time Graphs Two joggers run at a constant velocity of 7.5 m/s toward the east. At time $t = 0$, one is 15 m east of the origin and the other is 15 m west.

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?

14. Velocity Explain how you would use a velocity-time graph to find the time at which an object had a specified velocity.

15. 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.

16. Average Velocity and Average Acceleration A canoeist paddles upstream at 2 m/s and then turns around and floats downstream at 4 m/s. The turnaround time is 8 s.

a. What is the average velocity of the canoe?

b. What is the average acceleration of the canoe?

17. Critical Thinking A police officer clocked a driver going 32 km/h over the speed limit just as the driver passed a slower car. Both drivers were issued speeding tickets. The judge agreed with the officer that both were guilty. The judgement was issued based on the assumption that the cars must have been going the same speed because they were observed next to each other. Are the judge and the police officer correct? Explain with a sketch, a motion diagram, and a position-time graph.

Physics Online physicspp.com/self_check_quiz

3.2 Motion with Constant Acceleration

You have learned that the definition of 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.

▶ **Objectives**

- **Interpret** position-time graphs for motion with constant acceleration.
- **Determine** mathematical relationships among position, velocity, acceleration, and time.
- **Apply** graphical and mathematical relationships to solve problems related to constant acceleration.

Velocity with 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. The definition of average acceleration,

$$\bar{a} \equiv \frac{\Delta v}{\Delta t}, \text{ can be rewritten as follows:}$$

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

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

The equation for final velocity with average acceleration can be written as follows.

Final Velocity with Average Acceleration $v_f = v_i + \bar{a}\Delta t$

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

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

PRACTICE Problems

Additional Problems, Appendix B

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

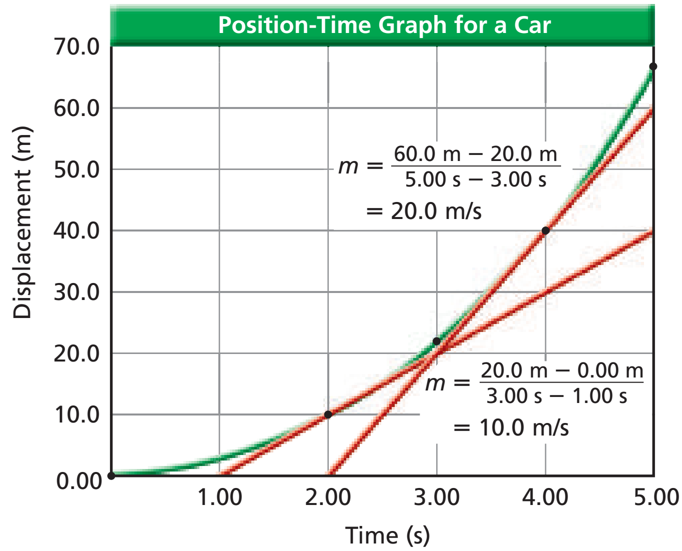
- **a.** If the golf ball starts with a speed of 2.0 m/s and slows at a constant rate of 0.50 m/s^2, what is its velocity after 2.0 s?
- **b.** What is the golf ball's velocity if the constant acceleration continues for 6.0 s?
- **c.** Describe the motion of the golf ball in words and with a motion diagram.

19. A bus that is traveling at 30.0 km/h speeds up at a constant rate of 3.5 m/s^2. What velocity does it reach 6.8 s later?

20. If a car accelerates from rest at a constant 5.5 m/s^2, how long will it take for the car to reach a velocity of 28 m/s?

21. A car slows from 22 m/s to 3.0 m/s at a constant rate of 2.1 m/s^2. How many seconds are required before the car is traveling at 3.0 m/s?

Table 3-2	
Position-Time Data for a Car	
Time (s)	Position (m)
0.00	0.00
1.00	2.50
2.00	10.0
3.00	22.5
4.00	40.0
5.00	62.5



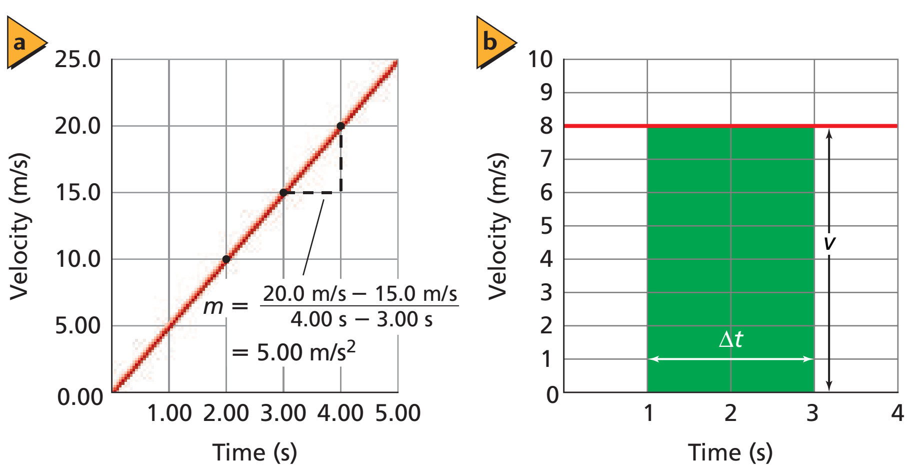
■ **Figure 3-9** The slope of a position-time graph of a car moving with a constant acceleration gets steeper as time goes on.

Position with Constant Acceleration

You have learned that an object experiencing constant acceleration changes its velocity at a constant rate. How does the position of an object with constant acceleration change? The position data at different time intervals for a car with constant acceleration are shown in **Table 3-2.**

The data from Table 3-2 are graphed in **Figure 3-9.** The graph shows that the car's motion is not uniform: the displacements for equal time intervals on the graph get larger and larger. Notice that the slope of the line in Figure 3-9 gets steeper as time goes on. The slopes from the position-time graph can be used to create a velocity-time graph. Note that the slopes shown in Figure 3-9 are the same as the velocities graphed in **Figure 3-10a.**

A unique position-time graph cannot be created using a velocity-time graph because it does not contain any information about the object's position. However, the velocity-time graph does contain information about the object's displacement. Recall that for an object moving at a constant velocity, $v = \bar{v} = \Delta d/\Delta t$, so $\Delta d = v\Delta t$. On the graph in **Figure 3-10b,** v is the height of the plotted line above the t-axis, while Δt is the width of the shaded rectangle. The area of the rectangle, then, is $v\Delta t$, or Δd. Thus, the area under the v-t graph is equal to the object's displacement.



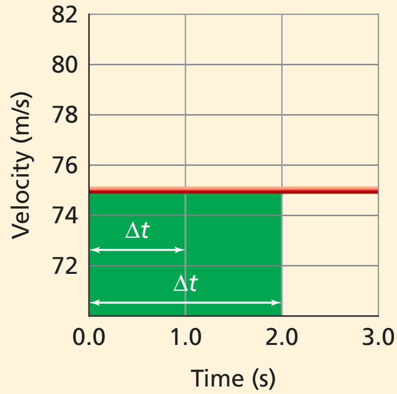
■ **Figure 3-10** The slopes of the p-t graph in Figure 3-9 are the values of the corresponding v-t graph **(a).** For any v-t graph, the displacement during a given time interval is the area under the graph **(b).**

EXAMPLE Problem 3

Finding the Displacement from a *v-t* Graph The *v-t* graph below shows the motion of an airplane. Find the displacement of the airplane at $\Delta t = 1.0$ s and at $\Delta t = 2.0$ s.

1 Analyze and Sketch the Problem

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



Known:	Unknown:
$v = +75$ m/s	$\Delta d = ?$
$\Delta t = 1.0$ s	
$\Delta t = 2.0$ s	

2 Solve for the Unknown

Solve for displacement during $\Delta t = 1.0$ s.

$\Delta d = v\Delta t$

$= (+75\text{ m/s})(1.0\text{ s})$ **Substitute $v = +75$ m/s, $\Delta t = 1.0$ s**

$= +75$ m

Solve for displacement during $\Delta t = 2.0$ s.

$\Delta d = v\Delta t$

$= (+75\text{ m/s})(2.0\text{ s})$ **Substitute $v = +75$ m/s, $\Delta t = 2.0$ s**

$= +150$ m

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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 equal to about one football field is reasonable for an airplane.

PRACTICE Problems

Additional Problems, Appendix B

22. Use **Figure 3-11** to determine the velocity of an airplane that is speeding up at each of the following times.

a. 1.0 s **b.** 2.0 s **c.** 2.5 s

23. Use dimensional analysis to convert an airplane's speed of 75 m/s to km/h.

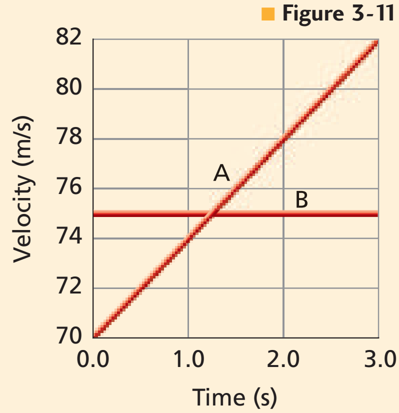
24. A position-time graph for a pony running in a field is shown in **Figure 3-12.** Draw the corresponding velocity-time graph using the same time scale.

25. A car is driven at a constant velocity of 25 m/s for 10.0 min. The car runs out of gas and the driver walks in the same direction at 1.5 m/s for 20.0 min to the nearest gas station. The driver takes 2.0 min to fill a gasoline can, then walks back to the car at 1.2 m/s and eventually drives home at 25 m/s in the direction opposite that of the original trip.

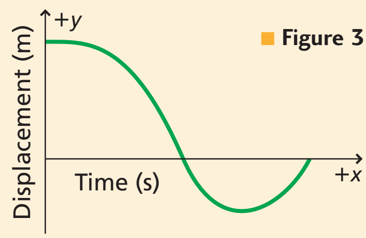
a. Draw a *v-t* graph using seconds as your time unit. Calculate the distance the driver walked to the gas station to find the time it took him to walk back to the car.

b. Draw a position-time graph for the situation using the areas under the velocity-time graph.

■ **Figure 3-11**



■ **Figure 3-12**



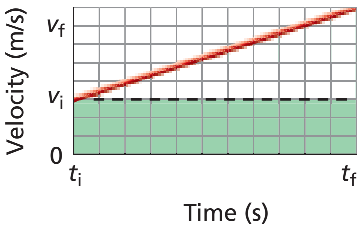


Figure 3-13 The displacement of an object moving with constant acceleration can be found by computing the area under the *v-t* graph.

The area under the *v-t* graph is equal to the object's displacement. Consider the *v-t* graph in **Figure 3-13** for an object moving with constant acceleration that started with an initial velocity of v_i. What is the object's displacement? The area under the graph can be calculated by dividing it into a rectangle and a triangle. The area of the rectangle can be found by $\Delta d_{\text{rectangle}} = v_i \Delta t$, and the area of the triangle can be found by $\Delta d_{\text{triangle}} = \frac{1}{2}\Delta v \Delta t$. Because average acceleration, $\bar{a}$, is equal to $\Delta v/\Delta t$, Δv can be rewritten as $\bar{a}\Delta t$. Substituting $\Delta v = \bar{a}\Delta t$ into the equation for the triangle's area yields $\Delta d_{\text{triangle}} = \frac{1}{2}(\bar{a}\Delta t)\Delta t$, or $\frac{1}{2}\bar{a}(\Delta t)^2$. Solving for the total area under the graph results in the following:

$$\Delta d = \Delta d_{\text{rectangle}} + \Delta d_{\text{triangle}} = v_i(\Delta t) + \frac{1}{2}\bar{a}(\Delta t)^2$$

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

$$d_f - d_i = v_i(\Delta t) + \frac{1}{2}\bar{a}(\Delta t)^2 \quad \text{or} \quad d_f = d_i + v_i(\Delta t) + \frac{1}{2}\bar{a}(\Delta t)^2$$

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

Position with Average Acceleration $\quad d_f = d_i + v_i t_f + \frac{1}{2}\bar{a}t_f^2$

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

An Alternative Expression

Often, it is useful to relate position, velocity, and constant acceleration without including time. Rearrange the equation $v_f = v_i + \bar{a}t_f$ to solve for time: $t_f = \frac{v_f - v_i}{\bar{a}}$.

Rewriting $d_f = d_i + v_i t_f + \frac{1}{2}\bar{a}t_f^2$ by substituting t_f yields the following:

$$d_f = d_i + v_i\frac{v_f - v_i}{\bar{a}} + \frac{1}{2}\bar{a}\left(\frac{v_f - v_i}{\bar{a}}\right)^2$$

This equation can be solved for the velocity, v_f, at any time, t_f.

Velocity with Constant Acceleration $\quad v_f^2 = v_i^2 + 2\bar{a}(d_f - d_i)$

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.

APPLYING PHYSICS

Drag Racing A dragster driver tries to obtain maximum acceleration over a 402-m (quarter-mile) course. The fastest time on record for the 402-m course is 4.480 s. The highest final speed on record is 147.63 m/s (330.23 mph).

The three equations for motion with constant acceleration are summarized in **Table 3-3.** Note that in a multi-step problem, it is useful to add additional subscripts to identify which step is under consideration.

Connecting Math to Physics

Table 3-3

Equations of Motion for Uniform Acceleration

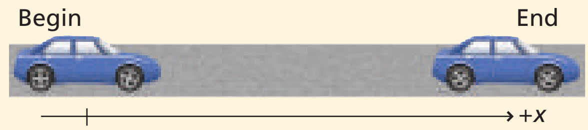
Equation	Variables	Initial Conditions
$v_f = v_i + \bar{a}t_f$	t_f, v_f, $\bar{a}$	v_i
$d_f = d_i + v_i t_f + \frac{1}{2}\bar{a}t_f^2$	t_f, d_f, $\bar{a}$	d_i, v_i
$v_f^2 = v_i^2 + 2\bar{a}(d_f - d_i)$	d_f, v_f, $\bar{a}$	d_i, v_i

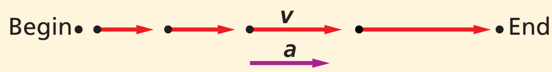
▶ EXAMPLE Problem 4

Displacement An automobile starts at rest and speeds up at 3.5 m/s^2 after the 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.
- Draw a motion diagram.





Known:	**Unknown:**
$d_i = 0.00$ m	$d_f = ?$
$v_i = 0.00$ m/s	
$v_f = 25$ m/s	
$\bar{a} = a = 3.5$ m/s^2	

2 Solve for the Unknown

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Solve for d_f.

$$v_f^2 = v_i^2 + 2a(d_f - d_i)$$

$$d_f = d_i + \frac{v_f^2 - v_i^2}{2a}$$

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

Substitute $d_i = 0.00$ m, $v_f = 25$ m/s, $v_i = 0.00$ m/s

$$= 89 \text{ m}$$

3 Evaluate the Answer

- **Are the units correct?** Position is measured in meters.
- **Does the sign 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. It seems large, but 25 m/s is fast (about 55 mph); therefore, the result is reasonable.

▶ PRACTICE Problems

Additional Problems, Appendix B

26. A skateboarder is moving at a constant velocity 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/s^2. How much time passes from when she begins to slow down until she begins to move back down the incline?

27. A race car travels on a racetrack at 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?

28. 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 this speed?

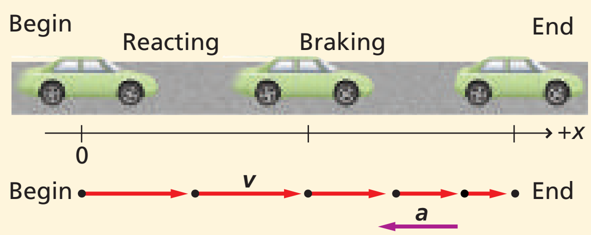
29. A bike rider pedals with constant acceleration to reach a velocity of 7.5 m/s over a time of 4.5 s. During the period of acceleration, the bike's displacement is 19 m. What was the initial velocity of the bike?

EXAMPLE Problem 5

Two-Part Motion You are driving a car, traveling at a constant velocity of 25 m/s, 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/s^2 and comes to a stop. What is the total distance that the car moves 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 v and a.



Known:

$v_{\text{reacting}} = 25$ m/s

$t_{\text{reacting}} = 0.45$ s

$\bar{a} = a_{\text{braking}} = -8.5$ m/s^2

$v_{\text{i, braking}} = 25$ m/s

$v_{\text{f, braking}} = 0.00$ m/s

Unknown:

$d_{\text{reacting}} = ?$

$d_{\text{braking}} = ?$

$d_{\text{total}} = ?$

2 Solve for the Unknown

Reacting:

Solve for the distance the car travels at a constant speed.

$$d_{\text{reacting}} = v_{\text{reacting}} t_{\text{reacting}}$$

$$d_{\text{reacting}} = (25 \text{ m/s})(0.45 \text{ s}) = 11 \text{ m}$$

Substitute $v_{\text{reacting}} = 25$ m/s, $t_{\text{reacting}} = 0.45$ s

Braking:

Solve for the distance the car moves while braking.

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

Solve for d_{braking}.

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

$$= \frac{(0.00 \text{ m/s})^2 - (25 \text{ m/s})^2}{2(-8.5 \text{ m/s}^2)}$$

$$= 37 \text{ m}$$

Substitute $v_{\text{f, braking}} = 0.00$ m/s, $v_{\text{reacting}} = 25$ m/s, $a_{\text{braking}} = -8.5$ m/s^2

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The total distance traveled is the sum of the reaction distance and the braking distance.

Solve for d_{total}.

$$d_{\text{total}} = d_{\text{reacting}} + d_{\text{braking}}$$

$$= 11 \text{ m} + 37 \text{ m}$$

$$= 48 \text{ m}$$

Substitute $d_{\text{reacting}} = 11$ m, $d_{\text{braking}} = 37$ m

3 Evaluate the Answer

- **Are the units correct?** Distance is measured in meters.
- **Do the signs make sense?** Both d_{reacting} and d_{braking} are positive, as they should be.
- **Is the magnitude realistic?** The braking distance is small because the magnitude of the acceleration is large.

PRACTICE Problems

Additional Problems, Appendix B

30. A man runs at a velocity of 4.5 m/s for 15.0 min. When going up an increasingly steep hill, he slows down at a constant rate of 0.05 m/s^2 for 90.0 s and comes to a stop. How far did he run?

31. Sekazi is learning to ride a bike without training wheels. His father pushes him with a constant acceleration of 0.50 m/s^2 for 6.0 s, and then Sekazi continues at 3.0 m/s 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.

32. 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?

33. Sunee is training for an upcoming 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?

You have learned several different tools that you can apply when solving problems dealing with motion in one dimension: motion diagrams, graphs, and equations. As you gain more experience, it will become easier to decide which tools are most appropriate in solving a given problem. In the following section, you will practice using these tools to investigate the motion of falling objects.

3.2 Section Review

34. Acceleration A woman driving at a speed of 23 m/s sees a deer on the road ahead and 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. Displacement If you were given initial and final velocities and the constant acceleration of an object, and you were asked to find the displacement, what equation would you use?

36. Distance An in-line skater first 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 a distance of 5.0×10^2 m while being accelerated uniformly from rest at the rate of 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 for 14 s. What final velocity did it attain?

39. Distance An airplane starts from rest and accelerates at a constant 3.00 m/s^2 for 30.0 s before leaving the ground.

a. How far did it move?

b. How fast was the airplane going when it took off?

40. Graphs A sprinter walks up to the starting blocks at a constant speed and positions herself for the start of the race. She waits until she hears the starting pistol go off, and then accelerates rapidly until she attains a constant velocity. She maintains this velocity until she crosses the finish line, and then she slows down 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 on the same time scale. Indicate on your *p*-*t* graph where the starting blocks and finish line are.

41. Critical Thinking Describe how you could calculate the acceleration of an automobile. Specify the measuring instruments and the procedures that you would use.

3.3 Free Fall

▶ **Objectives**

- **Define** acceleration due to gravity.
- **Solve** problems involving objects in free fall.

▶ **Vocabulary**

free fall
acceleration due to gravity

Drop a sheet of paper. Crumple it, and then drop it again. Drop a rock or a pebble. How do the three motions compare with each other? Do heavier objects fall faster than lighter ones? A light, spread-out object, such as a smooth sheet of paper or a feather, does not fall in the same manner as something more compact, such as a pebble. Why? As an object falls, it bumps into particles in the air. For an object such as a feather, these little collisions have a greater effect than they do on pebbles or rocks. To understand the behavior of falling objects, first consider the simplest case: an object such as a rock, for which the air does not have an appreciable effect on its motion. The term used to describe the motion of such objects is **free fall,** which is the motion of a body when air resistance is negligible and the action can be considered due to gravity alone.

Acceleration Due to Gravity

About 400 years ago, Galileo Galilei recognized that to make progress in the study of the motion of falling objects, the effects of the substance through which the object falls have to be ignored. At that time, Galileo had no means of taking position or velocity data for falling objects, so he rolled balls down inclined planes. By "diluting" gravity in this way, he could make careful measurements even with simple instruments.

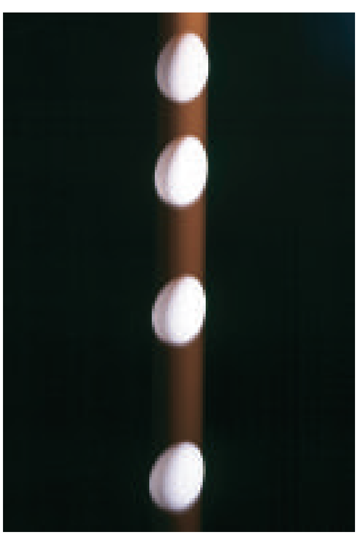
Galileo concluded that, neglecting the effect of the air, all objects in free fall had the same acceleration. It didn't matter what they were made of, how much they weighed, what height they were dropped from, or whether they were dropped or thrown. The acceleration of falling objects, given a special symbol, g, is equal to 9.80 m/s^2. It is now known that there are small variations in g at different places on Earth, and that 9.80 m/s^2 is the average value.

The **acceleration due to gravity** is the acceleration of an object in free fall that results from the influence of Earth's gravity. Suppose you drop a rock. After 1 s, its velocity is 9.80 m/s downward, and 1 s after that, its velocity is 19.60 m/s downward. For each second that the rock is falling, its downward velocity increases by 9.80 m/s. Note that g is a positive number. When analyzing free fall, whether you treat the acceleration as positive or negative depends upon the coordinate system that you use. If your coordinate system defines upward to be the positive direction, then the acceleration due to gravity is equal to $-g$; if you decide that downward is the positive direction, then the acceleration due to gravity is $+g$.

A strobe photo of a dropped egg is shown in **Figure 3-14.** The time interval between the images is 0.06 s. The displacement between each pair of images increases, so the speed is increasing. If the upward direction is chosen as positive, then the velocity is becoming more and more negative.

Ball thrown upward Instead of a dropped egg, could this photo also illustrate a ball thrown upward? If upward is chosen to be the positive direction, then the ball leaves the hand with a positive velocity of, for example, 20.0 m/s. The acceleration is downward, so a is negative. That is, $a = -g = -9.80$ m/s^2. Because the velocity and acceleration are in opposite directions, the speed of the ball decreases, which is in agreement with the strobe photo.

■ **Figure 3-14** An egg accelerates at 9.80 m/s^2 in free fall. If the upward direction is chosen as positive, then both the velocity and the acceleration of this egg in free fall are negative.



Richard Megna/Fundamental Photographs

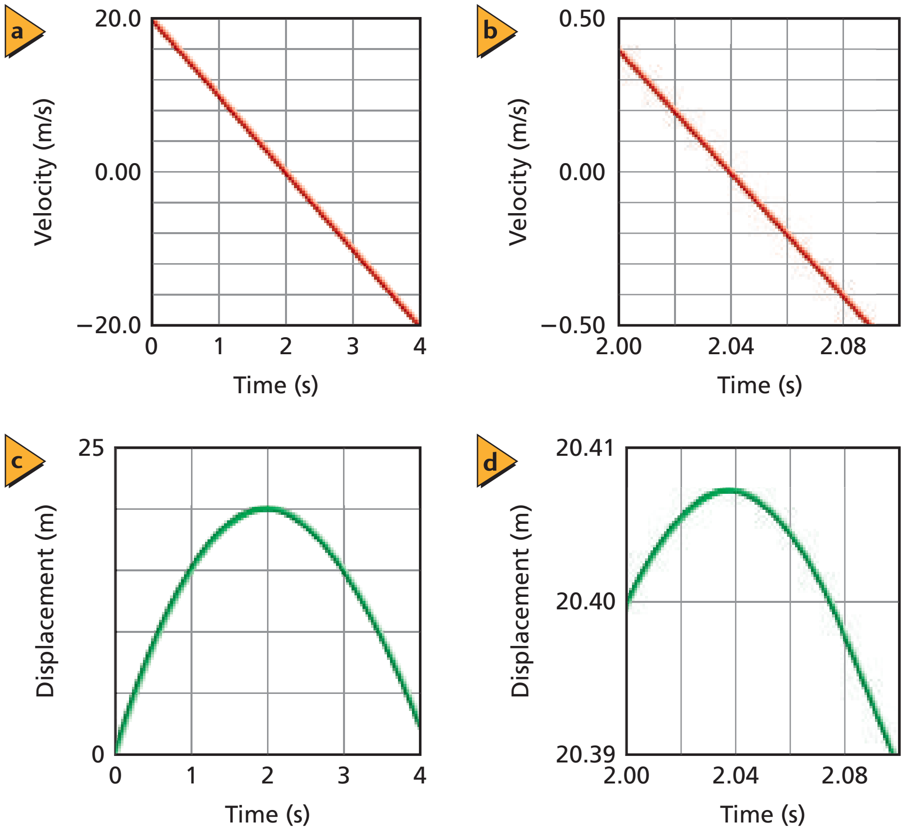


Figure 3-15 In a coordinate system in which the upward direction is positive, the velocity of the thrown ball decreases until it becomes zero at 2.04 s. Then it increases in the negative direction as the ball falls **(a, b).** The *p-t* graphs show the height of the ball at corresponding time intervals **(c, d).**

After 1 s, the ball's velocity is reduced by 9.80 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 9.80 m/s, and is equal to −9.4 m/s. The ball now is moving downward. After 4 s, the velocity is −19.2 m/s, meaning that the ball is falling even faster. **Figure 3-15a** shows the velocity-time graph for the ball as it goes up and comes back down. At around 2 s, the velocity changes smoothly from positive to negative. **Figure 3-15b** shows a closer view of the *v-t* graph around that point. At an instant of time, near 2.04 s, the ball's velocity is zero. Look at the position-time graphs in **Figure 3-15c** and **d,** which show how the ball's height changes. How are the ball's position and velocity related? The ball reaches its maximum height at the instant of time when its velocity is zero.

At 2.04 s, the ball reaches its maximum height and its velocity is zero. What is the ball's acceleration at that point? The slope of the line in the *v-t* graphs in Figure 3-15a and 3-15b is constant at $-9.80\ \mathrm{m/s^2}$.

Often, when people are asked about the acceleration of an object at the top of its flight, they do not take the time to fully analyze the situation, and respond that the acceleration at this point is zero. However, this is not the case. At the top of the flight, the ball's velocity is 0 m/s. What would happen if its acceleration were also zero? Then the ball's velocity would not be changing and would remain at 0 m/s. If this were the case, the ball would not gain any downward velocity and would simply hover in the air at the top of its flight. Because this is not the way objects tossed in the air behave on Earth, you know that the acceleration of an object at the top of its flight must not be zero. Further, because you know that the object will fall from that height, you know that the acceleration must be downward.

Free-fall rides Amusement parks use the concept of free fall 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 plunge 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 at an amusement park starts 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 0.00 m/s. To calculate the final velocity, use the equation for velocity with constant acceleration.

$$\begin{aligned} v_f &= v_i + \bar{a}t_f \\ &= 0.00\ \text{m/s} + (-9.80\ \text{m/s}^2)(1.5\ \text{s}) \\ &= -15\ \text{m/s} \end{aligned}$$

How far does the car fall? Use the equation for displacement when time and constant acceleration are known.

$$\begin{aligned} d_f &= d_i + v_i t_f + \frac{1}{2}\bar{a}t_f^2 \\ &= 0.00\ \text{m} + (0.00\ \text{m/s})(1.5\ \text{s}) + \frac{1}{2}(-9.80\ \text{m/s}^2)(1.5\ \text{s})^2 \\ &= -11\ \text{m} \end{aligned}$$

PRACTICE Problems

Additional Problems, Appendix B

42. 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?

43. 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?

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

45. 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.*

46. You decide to flip a coin to determine whether to do your physics or English homework first. The coin is flipped straight up.

a. If the coin reaches a high point of 0.25 m above where you released it, what was its initial speed?

b. If you catch it at the same height as you released it, how much time did it spend in the air?

CHALLENGE PROBLEM

You notice a water balloon fall past your classroom window. You estimate that it took the balloon about t seconds to fall the length of the window and that the window is about y meters high. Suppose the balloon started from rest. Approximately how high above the top of the window was it released? Your answer should be in terms of t, y, g, and numerical constants.

Remember to define the positive direction when establishing your coordinate system. As motion problems increase in complexity, it becomes increasingly important to keep all the signs consistent. This means that any displacement, velocity, or acceleration that is in the same direction as the one chosen to be positive will be positive. Thus, any displacement, velocity, or acceleration that is in the direction opposite to the one chosen to be positive should be indicated with a negative sign. Sometimes it might be appropriate to choose upward as positive. At other times, it might be easier to choose downward as positive. You can choose either direction you want, as long as you stay consistent with that convention throughout the solution of that particular problem. Suppose you solve one of the practice problems on the preceding page again, choosing the direction opposite to the one you previously designated as the positive direction for the coordinate system. You should arrive at the same answer, provided that you assigned signs to each of the quantities that were consistent with the coordinate system. It is important to be consistent with the coordinate system to avoid getting the signs mixed up.

3.3 Section Review

47. Maximum Height and Flight Time Acceleration due to gravity 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?

48. 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.

49. Final Velocity Your sister drops your house keys down to you from the second floor window. If you catch them 4.3 m from where your sister dropped them, what is the velocity of the keys when you catch them?

50. Initial Velocity A student trying out for the football team kicks the football straight up in the air. The ball hits him on the way back down. If it took 3.0 s from the time when the student punted the ball until he gets hit by the ball, what was the football's initial velocity?

51. Maximum Height When the student in the previous problem kicked the football, approximately how high did the football travel?

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

PHYSICS LAB • Internet

Alternate CBL instructions can be found on the Web site.
physicspp.com

Acceleration Due to Gravity

Small variations in the acceleration due to gravity, g, occur at different places on Earth. This is because g varies with distance from the center of Earth and is influenced by the subsurface geology. In addition, g varies with latitude due to Earth's rotation.

For motion with constant acceleration, the displacement is $d_f - d_i = v_i(t_f - t_i) + \frac{1}{2}a(t_f - t_i)^2$. If $d_i = 0$ and $t_i = 0$, then the displacement is $d_f = v_i t_f + \frac{1}{2}at_f^2$. Dividing both sides of the equation by t_f yields the following: $d_f/t_f = v_i + \frac{1}{2}at_f$. The slope of a graph of d_f/t_f versus t_f, is equal to $\frac{1}{2}a$. The initial velocity, v_i, is determined by the y-intercept. In this activity, you will be using a spark timer to collect free-fall data and use it to determine the acceleration due to gravity, g.

QUESTION

How does the value of *g* vary from place to place?

Objectives

- **Measure** free-fall data.
- **Make and use graphs** of velocity versus time.
- **Compare and contrast** values of g for different locations.

Safety Precautions

- **Keep clear of falling masses.**

Materials

spark timer
timer tape
1-kg mass
C-clamp
stack of newspapers
masking tape

Horizons Companies

Procedure

1. Attach the spark timer to the edge of the lab table with the C-clamp.
2. If the timer needs to be calibrated, follow your teacher's instructions or those provided with the timer. Determine the period of the timer and record it in your data table.
3. Place the stack of newspapers on the floor, directly below the timer so that the mass, when released, will not damage the floor.
4. Cut a piece of timer tape approximately 70 cm in length and slide it into the spark timer.
5. Attach the timer tape to the 1-kg mass with a small piece of masking tape. Hold the mass next to the spark timer, over the edge of the table so that it is above the newspaper stack.
6. Turn on the spark timer and release the mass.
7. Inspect the timer tape to make sure that there are dots marked on it and that there are no gaps in the dot sequence. If your timer tape is defective, repeat steps 4–6 with another piece of timer tape.
8. Have each member of your group perform the experiment and collect his or her own data.
9. Choose a dot near the beginning of the timer tape, a few centimeters from the point where the timer began to record dots, and label it *0.* Label the dots after that *1, 2, 3, 4, 5,* etc. until you get near the end where the mass is no longer in free fall. If the dots stop, or the distance between them begins to get smaller, the mass is no longer in free fall.

CONTENTS

Data Table	
Time period (#/s)	

Interval	Distance (cm)	Time (s)	Speed (cm/s)
1			
2			
3			
4			
5			
6			
7			
8			

10. Measure the total distance to each numbered dot from the zero dot, to the nearest millimeter and record it in your data table. Using the timer period, record the total time associated with each distance measurement and record it in your data table.

Analyze

1. **Use Numbers** Calculate the values for speed and record them in the data table.
2. **Make and Use Graphs** Draw a graph of speed versus time. Draw the best-fit straight line for your data.
3. Calculate the slope of the line. Convert your result to m/s^2.

Conclude and Apply

1. Recall that the slope is equal to $\frac{1}{2}a$. What is the acceleration due to gravity?
2. Find the relative error for your experimental value of g by comparing it to the accepted value.

   Relative error =

   $$\frac{\text{Accepted value} - \text{Experimental value}}{\text{Accepted value}} \times 100$$

3. What was the mass's velocity, v_i, when you began measuring distance and time?

Going Further

What is the advantage of measuring several centimeters away from the beginning of the timer tape rather than from the very first dot?

Real-World Physics

Why do designers of free-fall amusement-park rides design exit tracks that gradually curve toward the ground? Why is there a stretch of straight track?

Share Your Data

Communicate the average value of g to others. Go to **physicspp.com/internet_lab** and post the name of your school, city, state, elevation above sea level, and average value of g for your class. Obtain a map for your state and a map of the United States. Using the data posted on the Web site by other students, mark the values for g at the appropriate locations on the maps. Do you notice any variation in the acceleration due to gravity for different locations, regions and elevations?

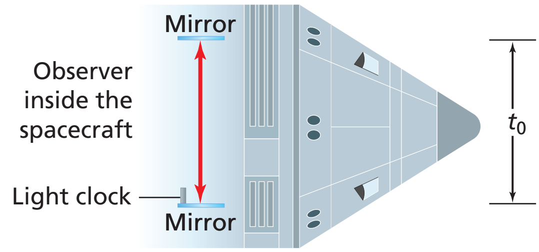
Physics Online

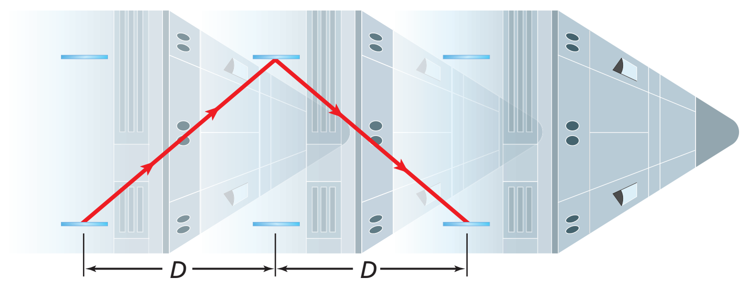
To find out more about accelerated motion, visit the Web site: **physicspp.com**

eXtreme physics

Time Dilation at High Velocities

Can time pass differently in two reference frames? How can one of a pair of twins age more than the other?





Observer on Earth

Light Clock Consider the following thought experiment using a light clock. A light clock is a vertical tube with a mirror at each end. A short pulse of light is introduced at one end and allowed to bounce back and forth within the tube. Time is measured by counting the number of bounces made by the pulse of light. The clock will be accurate because the speed of a pulse of light is always c, which is 3×10^8 m/s, regardless of the velocity of the light source or the observer.

Suppose this light clock is placed in a very fast spacecraft. When the spacecraft goes at slow speeds, the light beam bounces vertically in the tube. If the spacecraft is moving fast, the light beam still bounces vertically—at least as seen by the observer in the spacecraft.

A stationary observer on Earth, however, sees the pulse of light move diagonally because of the movement of the spacecraft. Thus, to the stationary observer, the light beam moves a greater distance. Distance = velocity × time, so if the distance traveled by the light beam increases, the product (velocity × time) also must increase.

Because the speed of the light pulse, c, is the same for any observer, time must be increasing for the stationary observer. That is, the stationary observer sees the moving clock ticking slower than the same clock on Earth.

Suppose the time per tick seen by the stationary observer on Earth is t_s, the time seen by the observer on the spacecraft is t_o, the length of the light clock is ct_o, the velocity of the spacecraft is v, and the speed of light is c. For every tick, the spacecraft moves vt_s and the light pulse moves ct_o. This leads to the following equation:

$$t_s = \frac{t_o}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$$

To the stationary observer, the closer v is to c, the slower the clock ticks. To the observer on the spacecraft, however, the clock keeps perfect time.

Time Dilation This phenomenon is called time dilation and it applies to every process associated with time aboard the spacecraft. For example, biological aging will proceed more slowly in the spacecraft than on Earth. So if the observer on the spacecraft is one of a pair of twins, he or she would age more slowly than the other twin on Earth. This is called the twin paradox. Time dilation has resulted in a lot of speculation about space travel. If spacecraft were able to travel at speeds close to the speed of light, trips to distant stars would take only a few years for the astronaut.

Going Further

1. **Calculate** Find the time dilation t_s/t_o for Earth's orbit about the Sun if v_{Earth} = 10,889 km/s.
2. **Calculate** Derive the equation for t_s above.
3. **Discuss** How is time dilation similar to or different from time travel?

Chapter 3 Study Guide

3.1 Acceleration

Vocabulary

- velocity-time graph (p. 58)
- acceleration (p.59)
- average acceleration (p. 59)
- instantaneous acceleration (p. 59)

Key Concepts

- A velocity-time graph can be used to find the velocity and acceleration of an object.
- The average acceleration of an object is the slope of its velocity-time graph.

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

- Average acceleration vectors on a motion diagram indicate the size and direction of the average acceleration during a time interval.
- When the acceleration and velocity are in the same direction, the object speeds up; when they are in opposite directions, the object slows down.
- Velocity-time graphs and motion diagrams can be used to determine the sign of an object's acceleration.

3.2 Motion with Constant Acceleration

Key Concepts

- If an object's average acceleration during a time interval is known, the change in velocity during that time can be found.

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

- The area under an object's velocity-time graph is its displacement.
- In motion with constant acceleration, there are relationships among the position, velocity, acceleration, and time.

$$d_f = d_i + v_i t_f + \frac{1}{2}\bar{a}{t_f}^2$$

- The velocity of an object with constant acceleration can be found using the following equation.

$${v_f}^2 = {v_i}^2 + 2\bar{a}(d_f - d_i)$$

3.3 Free Fall

Vocabulary

- free fall (p. 72)
- acceleration due to gravity (p. 72)

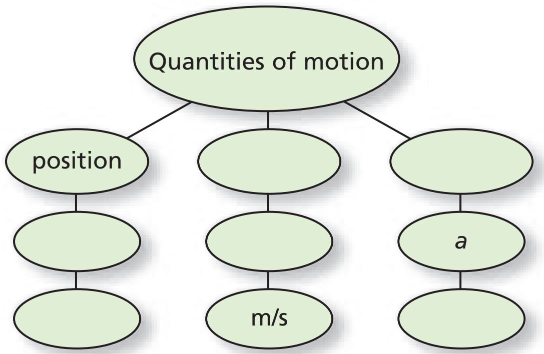
Key Concepts

- The acceleration due to gravity on Earth, g, is 9.80 m/s^2 downward. The sign associated with g in equations depends upon the choice of the coordinate system.
- Equations for motion with constant acceleration can be used to solve problems involving objects in free fall.

Assessment

Concept Mapping

53. Complete the following concept map using the following symbols or terms: *d*, *velocity*, *m/s*^{2}, *v*, *m*, *acceleration*.



Mastering Concepts

54. How are velocity and acceleration related? (3.1)

55. Give an example of each of the following. (3.1)
 a. an object that is slowing down, but has a positive acceleration
 b. an object that is speeding up, but has a negative acceleration

56. **Figure 3-16** shows the velocity-time graph for an automobile on a test track. Describe how the velocity changes with time. (3.1)

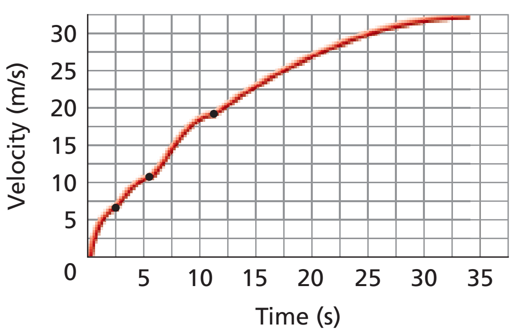


Figure 3-16

57. What does the slope of the tangent to the curve on a velocity-time graph measure? (3.1)

58. Can a car traveling on an interstate highway have a negative velocity and a positive acceleration at the same time? Explain. Can the car's velocity change signs while it is traveling with constant acceleration? Explain. (3.1)

59. Can the velocity of an object change when its acceleration is constant? If so, give an example. If not, explain. (3.1)

60. If an object's velocity-time graph is a straight line parallel to the *t*-axis, what can you conclude about the object's acceleration? (3.1)

61. What quantity is represented by the area under a velocity-time graph? (3.2)

62. Write a summary of the equations for position, velocity, and time for an object experiencing motion with uniform acceleration. (3.2)

63. Explain why an aluminum ball and a steel ball of similar size and shape, dropped from the same height, reach the ground at the same time. (3.3)

64. Give some examples of falling objects for which air resistance cannot be ignored. (3.3)

65. Give some examples of falling objects for which air resistance can be ignored. (3.3)

Applying Concepts

66. Does a car that is slowing down always have a negative acceleration? Explain.

67. **Croquet** A croquet ball, after being hit by a mallet, slows down and stops. Do the velocity and acceleration of the ball have the same signs?

68. If an object has zero acceleration, does it mean its velocity is zero? Give an example.

69. If an object has zero velocity at some instant, is its acceleration zero? Give an example.

70. If you were given a table of velocities of an object at various times, how would you find out whether the acceleration was constant?

71. The three notches in the graph in Figure 3-16 occur where the driver changed gears. Describe the changes in velocity and acceleration of the car while in first gear. Is the acceleration just before a gear change larger or smaller than the acceleration just after the change? Explain your answer.

72. Use the graph in Figure 3-16 and determine the time interval during which the acceleration is largest and the time interval during which the acceleration is smallest.

73. Explain how you would walk to produce each of the position-time graphs in **Figure 3-17.**

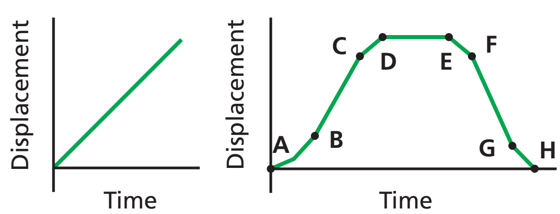


Figure 3-17

 For more problems, go to Additional Problems, Appendix B.

74. Draw a velocity-time graph for each of the graphs in **Figure 3-18.**

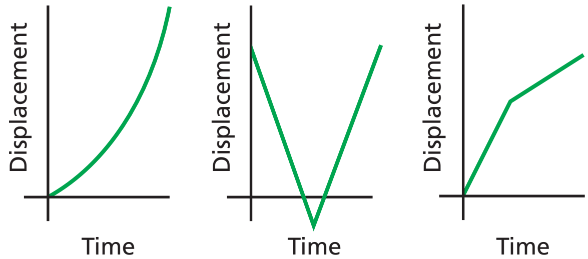


Figure 3-18

75. An object shot straight up rises for 7.0 s before it reaches its maximum height. A second object falling from rest takes 7.0 s to reach the ground. Compare the displacements of the two objects during this time interval.

76. The Moon The value of g on the Moon is one-sixth of its value on Earth.
- **a.** Would a ball that is dropped by an astronaut hit the surface of the Moon with a greater, equal, or lesser speed than that of a ball dropped from the same height to Earth?
- **b.** Would it take the ball more, less, or equal time to fall?

77. Jupiter The planet Jupiter has about three times the gravitational acceleration of Earth. Suppose a ball is thrown vertically upward with the same initial velocity on Earth and on Jupiter. Neglect the effects of Jupiter's atmospheric resistance and assume that gravity is the only force on the ball.
- **a.** How does the maximum height reached by the ball on Jupiter compare to the maximum height reached on Earth?
- **b.** If the ball on Jupiter were thrown with an initial velocity that is three times greater, how would this affect your answer to part **a?**

78. Rock A is dropped from a cliff and rock B is thrown upward from the same position.
- **a.** When they reach the ground at the bottom of the cliff, which rock has a greater velocity?
- **b.** Which has a greater acceleration?
- **c.** Which arrives first?

Mastering Problems

3.1 Acceleration

79. A car is driven for 2.0 h at 40.0 km/h, then for another 2.0 h at 60.0 km/h in the same direction.
- **a.** What is the car's average velocity?
- **b.** What is the car's average velocity if it is driven 1.0×10^2 km at each of the two speeds?

80. Find the uniform acceleration that causes a car's velocity to change from 32 m/s to 96 m/s in an 8.0-s period.

81. A car with a velocity of 22 m/s is accelerated uniformly at the rate of 1.6 m/s^2 for 6.8 s. What is its final velocity?

82. Refer to **Figure 3-19** to find the acceleration of the moving object at each of the following times.
- **a.** during the first 5.0 s of travel
- **b.** between 5.0 s and 10.0 s
- **c.** between 10.0 s and 15.0 s
- **d.** between 20.0 s and 25.0 s

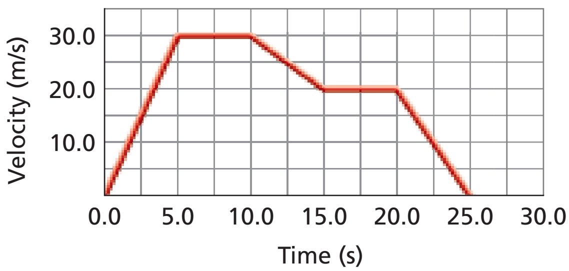


Figure 3-19

83. Plot a velocity-time graph using the information in **Table 3-4,** and answer the following questions.
- **a.** During what time interval is the object speeding up? Slowing down?
- **b.** At what time does the object reverse direction?
- **c.** How does the average acceleration of the object in the interval between 0.0 s and 2.0 s differ from the average acceleration in the interval between 7.0 s and 12.0 s?

Table 3-4
Velocity v. Time

Time (s)	Velocity (m/s)
0.00	4.00
1.00	8.00
2.00	12.0
3.00	14.0
4.00	16.0
5.00	16.0
6.00	14.0
7.00	12.0
8.00	8.00
9.00	4.00
10.0	0.00
11.0	−4.00
12.0	−8.00

84. Determine the final velocity of a proton that has an initial velocity of 2.35×10^5 m/s and then is accelerated uniformly in an electric field at the rate of -1.10×10^{12} m/s^2 for 1.50×10^{-7} s.

85. Sports Cars Marco is looking for a used sports car. He wants to buy the one with the greatest acceleration. Car A can go from 0 m/s to 17.9 m/s in 4.0 s; car B can accelerate from 0 m/s to 22.4 m/s in 3.5 s; and car C can go from 0 to 26.8 m/s in 6.0 s. Rank the three cars from greatest acceleration to least, specifically indicating any ties.

86. Supersonic Jet A supersonic jet flying at 145 m/s experiences uniform acceleration at the rate of 23.1 m/s^2 for 20.0 s.
a. What is its final velocity?
b. The speed of sound in air is 331 m/s. What is the plane's speed in terms of the speed of sound?

3.2 Motion with Constant Acceleration

87. Refer to Figure 3-19 to find the distance traveled during the following time intervals.
a. t = 0.0 s and t = 5.0 s
b. t = 5.0 s and t = 10.0 s
c. t = 10.0 s and t = 15.0 s
d. t = 0.0 s and t = 25.0 s

88. A dragster starting from rest accelerates at 49 m/s^2. How fast is it going when it has traveled 325 m?

89. A car moves at 12 m/s and coasts up a hill with a uniform acceleration of -1.6 m/s^2.
a. What is its displacement after 6.0 s?
b. What is its displacement after 9.0 s?

90. Race Car A race car can be slowed with a constant acceleration of -11 m/s^2.
a. If the car is going 55 m/s, how many meters will it travel before it stops?
b. How many meters will it take to stop a car going twice as fast?

91. A car is traveling 20.0 m/s when the driver sees a child standing on the road. She takes 0.80 s to react, then steps on the brakes and slows at 7.0 m/s^2. How far does the car go before it stops?

92. Airplane Determine the displacement of a plane that experiences uniform acceleration from 66 m/s to 88 m/s in 12 s.

93. How far does a plane fly in 15 s while its velocity is changing from 145 m/s to 75 m/s at a uniform rate of acceleration?

94. Police Car A speeding car is traveling at a constant speed of 30.0 m/s when it passes a stopped police car. The police car accelerates at 7.0 m/s^2. How fast will it be going when it catches up with the speeding car?

95. Road Barrier The driver of a car going 90.0 km/h suddenly sees the lights of a barrier 40.0 m ahead. It takes the driver 0.75 s to apply the brakes, and the average acceleration during braking is -10.0 m/s^2.
a. Determine whether the car hits the barrier.
b. What is the maximum speed at which the car could be moving and not hit the barrier 40.0 m ahead? Assume that the acceleration doesn't change.

3.3 Free Fall

96. A student drops a penny from the top of a tower and decides that she will establish a coordinate system in which the direction of the penny's motion is positive. What is the sign of the acceleration of the penny?

97. Suppose an astronaut drops a feather from 1.2 m above the surface of the Moon. If the acceleration due to gravity on the Moon is 1.62 m/s^2 downward, how long does it take the feather to hit the Moon's surface?

98. A stone that starts at rest is in free fall for 8.0 s.
a. Calculate the stone's velocity after 8.0 s.
b. What is the stone's displacement during this time?

99. A bag is dropped from a hovering helicopter. The bag has fallen for 2.0 s. What is the bag's velocity? How far has the bag fallen?

100. You throw a ball downward from a window at a speed of 2.0 m/s. How fast will it be moving when it hits the sidewalk 2.5 m below?

101. If you throw the ball in the previous problem up instead of down, how fast will it be moving when it hits the sidewalk?

102. Beanbag You throw a beanbag in the air and catch it 2.2 s later.
a. How high did it go?
b. What was its initial velocity?

Mixed Review

103. A spaceship far from any star or planet experiences uniform acceleration from 65.0 m/s to 162.0 m/s in 10.0 s. How far does it move?

104. **Figure 3-20** is a strobe photo of a horizontally moving ball. What information about the photo would you need and what measurements would you make to estimate the acceleration?

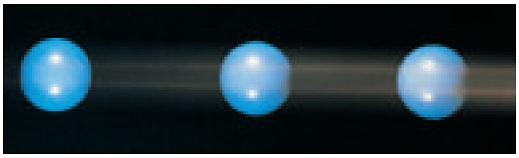


Figure 3-20

Skip Peticolas/Fundamental Photographs

105. **Bicycle** A bicycle accelerates from 0.0 m/s to 4.0 m/s in 4.0 s. What distance does it travel?

106. A weather balloon is floating at a constant height above Earth when it releases a pack of instruments.

a. If the pack hits the ground with a velocity of −73.5 m/s, how far did the pack fall?

b. How long did it take for the pack to fall?

107. **Baseball** A baseball pitcher throws a fastball at a speed of 44 m/s. The acceleration occurs as the pitcher holds the ball in his hand and moves it through an almost straight-line distance of 3.5 m. Calculate the acceleration, assuming that it is constant and uniform. Compare this acceleration to the acceleration due to gravity.

108. The total distance a steel ball rolls down an incline at various times is given in **Table 3-5.**

a. Draw a position-time graph of the motion of the ball. When setting up the axes, use five divisions for each 10 m of travel on the *d*-axis. Use five divisions for 1 s of time on the *t*-axis.

b. Calculate the distance the ball has rolled at the end of 2.2 s.

Table 3-5

Distance v. Time

Time (s)	Distance (m)
0.0	0.0
1.0	2.0
2.0	8.0
3.0	18.0
4.0	32.0
5.0	50.0

109. Engineers are developing new types of guns that might someday be used to launch satellites as if they were bullets. One such gun can give a small object a velocity of 3.5 km/s while moving it through a distance of only 2.0 cm.

a. What acceleration does the gun give this object?

b. Over what time interval does the acceleration take place?

110. **Sleds** Rocket-powered sleds are used to test the responses of humans to acceleration. Starting from rest, one sled can reach a speed of 444 m/s in 1.80 s and can be brought to a stop again in 2.15 s.

a. Calculate the acceleration of the sled when starting, and compare it to the magnitude of the acceleration due to gravity, 9.80 m/s^2.

b. Find the acceleration of the sled as it is braking and compare it to the magnitude of the acceleration due to gravity.

111. The velocity of a car changes over an 8.0-s time period, as shown in **Table 3-6.**

a. Plot the velocity-time graph of the motion.

b. Determine the displacement of the car during the first 2.0 s.

c. What displacement does the car have during the first 4.0 s?

d. What is the displacement of the car during the entire 8.0 s?

e. Find the slope of the line between $t = 0.0$ s and $t = 4.0$ s. What does this slope represent?

f. Find the slope of the line between $t = 5.0$ s and $t = 7.0$ s. What does this slope indicate?

Table 3-6

Velocity v. Time

Time (s)	Velocity (m/s)
0.0	0.0
1.0	4.0
2.0	8.0
3.0	12.0
4.0	16.0
5.0	20.0
6.0	20.0
7.0	20.0
8.0	20.0

112. A truck is stopped at a stoplight. When the light turns green, the truck accelerates at 2.5 m/s^2. At the same instant, a car passes the truck going 15 m/s. Where and when does the truck catch up with the car?

113. **Safety Barriers** Highway safety engineers build soft barriers, such as the one shown in **Figure 3-21,** so that cars hitting them will slow down at a safe rate. A person wearing a safety belt can withstand an acceleration of -3.0×10^2 m/s^2. How thick should barriers be to safely stop a car that hits a barrier at 110 km/h?

Figure 3-21

114. **Karate** The position-time and velocity-time graphs of George's fist breaking a wooden board during karate practice are shown in **Figure 3-22.**

a. Use the velocity-time graph to describe the motion of George's fist during the first 10 ms.

b. Estimate the slope of the velocity-time graph to determine the acceleration of his fist when it suddenly stops.

c. Express the acceleration as a multiple of the gravitational acceleration, $g = 9.80\ \text{m/s}^2$.

d. Determine the area under the velocity-time curve to find the displacement of the fist in the first 6 ms. Compare this with the position-time graph.

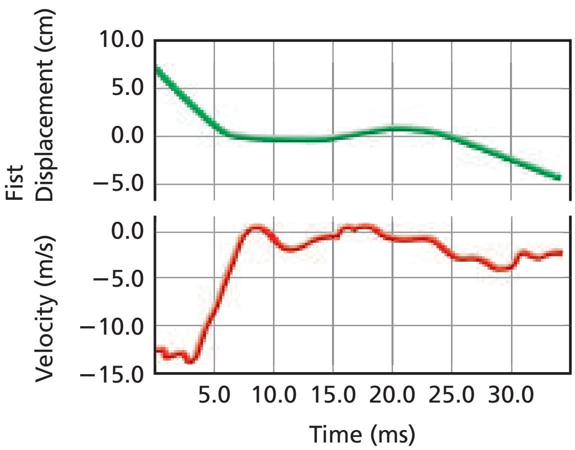


Figure 3-22

115. **Cargo** A helicopter is rising at 5.0 m/s when a bag of its cargo is dropped. The bag falls for 2.0 s.

a. What is the bag's velocity?

b. How far has the bag fallen?

c. How far below the helicopter is the bag?

Thinking Critically

116. **Apply CBLs** Design a lab to measure the distance an accelerated object moves over time. Use equal time intervals so that you can plot velocity over time as well as distance. A pulley at the edge of a table with a mass attached is a good way to achieve uniform acceleration. Suggested materials include a motion detector, CBL, lab cart, string, pulley, C-clamp, and masses. Generate distance-time and velocity-time graphs using different masses on the pulley. How does the change in mass affect your graphs?

117. **Analyze and Conclude** Which has the greater acceleration: a car that increases its speed from 50 km/h to 60 km/h, or a bike that goes from 0 km/h to 10 km/h in the same time? Explain.

118. **Analyze and Conclude** An express train, traveling at 36.0 m/s, is accidentally sidetracked onto a local train track. The express engineer spots a local train exactly 1.00×10^2 m ahead on the same track and traveling in the same direction. The local engineer is unaware of the situation. The express engineer jams on the brakes and slows the express train at a constant rate of $3.00\ \text{m/s}^2$. If the speed of the local train is 11.0 m/s, will the express train be able to stop in time, or will there be a collision? To solve this problem, take the position of the express train when the engineer first sights the local train as a point of origin. Next, keeping in mind that the local train has exactly a 1.00×10^2 m lead, calculate how far each train is from the origin at the end of the 12.0 s it would take the express train to stop (accelerate at $-3.00\ \text{m/s}^2$ from 36 m/s to 0 m/s).

a. On the basis of your calculations, would you conclude that a collision will occur?

b. The calculations that you made do not allow for the possibility that a collision might take place before the end of the 12 s required for the express train to come to a halt. To check this, take the position of the express train when the engineer first sights the local train as the point of origin and calculate the position of each train at the end of each second after the sighting. Make a table showing the distance of each train from the origin at the end of each second. Plot these positions on the same graph and draw two lines. Use your graph to check your answer to part **a.**

Writing in Physics

119. Research and describe Galileo's contributions to physics.

120. Research the maximum acceleration a human body can withstand without blacking out. Discuss how this impacts the design of three common entertainment or transportation devices.

Cumulative Review

121. Solve the following problems. Express your answers in scientific notation. (Chapter 1)

a. 6.2×10^{-4} m + 5.7×10^{-3} m

b. 8.7×10^{8} km − 3.4×10^{7} m

c. $(9.21\times10^{-5}\ \text{cm})(1.83\times10^{8}\ \text{cm})$

d. $(2.63\times10^{-6}\ \text{m})/(4.08\times10^{6}\ \text{s})$

122. The equation below describes the motion of an object. Create the corresponding position-time graph and motion diagram. Then write a physics problem that could be solved using that equation. Be creative. $d = (35.0\ \text{m/s})\,t - 5.0\ \text{m}$ (Chapter 2)

 For more problems, go to Additional Problems, Appendix B.

Standardized Test Practice

Multiple Choice

Use the following information to answer the first two questions.

A ball rolls down a hill with a constant acceleration of 2.0 m/s^2. The ball starts at rest and travels for 4.0 s before it stops.

1. How far did the ball travel before it stopped?

- (A) 8.0 m
- (B) 12 m
- (C) 16 m
- (D) 20 m

2. What was the ball's velocity just before it stopped?

- (A) 2.0 m/s
- (B) 8.0 m/s
- (C) 12 m/s
- (D) 16 m/s

3. A driver of a car enters a new 110-km/h speed zone on the highway. The driver begins to accelerate immediately and reaches 110 km/h after driving 500 m. If the original speed was 80 km/h, what was the driver's rate of acceleration?

- (A) 0.44 m/s^2
- (B) 0.60 m/s^2
- (C) 8.4 m/s^2
- (D) 9.80 m/s^2

4. A flowerpot falls off the balcony of a penthouse suite 85 m above the street. How long does it take to hit the ground?

- (A) 4.2 s
- (B) 8.3 s
- (C) 8.7 s
- (D) 17 s

5. A rock climber's shoe loosens a rock, and her climbing buddy at the bottom of the cliff notices that the rock takes 3.20 s to fall to the ground. How high up the cliff is the rock climber?

- (A) 15.0 m
- (B) 31.0 m
- (C) 50.0 m
- (D) 1.00×10^2 m

6. A car traveling at 91.0 km/h approaches the turnoff for a restaurant 30.0 m ahead. If the driver slams on the brakes with an acceleration of -6.40 m/s^2, what will be her stopping distance?

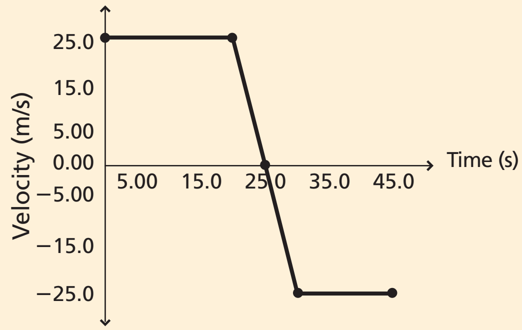
- (A) 14.0 m
- (B) 29.0 m
- (C) 50.0 m
- (D) 100.0 m

7. What is the correct formula manipulation to find acceleration when using the equation $v_f^2 = v_i^2 + 2ad$?

- (A) $(v_f^2 - v_i^2)/d$
- (B) $(v_f^2 + v_i^2)/2d$
- (C) $(v_f + v_i)^2/2d$
- (D) $(v_f^2 - v_i^2)/2d$

8. The graph shows the motion of a farmer's truck. What is the truck's total displacement? Assume that north is the positive direction.

- (A) 150 m south
- (B) 125 m north
- (C) 300 m north
- (D) 600 m south



9. How can the instantaneous acceleration of an object with varying acceleration be calculated?

- (A) by calculating the slope of the tangent on a distance-time graph
- (B) by calculating the area under the graph on a distance-time graph
- (C) by calculating the area under the graph on a velocity-time graph
- (D) by calculating the slope of the tangent on a velocity-time graph

Extended Answer

10. Graph the following data, and then show calculations for acceleration and displacement after 12.0 s on the graph.

Time (s)	Velocity (m/s)
0.00	8.10
6.00	36.9
9.00	51.3
12.00	65.7

✓ Test-Taking TIP

Tables

If a test question involves a table, skim the table before reading the question. Read the title, column heads, and row heads. Then read the question and interpret the information in the table.

Chapter 4 Forces in One Dimension

What You'll Learn

- You will use Newton's laws to solve problems.
- You will determine the magnitude and direction of the net force that causes a change in an object's motion.
- You will classify forces according to the agents that cause them.

Why It's Important

Forces act on you and everything around you at all times.

Sports A soccer ball is headed by a player. Before play began, the ball was motionless. During play, the ball started, stopped, and changed directions many times.

Think About This ▶

What causes a soccer ball, or any other object, to stop, start, or change direction?

Physics Online

physicspp.com

Joe McBride/CORBIS

LAUNCH Lab

Which force is stronger?

Question

What forces can act on an object that is suspended by a string?

Procedure

1. Tie a piece of heavy cord around the middle of a book. Tie one piece of lightweight string to the center of the cord on the top of the book. Tie another piece to the bottom.
2. While someone holds the end of the top lightweight string so that the book is suspended in the air, pull very slowly, but firmly, on the end of the bottom lightweight string. Record your observations. ***CAUTION: Keep feet clear of falling objects.***
3. Replace the broken string and repeat step 2, but this time pull very fast and very hard on the bottom string. Record your observations.

Analysis

Which string broke in step 2? Why? Which string broke in step 3? Why?

Critical Thinking Draw a diagram of the experimental set-up. Use arrows to show the forces acting on the book.

4.1 Force and Motion

Imagine that a train is speeding down a railroad track at 80 km/h when suddenly the engineer sees a truck stalled at a railroad crossing ahead. The engineer applies the brakes to try to stop the train before it crashes into the truck. Because the brakes cause an acceleration in the direction opposite the train's velocity, the train will slow down. Imagine that, in this case, the engineer is able to stop the train just before it crashes into the truck. But what if instead of moving at 80 km/h the train had been moving at 100 km/h? What would have to happen for the train to avoid hitting the truck? The acceleration provided by the train's brakes would have to be greater because the engineer still has the same distance in which to stop the train. Similarly, if the train was going 80 km/h but had been much closer to the truck when the engineer started to apply the brake, the acceleration also would need to be greater because the train would need to stop in less time.

Objectives

- **Define** force.
- **Apply** Newton's second law to solve problems.
- **Explain** the meaning of Newton's first law.

Vocabulary

force
free-body diagram
net force
Newton's second law
Newton's first law
inertia
equilibrium

Force and Motion

What happened to make the train slow down? A **force** is a push or pull exerted on an object. Forces can cause objects to speed up, slow down, or change direction as they move. When an engineer applies the brakes, the brakes exert a force on the wheels and cause the train to slow down. Based on the definitions of velocity and acceleration, this can be restated as follows: a force exerted on an object causes that object's velocity to change; that is, a force causes an acceleration.

Consider a textbook resting on a table. How can you cause it to move? Two possibilites are that you can push on it or you can pull on it. The push or pull is a force that you exert on the textbook. If you push harder on an object, you have a greater effect on its motion. The direction in which the force is exerted also matters—if you push the book to the right, the book moves in a different direction from the direction it would move if you pushed it to the left. The symbol $\boldsymbol{F}$ is a vector and represents the size and direction of a force, while F represents only the magnitude.

When considering how a force affects motion, it is important to identify the object of interest. This object is called the system. Everything around the object that exerts forces on it is called the external world. In the case of the book in **Figure 4-1,** the book is the system. Your hand and gravity are parts of the external world that can interact with the book by pushing or pulling on it and potentially causing its motion to change.

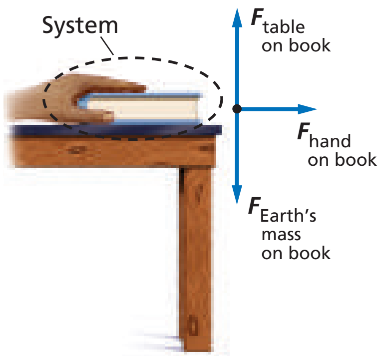


Figure 4-1 The book is the system. The table, the hand, and Earth's mass (through gravity) all exert forces on the book.

Contact Forces and Field Forces

Again, think about the different ways in which you could move a textbook. You could touch it directly and push or pull 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 and thereby exerts 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 force on the book. The table, however, is exerting a force because the table and the book are in contact.

There are other ways in which you could change the motion of the textbook. You could drop it, and as you learned in Chapter 3, 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. This 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 experimented with magnets, you know that they exert forces without touching. You will investigate magnetism and other similar forces in more detail in future chapters. For now, the only field force that you need to consider is the gravitational force.

Forces result from interactions; thus, each 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? If you allow your textbook to fall, the agent is the mass of Earth exerting a field force on the book.

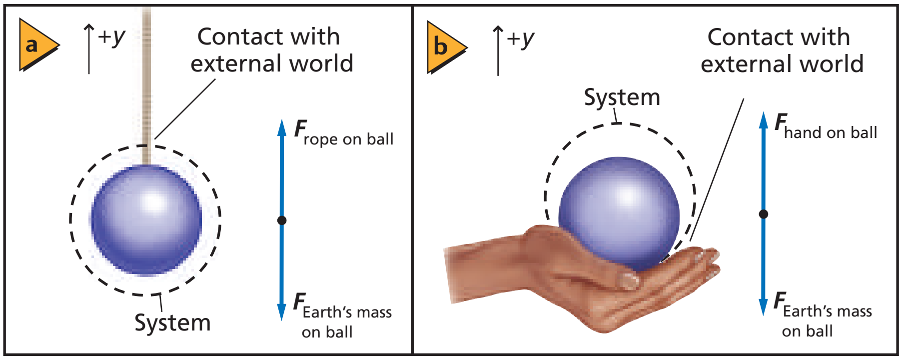


Figure 4-2 To make a physical model of the forces acting on an object, apply the particle model and draw an arrow to represent each force. Label each force, including its agent.

Free-body diagrams Just as pictorial models and motion diagrams are useful in solving problems about motion, similar representations will help you to analyze how forces affect motion. The first step in solving any problem is to create a pictorial model. For example, to represent the forces on a ball tied to a string or held in your hand, sketch the situations, as shown in **Figures 4-2a** and **4-2b.** Circle the system and identify every place where the system touches the external world. It is at these places that contact forces are exerted. Identify the contact forces. Then identify any field forces on the system. This gives you the pictorial model.

To make a physical representation of the forces acting on the ball in Figures 4-2a and 4-2b, apply the particle model and represent the object with a dot. Represent each force with a blue arrow that points in the direction that the force is applied. Try to 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. Always draw the force arrows pointing away from the particle, even when the force is a push. Make sure that you label each force. Use the symbol $\boldsymbol{F}$ with a subscript label to identify both the agent and the object on which the force is exerted. Finally, choose a direction to be positive and indicate this off to the side of your diagram. Usually, you select the positive direction to be in the direction of the greatest amount of force. This typically makes the problem easiest to solve by reducing the number of negative values in your calculations. This type of physical model, which represents the forces acting on a system, is called a **free-body diagram.**

PRACTICE Problems

Additional Problems, Appendix B

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.

1. A flowerpot falls freely from a windowsill. (Ignore any forces due to air resistance.)

2. A sky diver falls downward through the air at constant velocity. (The air exerts an upward force on the person.)

3. A cable pulls a crate at a constant speed across a horizontal surface. The surface provides a force that resists the crate's motion.

4. A rope lifts a bucket at a constant speed. (Ignore air resistance.)

5. A rope lowers a bucket at a constant speed. (Ignore air resistance.)

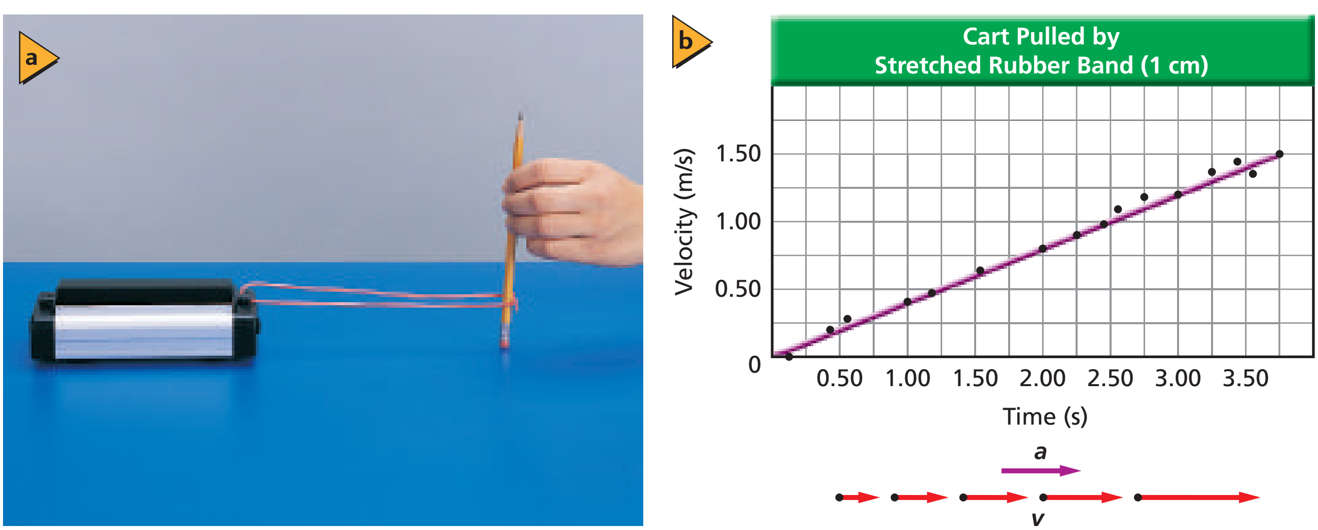
Force and Acceleration

How does an object move when one or more forces are exerted on it? One way to find out is by doing experiments. As before, begin by considering a simple situation. Once you fully understand that situation, then you can add more complications to it. In this case, begin with one controlled force exerted horizontally on an object. The horizontal direction is a good place to start because gravity does not act horizontally. Also, to reduce complications resulting from the object rubbing against the surface, do the experiments on a very smooth surface, such as ice or a very well-polished table, and use an object with wheels that spin easily. In other words, you are trying to reduce the resistance to motion in the situation.

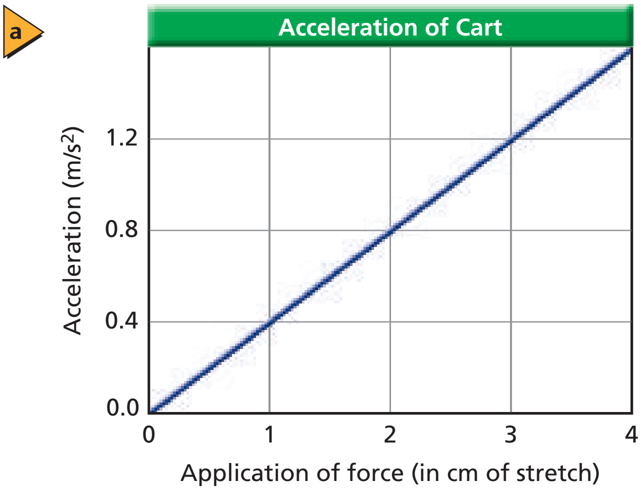
To determine how force, acceleration, and velocity are related, you need to be able to exert a constant and controlled force on an object. How can you exert such a controlled force? A stretched rubber band exerts a pulling force; the farther you stretch it, the greater the force with which it pulls back. If you always stretch the rubber band the same amount, you always exert the same force. **Figure 4-3a** shows a rubber band, stretched a constant 1 cm, pulling a low-resistance cart. If you perform this experiment and determine the cart's velocity for some period of time, you could construct a graph like the one shown in **Figure 4-3b.** Does this graph look different from what you expected? What do you notice about the velocity? The constant increase in the velocity is a result of the constant acceleration the stretched rubber band gives the cart.

How does this acceleration depend upon the force? To find out, repeat the experiment, this time with the rubber band stretched to a constant 2 cm, and then repeat it again with the rubber band stretched longer and longer each time. For each experiment, plot a velocity-time graph like the one in Figure 4-3b, calculate the acceleration, and then plot the accelerations and forces for all the trials to make a force-acceleration graph, as shown in **Figure 4-4a.** What is the relationship between the force and acceleration? It's a linear relationship where the greater the force is, the greater the resulting acceleration. As you did in Chapters 2 and 3, you can apply the straight-line equation $y = mx + b$ to this graph.

Figure 4-3 Because the rubber band is stretched a constant amount, it applies a constant force on the cart, which is designed to be low-friction **(a).** The cart's motion can be graphed and shown to be a linear relationship **(b).**



Matt Meadows



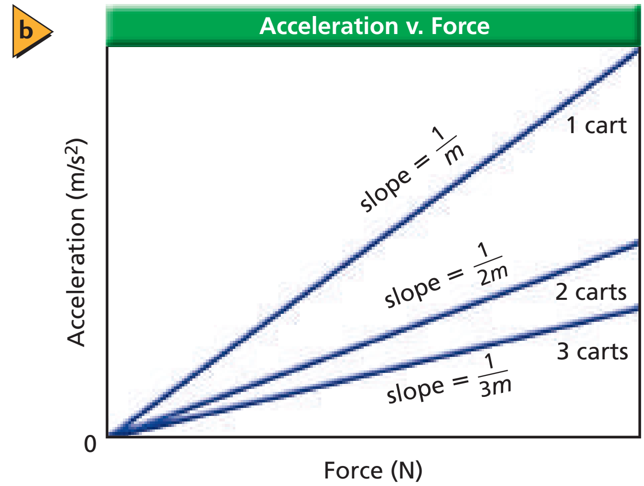


Figure 4-4 The graph shows that as the force increases, so does the acceleration **(a).** You can see that the slope of the force-acceleration graph depends upon the number of carts **(b).**

What is the physical meaning of this slope? Perhaps it describes something about the object that is accelerating. What happens if the object changes? Suppose that a second, identical cart is placed on top of the first, and then a third cart is added. The rubber band would be pulling two carts, and then three. A plot of the force versus acceleration for one, two, and three carts is shown in **Figure 4-4b.** The graph shows that if the same force is applied in each situation, 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 is increased, a greater force is needed to produce the same acceleration. In this example, you would have to stretch the rubber band farther to get a greater amount of force. The slopes of the lines in Figure 4-4b depend upon the number of carts; that is, the slope depends on the total mass of the carts. If the slope, k in this case, is defined as the reciprocal of the mass ($k = 1/m$), then $a = F/m$, or $F = ma$.

What information is contained in the equation $a = F/m$? It tells you that a 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 several different objects, the one with the most mass will have the smallest acceleration and the one with the least mass will have the greatest acceleration.

What are the proper units for measuring force? Because $F = ma$, one unit of force causes a 1-kg mass to accelerate at 1 m/s^2, so one force unit has the dimensions 1 $kg \cdot m/s^2$. The unit 1 $kg \cdot m/s^2$ is called the newton, represented by N. One newton of force applied to a 1-kg object will cause it to have an acceleration of 1 m/s^2. Do these units make sense? Think about a sky diver who is falling through the air. The properties affecting his motion are his mass and the acceleration due to the gravitational force, so these units do make sense. **Table 4-1** shows the magnitude of some common forces.

Table 4-1
Common Forces

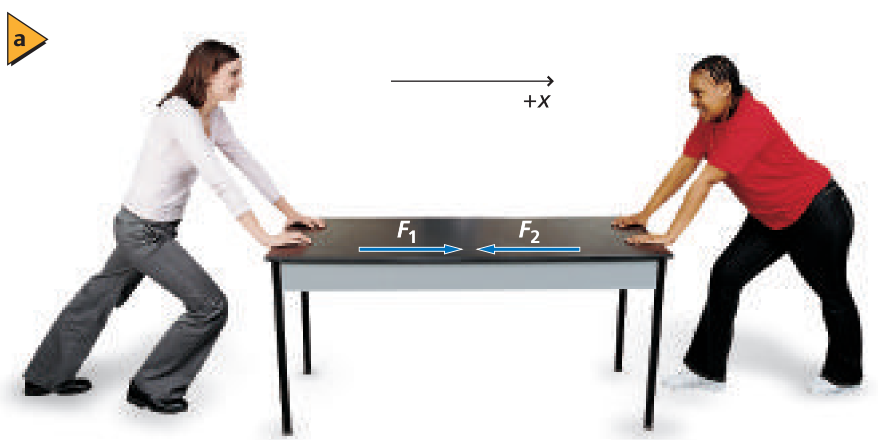
Description	*F* (N)
Force of gravity on a coin (nickel)	0.05
Force of gravity on 1 lb (0.45 kg) of sugar	4.5
Force of gravity on a 150-lb (70-kg) person	686
Force of an accelerating car	3000
Force of a rocket motor	5,000,000

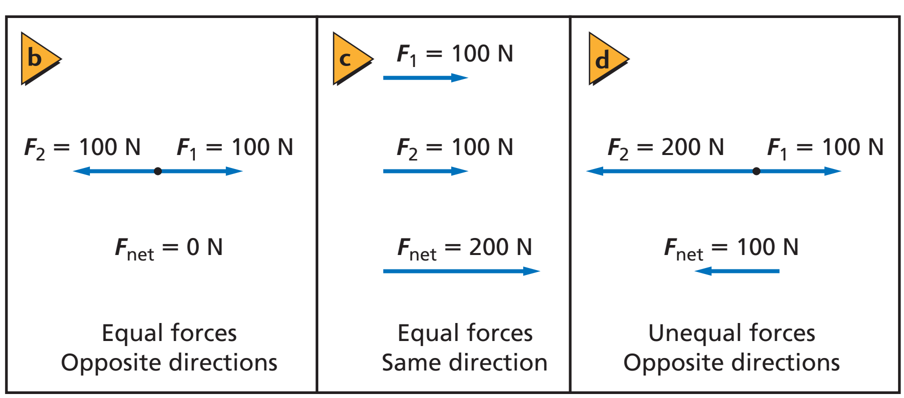
Combining Forces

What happens if you and a friend each push a table and exert 100 N of force on it? When you and your friend push together, you give the table a greater acceleration than when you push against each other. In fact, when you push together, 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 4-5a,** the table does not move at all.

Figure 4-5b and **c** show free-body diagrams for these two situations. **Figure 4-5d** shows a third free-body diagram 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 total result 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 resulting vector 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. Assume that you are pushing the table in the positive direction with a 100 N force in the above cases. 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 will accelerate in the negative direction.





■ **Figure 4-5** Pushing on the table with equal force in opposite directions **(a)** results in no net force on the table, as shown by the vector addition in the free-body diagram **(b).** However, there is a net force applied in **(c)** and **(d),** as shown by the free-body diagrams.

Aaron Haupt

Newton's Second Law

You could conduct a series of experiments in which you and your friend vary the net force exerted on the table and measure the acceleration in each case. You would find that the acceleration of the table is proportional to the net force exerted on it and inversely proportional to its mass. In other words, if the net force of you and your friend acting on the table is 100 N, the table will experience the same acceleration as it would if only you were acting on it with a force of 100 N. Taking this into account, the mathematical relationship among force, mass, and acceleration can be rewritten in terms of the net force. The observation that the acceleration of an object is proportional to the net force and inversely proportional to the mass of the object being accelerated is **Newton's second law,** which is represented by the following equation.

Newton's Second Law $\boldsymbol{a} = \frac{\boldsymbol{F}_{\text{net}}}{m}$

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

Notice that Newton's second law can be rearranged to the form $F = ma$, which you learned about previously. If the table that you and your friend were pushing was 15.0 kg and the two of you each pushed with a force of 50.0 N in the same direction, what would be the acceleration of the table? To find out, calculate the net force, 50.0 N + 50.0 N = 100.0 N, and apply Newton's second law by dividing the net force of 100.0 N by the mass of the table, 15.0 kg, to get an acceleration of 6.67 m/s^2.

Here is a useful strategy for finding how the motion of an object depends on the forces exerted on it. First, identify all the forces acting on the object. Draw a free-body diagram showing the direction and relative strength of each force acting on the system. Then, add the forces to find the net force. Next, use Newton's second law to calculate the acceleration. Finally, if necessary, use kinematics to find the velocity or position of the object. When you learned about kinematics in Chapters 2 and 3, you studied the motion of objects without regard for the causes of motion. You now know that an unbalanced force, a net force, is the cause of a change in velocity (an acceleration).

PRACTICE Problems

Additional Problems, Appendix B

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 canoe.

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. Three confused sleigh 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?

Newton's First Law

What is the motion of an object with no net force acting on it? A stationary object with no net force acting on it will stay at its position. Consider a moving object, such as a ball rolling on a surface. How long will the ball continue to roll? It will depend on the quality of the surface. If the ball is rolled on a thick carpet that offers much resistance, it will come to rest quickly. If it is rolled on a hard, smooth surface that offers little resistance, 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 in the ideal case of zero resistance, 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 the ideal case, in which there is no resistance to slow down an object's motion.

In the absence of a net force, the motion (or lack of motion) of both the moving ball and the stationary object continues as it was. Newton recognized this and generalized Galileo's results in a single statement. This 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.**

Table 4-2

Some Types of Forces

Force	Symbol	Definition	Direction
Friction	$\boldsymbol{F}_{\mathrm{f}}$	The contact force that acts to oppose sliding motion between surfaces	Parallel to the surface and opposite the direction of sliding
Normal	$\boldsymbol{F}_{\mathrm{N}}$	The contact force exerted by a surface on an object	Perpendicular to and away from the surface
Spring	$\boldsymbol{F}_{\mathrm{sp}}$	A restoring force; that is, the push or pull a spring exerts on an object	Opposite the displacement of the object at the end of the spring
Tension	$\boldsymbol{F}_{\mathrm{T}}$	The pull exerted by a string, rope, or cable when attached to a body and pulled taut	Away from the object and parallel to the string, rope, or cable at the point of attachment
Thrust	$\boldsymbol{F}_{\mathrm{thrust}}$	A general term for the forces that move objects such as rockets, planes, cars, and people	In the same direction as the acceleration of the object, barring any resistive forces
Weight	$\boldsymbol{F}_{\mathrm{g}}$	A field force due to gravitational attraction between two objects, generally Earth and an object	Straight down toward the center of Earth

Inertia Newton's first law is sometimes called the law of inertia. Is inertia a force? No. **Inertia** is the tendency of an object to resist change. If an object is at rest, it tends to remain at rest. If it is moving at a constant velocity, it tends to continue moving at that velocity. 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 direction of an object's motion.

Equilibrium According to Newton's first law, a net force is something that 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 at rest or if it is moving at a constant velocity. Note that being at rest is simply a special case 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.

By understanding and applying Newton's first and second laws, you can often figure out something about the relative sizes of forces, even in situations in which you do not have numbers to work with. Before looking at an example of this, review **Table 4-2,** which lists some of the common types of forces. You will be dealing with many of these throughout your study of physics.

When analyzing forces and motion, it is important to keep in mind that the world is dominated by resistance. Newton's ideal, resistance-free world is not easy to visualize. If you analyze a situation and find that the result is different from a similar experience that you have had, ask yourself if this is because of the presence of resistance. In addition, many terms used in physics have everyday meanings that are different from those understood in physics. When talking or writing about physics issues, be careful to use these terms in their precise, scientific way.

APPLYING PHYSICS

Shuttle Engine Thrust The Space Shuttle Main Engines (SSMEs) each are rated to provide 1.6 million N of thrust. Powered by the combustion of hydrogen and oxygen, the SSMEs are throttled anywhere from 65 percent to 109 percent of their rated thrust.

4.1 Section Review

9. Force Identify each of the following as either **a, b,** or **c:** weight, mass, inertia, the push of a hand, thrust, resistance, air resistance, spring force, and acceleration.

a. a contact force

b. a field force

c. not a force

10. Inertia Can you feel the inertia of a pencil? Of a book? If you can, describe how.

11. Free-Body Diagram Draw a free-body diagram of a bag of sugar being lifted by your hand at a constant speed. Specifically identify the system. Label all forces with their agents and make the arrows the correct lengths.

12. Direction of Velocity If you push a book in the forward direction, does this mean its velocity has to be forward?

13. 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.

14. Critical Thinking A force of 1 N is the only force exerted on a block, and the acceleration of the block is measured. When the same force is the only force exerted on a second block, the acceleration is three times as large. What can you conclude about the masses of the two blocks?

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CONTENTS

4.2 Using Newton's Laws

▶ **Objectives**

- **Describe** how the weight and the mass of an object are related.
- **Differentiate** between actual weight and apparent weight.

▶ **Vocabulary**

apparent weight
weightlessness
drag force
terminal velocity

Newton's second law describes the connection between the cause of a change in an object's velocity and the resulting displacement. This law identifies the relationship between the net force exerted on an object and the object's acceleration.

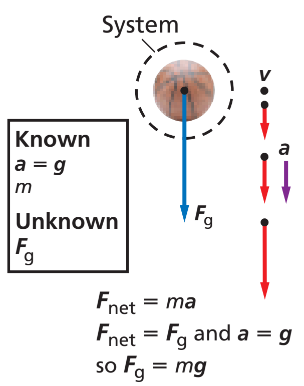
Using Newton's Second Law

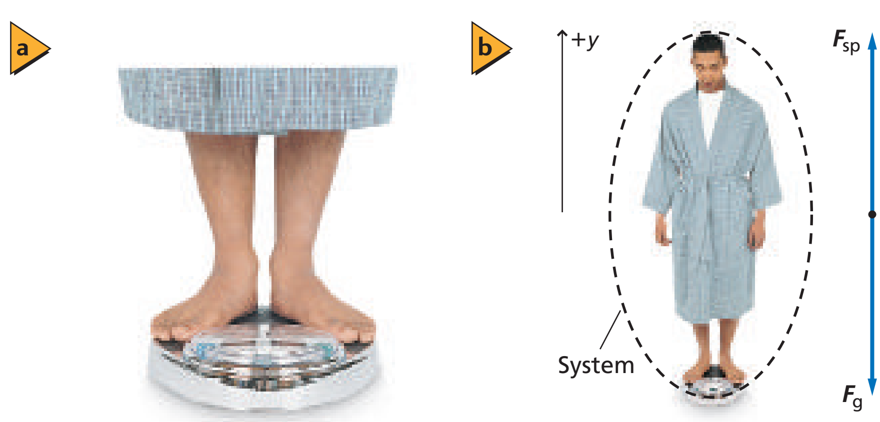
What is the weight force, $\mathbf{F}_g$, exerted on an object of mass m? Newton's second law can help answer this question. Consider the pictorial and physical models in **Figure 4-6,** which show a free-falling ball in midair. With what objects is it interacting? Because it is touching nothing and air resistance can be neglected, the only force acting on it is $\mathbf{F}_g$. You know from Chapter 3 that the ball's acceleration is $\mathbf{g}$. Newton's second law then becomes $\mathbf{F}_g = m\mathbf{g}$. Both the force and the acceleration are downward. The magnitude of an object's weight is equal to its mass times the acceleration it would have if it were falling freely. It is important to keep in mind that even when an object is not experiencing free-fall, the gravitational force of Earth is still acting on the object.

This result is true on Earth, as well as on any other planet, although the magnitude of g will be different on other planets. Because the value of g is much less on the Moon than on Earth, astronauts who landed on the Moon weighed much less while on the Moon, even though their mass had not changed.

Scales A bathroom scale contains springs. When you stand on the scale, the scale exerts an upward force on you because you are in contact with it. Because you are not accelerating, the net force acting on you must be zero. Therefore, the spring force, F_{sp}, pushing up on you must be the same magnitude as your weight, F_g, pulling down on you, as shown in the pictorial and physical models in **Figure 4-7.** The reading on the scale is determined by the amount of force the springs inside it exert on you. A spring scale, therefore, measures weight, not mass. If you were on a different planet, the compression of the spring would be different, and consequently, the scale's reading would be different. Remember that the proper unit for expressing mass is kilograms and because weight is a force, the proper unit used to express weight is the newton.

■ **Figure 4-6** The net force on the ball is the weight force, $\mathbf{F}_g$.





■ **Figure 4-7** The upward force of the spring in the scale is equal to your weight when you step on the bathroom scale **(a).** The free-body diagram in **(b)** shows that the system is in equilibrium because the force of the spring is equal to your weight.

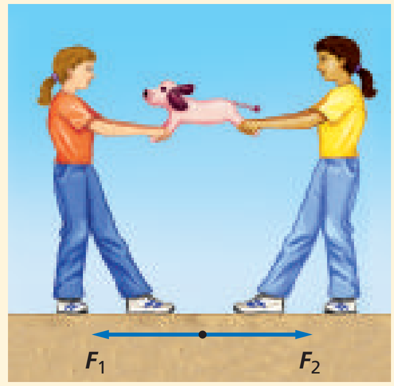
Aaron Haupt

EXAMPLE Problem 1

Fighting Over a Toy Anudja is holding a stuffed dog, 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 dog 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 dog?

1 Analyze and Sketch the Problem

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



Known:

$m = 0.30$ kg

$F_{\text{Anudja on dog}} = 11.0$ N

$F_{\text{Sarah on dog}} = 10.0$ N

Unknown:

$a = ?$

2 Solve for the Unknown

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

Use Newton's second law.

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

$$= \frac{F_{\text{Anudja on dog}} + (-F_{\text{Sarah on dog}})}{m}$$ **Substitute $F_{\text{net}} = F_{\text{Anudja on dog}} + (-F_{\text{Sarah on dog}})$**

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

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

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

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3 Evaluate the Answer

- **Are the units correct?** m/s^2 is the correct unit for acceleration.
- **Does the sign make sense?** The acceleration is in the positive direction, which is expected, because Anudja is pulling in the positive direction with a greater force than Sarah is pulling in the negative direction.
- **Is the magnitude realistic?** It is a reasonable acceleration for a light, stuffed toy.

PRACTICE Problems

Additional Problems, Appendix B

15. You place a watermelon on a spring scale at the supermarket. If the mass of the watermelon is 4.0 kg, what is the reading on the scale?

16. 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/s^2. 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.)

17. Taru and Reiko simultaneously grab a 0.75-kg piece of rope and begin tugging on it in opposite directions. If Taru pulls with a force of 16.0 N and the rope accelerates away from her at 1.25 m/s^2, with what force is Reiko pulling?

18. In **Figure 4-8,** the block has a mass of 1.2 kg and the sphere has a mass of 3.0 kg. What are the readings on the two scales? (Neglect the masses of the scales.)

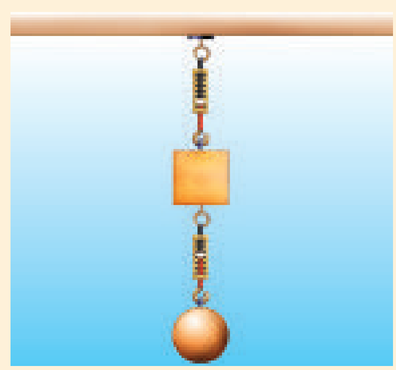


Figure 4-8

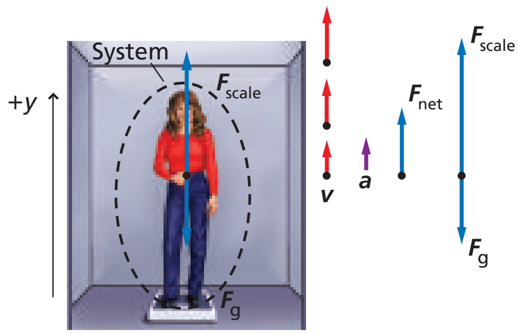


Figure 4-9 If you stand on a scale in an elevator accelerating upward, the scale must exert an upward force greater than the downward force of your weight.

Apparent weight What is weight? Because the weight force is defined as $\mathbf{F}_g = m\mathbf{g}$, $\mathbf{F}_g$ changes when $\mathbf{g}$ varies. On or near the surface of Earth, $\mathbf{g}$ 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 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 the elevator is in equilibrium, the scale will read your weight. What would the scale read if the elevator accelerates upward? **Figure 4-9** shows the pictorial and physical models for this situation. You are the system, and upward is the positive direction. Because the acceleration of the system is 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. If you ride in an elevator like this, you would feel heavier because the floor would press harder on your feet. On the other hand, if the acceleration is downward, then you would feel lighter, and the scale would have a lower reading. The force exerted by the scale is called the apparent weight. An object's **apparent weight** is the force an object experiences as a result of all the forces acting on it, giving the object an acceleration.

Imagine that the cable holding the elevator breaks. What would the scale read then? The scale and you would both accelerate with $\mathbf{a} = -\mathbf{g}$. 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 pushing up on the object, and the object's apparent weight is zero.

PROBLEM-SOLVING Strategies

Force and Motion

When solving force and motion problems, use the following strategies.

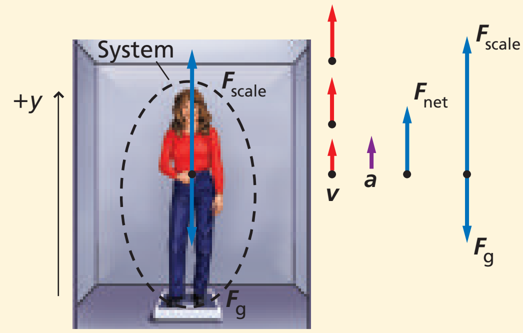
1. Read the problem carefully, and sketch a pictorial model.
2. Circle the system and choose a coordinate system.
3. Determine which quantities are known and which are unknown.
4. Create a physical model by drawing a motion diagram showing the direction of the acceleration, and create a free-body diagram showing the net force.
5. Use Newton's laws to link acceleration and net force.
6. Rearrange the equation to solve for the unknown quantity.
7. Substitute known quantities with their units into the equation and solve.
8. Check your results to see if they are reasonable.

▶ EXAMPLE Problem 2

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/s^2 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 $\boldsymbol{v}$ and $\boldsymbol{a}$.
- 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/s^2	
$t = 2.00$ s	
$g = 9.80$ N	

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:

$$\begin{aligned} F_{scale} &= F_{net} + F_g \\ &= F_g \\ &= mg \\ &= (75.0\text{ kg})(9.80\text{ m/s}^2) \\ &= 735\text{ N} \end{aligned}$$

The elevator is not accelerating. Thus, $F_{net} = 0.00$ N.
Substitute $F_{net} = 0.00$ N
Substitute $F_g = mg$
Substitute $m = 75.0$ kg, $g = 9.80$ m/s^2

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Acceleration of the elevator:

$$\begin{aligned} F_{scale} &= F_{net} + F_g \\ &= ma + mg \\ &= m(a + g) \\ &= (75.0\text{ kg})(2.00\text{ m/s}^2 + 9.80\text{ m/s}^2) \\ &= 885\text{ N} \end{aligned}$$

Substitute $F_{net} = ma$, $F_g = mg$
Substitute $m = 75.0$ kg, $a = 2.00$ m/s^2, $g = 9.80$ m/s^2

The scale reading when the elevator is accelerating (885 N) is larger than the scale reading at rest (735 N).

3 Evaluate the Answer

- **Are the units correct?** kg·m/s^2 is the force unit, N.
- **Does the sign make sense?** The positive sign agrees with the coordinate system.
- **Is the magnitude realistic?** F_{scale} is larger than it would be at rest when F_{scale} would be 735 N, so the magnitude is reasonable.

PRACTICE Problems **Additional Problems, Appendix B**

19. On Earth, a scale shows that you weigh 585 N.

a. What is your mass?

b. What would the scale read on the Moon ($g = 1.60\ m/s^2$)?

20. Use the results from Example Problem 2 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 at constant speed.

b. It slows at $2.00\ m/s^2$ while moving upward.

c. It speeds up at $2.00\ m/s^2$ while moving downward.

d. It moves downward at constant speed.

e. It slows to a stop at a constant magnitude of acceleration.

Drag Force and Terminal Velocity

It is true that the particles in the air around an object exert forces on it. Air actually exerts a huge force, but in most cases, it exerts a balanced force on all sides, and therefore it has no net effect. Can you think of any experiences that help to prove that air exerts a force? When you stick a suction cup on a smooth wall or table, you remove air from the "inside" of it. The suction cup is difficult to remove because of the net force of the air on the "outside."

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 drag force on the moving object in the direction opposite to its motion. A **drag force** is the force exerted by a fluid on the object moving 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 affects the drag force. The drag force is also affected by the properties of the fluid, such as its viscosity and temperature.

CHALLENGE PROBLEM

An air-track glider passes through a photoelectric gate at an initial speed of 0.25 m/s. As it passes through the gate, a constant force of 0.40 N is applied to the glider in the same direction as its motion. The glider has a mass of 0.50 kg.

1. What is the acceleration of the glider?

2. It takes the glider 1.3 s to pass through a second gate. What is the distance between the two gates?

3. The 0.40-N force is applied by means of a string attached to the glider. The other end of the string passes over a resistance-free pulley and is attached to a hanging mass, *m*. How big is *m*?

4. Derive an expression for the tension, *T*, in the string as a function of the mass, *M*, of the glider, the mass, *m*, of the hanging mass, and *g*.

If you drop a table-tennis ball, as in **Figure 4-10,** 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 are falling, 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, that of a basketball is 20 m/s, and that of a baseball is 42 m/s. Competitive skiers increase their terminal velocities by decreasing the drag force on them. They hold their bodies in an egg shape and wear smooth clothing and streamlined helmets. Sky divers can increase or decrease their terminal velocity by changing their body orientation and shape. A horizontal, spread-eagle shape produces the slowest terminal velocity, about 60 m/s. Because a parachute changes the shape of the sky diver when it opens, a sky diver becomes part of a very large object with a correspondingly large drag force and a terminal velocity of about 5 m/s.

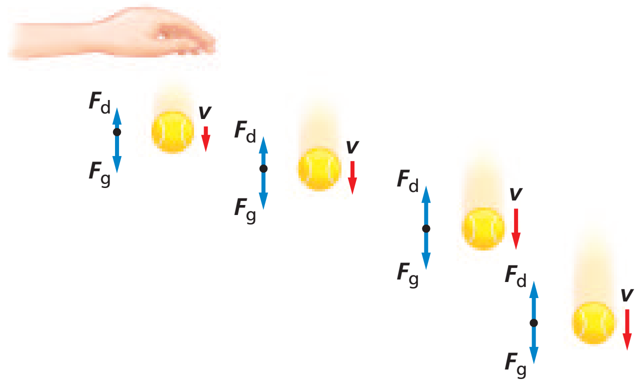


Figure 4-10 The drag force on an object increases as its velocity increases. When the drag force increases to the point that it equals the force of gravity, the object will no longer be accelerated.

4.2 Section Review

21. Lunar Gravity Compare the force holding a 10.0-kg rock on Earth and on the Moon. The acceleration due to gravity on the Moon is 1.62 m/s^2.

22. Real and Apparent Weight You take a ride in a fast elevator to the top of a tall building and ride back down while standing on a bathroom scale. During which parts of the ride will your apparent and real weights be the same? During which parts will your apparent weight be less than your real weight? More than your real weight? Sketch free-body diagrams to support your answers.

23. Acceleration Tecle, with a mass of 65.0 kg, is standing by the boards at the side of an ice-skating rink. He pushes off the boards with a force of 9.0 N. What is his resulting acceleration?

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, if anything, can you conclude about the elevator's motion at that time?

25. Mass Marcos is playing tug-of-war with his cat using a stuffed toy. At one instant during the game, Marcos pulls on the toy with a force of 22 N, the cat pulls in the opposite direction with a force of 19.5 N, and the toy experiences an acceleration of 6.25 m/s^2. What is the mass of the toy?

26. Acceleration A sky diver falls at a constant speed in the spread-eagle position. After he opens his parachute, is the sky diver accelerating? If so, in which direction? Explain your answer using Newton's laws.

27. Critical Thinking You have a job at a meat warehouse loading inventory onto trucks for shipment to grocery stores. 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. However, right after you weigh a 1000-N crate, the scale breaks. Describe a way in which you could apply Newton's laws to figure out the approximate masses of the remaining crates.

4.3 Interaction Forces

▶ **Objectives**

- **Define** Newton's third law.
- **Explain** the tension in ropes and strings in terms of Newton's third law.
- **Define** the normal force.
- **Determine** the value of the normal force by applying Newton's second law.

▶ **Vocabulary**

interaction pair
Newton's third law
tension
normal force

You have learned that when an agent exerts a net force upon an object, the object undergoes acceleration. You know that this force can be either a field force or a contact force. But what causes the force? If you experiment with two magnets, you can feel each magnet pushing or pulling the other. Similarly, if you pull on a lever, you can feel the lever pulling back against you. Which is the agent and which is the object?

Identifying Interaction Forces

Imagine that you and a friend are each wearing in-line skates (with all the proper safety gear), and your friend is standing right in front of you, with his back to you. You push your friend so that he starts rolling forward. What happens to you? You move backwards. Why? Recall that a force is the result of an interaction between two objects. When you push your friend forward, you come into contact with him and exert a force that moves him forward. However, because he is also in contact with you, he also exerts a force on you, and this results in a change in your motion.

Forces always come in pairs. Consider you (Student A) as one system and your friend (Student B) as another. What horizontal forces act on each of the two systems? **Figure 4-11** shows the free-body diagram for the systems. Looking at this diagram, you can see that each system experiences a force exerted by the other. The two forces, $\boldsymbol{F}_{\text{A on B}}$ and $\boldsymbol{F}_{\text{B on A}}$, are the forces of interaction between the two of you. Notice the symmetry in the subscripts: A on B and B on A. What do you notice about the directions of these forces? What do you expect to be true about their relative magnitudes?

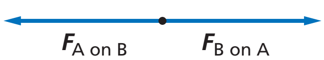


Figure 4-11 When you exert a force on your friend to push him forward, he exerts an equal and opposite force on you, which causes you to move backwards.

The forces $\boldsymbol{F}_{\text{A on B}}$ and $\boldsymbol{F}_{\text{B on A}}$ are an interaction pair. An **interaction pair** is two forces that are in opposite directions and have equal magnitude. Sometimes, this also is called an action-reaction pair of forces. This might suggest that one causes the other; however, this is not true. For example, the force of you pushing your friend doesn't cause your friend to exert a force on you. The two forces either exist together or not at all. They both result from the contact between the two of you.

Newton's Third Law

The force of you on your friend is equal in magnitude and opposite in direction to the force of your friend on you. This is summarized in **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.

Newton's Third Law $\boldsymbol{F}_{\text{A on B}} = -\boldsymbol{F}_{\text{B on A}}$

The force of A on B is equal in magnitude and opposite in direction of the force of B on A.

Consider the situation of you holding a book in your hand. Draw one free-body diagram each for you and for the book. Are there any interaction pairs? When identifying interaction pairs, keep in mind that they always will occur in two different free-body diagrams, and they always will have the symmetry of subscripts noted on the previous page. In this case, there is one interaction pair, $\boldsymbol{F}_{\text{book on hand}}$ and $\boldsymbol{F}_{\text{hand on book}}$. Notice also that each object has a weight. If the weight force is due to an interaction between the object and Earth's mass, then shouldn't each of these objects also exert a force on Earth? If this is the case, shouldn't Earth be accelerating?

Consider a soccer ball sitting on a table. The table, in turn, is sitting on Earth, as shown in **Figure 4-12.** First, analyze the forces acting on 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 the opposite direction on the same object, they are not an interaction pair. They are simply two forces acting on the same object, not the interaction between two objects. 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 one pair of forces. The ball and Earth also have an interaction pair. Thus, the interaction pairs related to the soccer ball are $\boldsymbol{F}_{\text{ball on table}} = -\boldsymbol{F}_{\text{table on ball}}$ and $\boldsymbol{F}_{\text{ball on Earth}} = -\boldsymbol{F}_{\text{Earth on ball}}$. It is important to keep in mind that an interaction pair must consist of two forces of equal magnitude pointing in opposite directions. These opposing forces must act on two different objects that can exert a force against each other.

The acceleration caused by the force of an object interacting with Earth is usually a very small number. Under most circumstances, the number is so small that for problems involving falling or stationary objects, Earth can be treated as part of the external world rather than as a second system. Consider Example Problem 3 using the following problem-solving strategies.

Figure 4-12 A soccer ball on a table on Earth is part of two interaction pairs—the interaction between the ball and table and the interaction between the ball and Earth. (Not to scale)

PROBLEM-SOLVING Strategies

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 and a physical model that includes free-body diagrams for each system.
3. Connect interaction pairs by dashed lines.
4. To calculate your answer, use Newton's second law to relate the net force and acceleration for each system.
5. Use Newton's third law to equate the magnitudes of the interaction pairs and give the relative direction of each force.
6. Solve the problem and check the units, signs, and magnitudes for reasonableness.

MINI LAB

Tug-of-War Challenge

In a tug-of-war, predict how the force you exert on your end of the rope compares to the force your opponent exerts if you pull and your opponent just holds the rope.

1. **Predict** how the forces compare if the rope moves in your direction.
2. **Test** your prediction. ***CAUTION: Do not suddenly let go of the rope.***

Analyze and Conclude

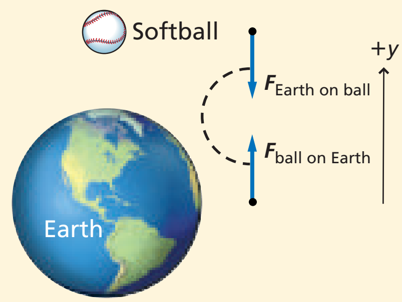
3. **Compare** the force on your end of the rope to the force on your opponent's end of the rope. What happened when you started to move your opponent's direction?

▶ EXAMPLE Problem 3

Earth's Acceleration When a softball with a mass of 0.18 kg is dropped, its acceleration toward Earth is equal to g, the acceleration due to gravity. What is the 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:

$m_{\text{ball}} = 0.18$ kg

$m_{\text{Earth}} = 6.0\times10^{24}$ kg

$g = 9.80$ m/s^2

Unknown:

$F_{\text{Earth on ball}} = ?$

$a_{\text{Earth}} = ?$

2 Solve for the Unknown

Use Newton's second law to find the weight of the ball.

$$\begin{aligned} F_{\text{Earth on ball}} &= m_{\text{ball}}a \\ &= m_{\text{ball}}(-g) && \textbf{Substitute } a = -g \\ &= (0.18\text{ kg})(9.80\text{ m/s}^2) && \textbf{Substitute } m_{\text{ball}} = \textbf{0.18 kg, } g = \textbf{9.80 m/s}^2 \\ &= -1.8\text{ N} \end{aligned}$$

Use Newton's third law to find $F_{\text{ball on Earth}}$.

$$\begin{aligned} F_{\text{ball on Earth}} &= -F_{\text{Earth on ball}} \\ &= -(-1.8\text{ N}) && \textbf{Substitute } F_{\text{Earth on ball}} = \textbf{−1.8 N} \\ &= +1.8\text{ N} \end{aligned}$$

Use Newton's second law to find a_{Earth}.

$$\begin{aligned} a_{\text{Earth}} &= \frac{F_{\text{net}}}{m_{\text{Earth}}} \\ &= \frac{1.8\text{ N}}{6.0\times10^{24}\text{ kg}} && \textbf{Substitute } F_{\text{net}} = \textbf{1.8 N, } m_{\text{Earth}} = \mathbf{6.0\times10^{24}}\textbf{ kg} \\ &= 2.9\times10^{-25}\text{ m/s}^2 \text{ toward the softball} \end{aligned}$$

Math Handbook
Operations with Scientific Notation
pages 842–843

3 Evaluate the Answer

- **Are the units correct?** Dimensional analysis verifies force in N and acceleration in m/s^2.
- **Do the signs make sense?** Force and acceleration should be positive.
- **Is the magnitude realistic?** Because of Earth's large mass, the acceleration should be small.

▶ PRACTICE Problems

Additional Problems, Appendix B

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 that the brick exerts and the objects on which these forces are exerted. (Air resistance may be ignored.)

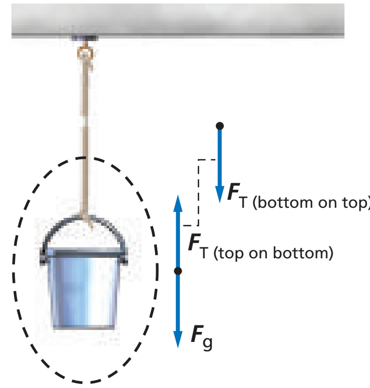
30. You toss a ball up in the air. Draw a free-body diagram for the ball while it is still moving upward. Identify any forces acting on the ball. Also identify any forces that the ball exerts and the objects on which these forces are exerted.

Figure 4-13

31. A suitcase sits on a stationary airport luggage cart, as in **Figure 4-13.** Draw a free-body diagram for each object and specifically indicate any interaction pairs between the two.

Forces of Ropes and Strings

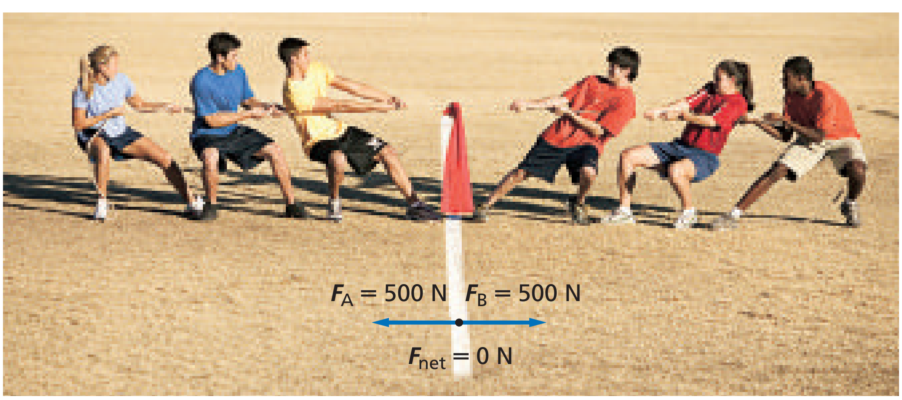
Tension is simply a specific name for the force exerted by a string or rope. A simplification within this textbook is the assumption that all strings and ropes are massless. To understand tension in more detail, consider the situation in **Figure 4-14,** where a bucket hangs from a rope attached to the ceiling. The rope is about to break in the middle. If the rope breaks, the bucket will fall; thus, 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 exerts on the top, $\boldsymbol{F}_{\text{bottom on top}}$. These forces, equal in magnitude but opposite in direction, also are shown in Figure 4-14.



■ **Figure 4-14** 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 are pulling equally in both directions. Because the very bottom of the rope has a tension equal to the weight of the bucket, the tension everywhere in the rope is equal to the weight of the bucket. Thus, the tension in the rope is the weight of all objects below it. Because the rope is assumed to be massless, the tension everywhere in the rope is equal to the bucket's weight.

Tension forces also are at work in a tug-of-war, like the one shown in **Figure 4-15.** If team A, on the left, is exerting a force of 500 N and the rope does not move, then team B, on the right, also must be pulling with a force of 500 N. What is the tension in the rope in this case? 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-hand end is not moving, so the net force on it is zero. Thus, $F_{\text{A on rope}} = F_{\text{right on left}} = 500$ N. Similarly, $F_{\text{B on rope}} = F_{\text{left on right}} = 500$ N. But the two tensions, $F_{\text{right on left}}$ and $F_{\text{left on right}}$, 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, tie the ends to a spring scale, and ask the two teams each to pull with 500 N of force. You would see that the scale reads 500 N.



■ **Figure 4-15** In a tug-of-war, the teams exert equal and opposite forces on each other via the tension in the rope, as long as neither side moves.

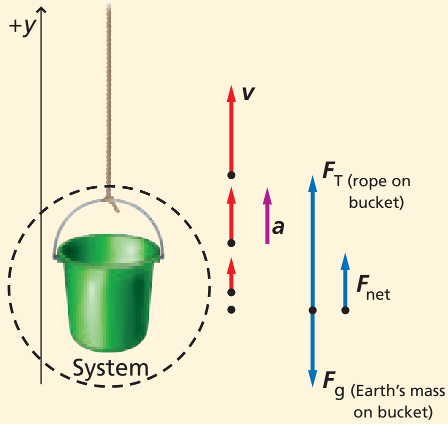
Tim Fuller

▶ EXAMPLE Problem 4

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 is moving 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 including v and a.
- Draw the free-body diagram, labeling the forces.



Known:		Unknown:
$m = 50.0$ kg	$v_f = 3.0$ m/s	$F_T = ?$
$v_i = 0.0$ m/s	$d = 3.0$ m	

2 Solve for the Unknown

F_{net} is the sum of the positive force of the rope pulling up, F_T, and the negative weight force, $-F_g$, pulling down as defined by the coordinate system.

$$F_{net} = F_T + (-F_g)$$
$$F_T = F_{net} + F_g$$
$$= ma + mg \qquad \text{Substitute } F_{net} = ma,\ F_g = mg$$
$$= m(a + g)$$

v_i, v_f, and d are known. Use this motion equation to solve for a.

$$v_f^2 = v_i^2 + 2ad$$
$$a = \frac{v_f^2 - v_i^2}{2d}$$
$$= \frac{v_f^2}{2d} \qquad \text{Substitute } v_i = 0.0 \text{ m/s}^2$$
$$F_T = m(a + g)$$
$$= m\left(\frac{v_f^2}{2d} + g\right) \qquad \text{Substitute } a = \frac{v_f^2}{2d}$$
$$= (50.0 \text{ kg})\left(\frac{(3.0 \text{ m/s})^2}{2(3.0 \text{ m})} + 9.80 \text{ m/s}^2\right) \qquad \text{Substitute } m = 50.0 \text{ kg},\ v_f = 3.0 \text{ m/s},\ d = 3.0 \text{ m},\ g = 9.80 \text{ m/s}^2$$
$$= 570 \text{ N}$$

The rope is in danger of breaking because the tension exceeds 525 N.

Math Handbook
Isolating a Variable
page 845

3 Evaluate the Answer

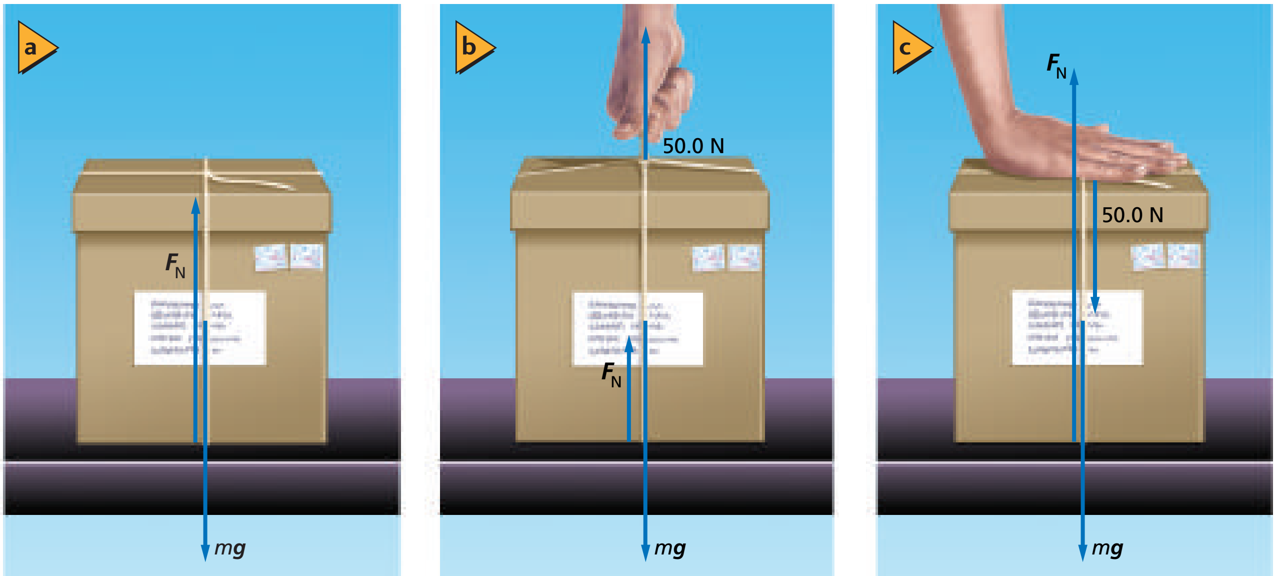
- **Are the units correct?** Dimensional analysis verifies kg·m/s^2, which is N.
- **Does the sign make sense?** The upward force should be positive.
- **Is the magnitude realistic?** The magnitude is a little larger than 490 N, which is the weight of the bucket. $F_g = mg = (50.0 \text{ kg})(9.80 \text{ m/s}^2) = 490$ N

▶ PRACTICE Problems

Additional Problems, Appendix B

32. You are helping to repair a roof by loading equipment into a bucket that workers hoist to the rooftop. If the rope is guaranteed not to 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 that the workers can give the bucket as they pull it to the roof?

33. Diego and Mika are trying to fix a tire on Diego's car, but they are having trouble getting the tire loose. When they pull together, Mika with a force of 23 N and Diego with a force of 31 N, they just barely get the tire to budge. What is the magnitude of the strength of the force between the tire and the wheel?



■ **Figure 4-16** The normal force on an object is not always equal to its weight. In **(a)** the normal force is equal to the object's weight. In **(b)** the normal force is less than the object's weight. In **(c)** the normal force is greater than the object's weight.

The Normal Force

Any time two objects are in contact, they each exert a force on each other. Think about a box sitting on a table. There is a downward force due to the gravitational attraction of Earth. 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 exerted by a surface on another object.

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 as in **Figure 4-16a?** What if you tied a string to the box and pulled up on it a little bit, but not enough to move the box, as shown in **Figure 4-16b?** When you apply Newton's second law to the box, you see that $F_N + F_{\text{string on box}} - F_g = ma = 0$, which rearranges to $F_N = F_g - F_{\text{string on box}}$.

You can see that in this case, the normal force exerted by the table 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 **Figure 4-16c,** the normal force would be more than the box's weight. Finding the normal force will be important in the next chapter, when you begin dealing with resistance.

4.3 Section Review

34. Force Hold a book motionless in your hand in the air. Identify each force and its interaction pair on the book.

35. Force Lower the book from problem 34 at increasing speed. Do any of the forces or their interaction-pair partners change? Explain.

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 each rope?

37. Tension If the bottom block in problem 36 has a mass of 3.0 kg and the tension in the top rope is 63.0 N, calculate the tension in the bottom rope and the mass of the top block.

38. Normal Force Poloma hands a 13-kg box to 61-kg Stephanie, who stands on a platform. What is the normal force exerted by the platform on Stephanie?

39. 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? Explain.

PHYSICS LAB • Internet

Alternate CBL instructions can be found on the Web site.
physicspp.com

Forces in an Elevator

Have you ever been in a fast-moving elevator? Was the ride comfortable? How about an amusement ride that quickly moves upward or one that free-falls? What forces are acting on you during your ride? In this experiment, you will investigate the forces that affect you during vertical motion when gravity is involved with a bathroom scale. Many bathroom scales measure weight in pounds mass (lbm) or pounds force (lbf) rather than newtons. In the experiment, you will need to convert weights measured on common household bathroom scales to SI units.

QUESTION

What one-dimensional forces act on an object that is moving in a vertical direction in relation to the ground?

Objectives

- **Measure** Examine forces that act on objects that move vertically.
- **Compare and Contrast** Differentiate between actual weight and apparent weight.
- **Analyze and Conclude** Share and compare data of the acceleration of elevators.

Laura Sifferlin

Safety Precautions

- **Use caution when working around elevator doors.**
- **Do not interfere with normal elevator traffic.**
- **Watch that the mass on the spring scale does not fall and hit someone's feet or toes.**

Materials

elevator
bathroom scale
spring scale
mass

Procedure

1. Securely attach a mass to the hook on a spring scale. Record the force of the mass in the data table.
2. Accelerate the mass upward, then move it upward at a constant velocity, and then slow the mass down. Record the greatest amount of force on the scale, the amount of force at constant velocity, and the lowest scale reading.
3. Get your teacher's permission and proceed to an elevator on the ground floor. Before entering the elevator, measure your weight on a bathroom scale. Record this weight in the data table.

Data Table	
Force (step 1)	
Highest Reading (step 2)	
Reading at Constant Velocity (step 2)	
Lowest Reading (step 2)	
Your Weight (step 3)	
Highest Reading (step 4)	
Reading at Constant Velocity (step 5)	
Lowest Reading (step 6)	

4. Place the scale in the elevator. Step on the scale and record the mass at rest. Select the highest floor that the elevator goes up to. Once the elevator starts, during its upward acceleration, record the highest reading on the scale in the data table.
5. When the velocity of the elevator becomes constant, record the reading on the scale in the data table.
6. As the elevator starts to decelerate, watch for the lowest reading on the scale and record it in the data table.

Analyze

1. **Explain** In step 2, why did the mass appear to gain weight when being accelerated upward? Provide a mathematical equation to summarize this concept.
2. **Explain** Why did the mass appear to lose weight when being decelerated at the end of its movement during step 3? Provide a mathematical equation to summarize this concept.
3. **Measure in SI** Most bathroom scales read in pounds mass (lbm). Convert your reading in step 4 in pounds mass to kilograms. (1 kg = 2.21 lbm) (Note: skip this step if your scale measures in kilograms.)
4. **Measure in SI** Some bathroom scales read in pounds force (lbf). Convert all of the readings you made in steps 4–6 to newtons. (1 N = 0.225 lbf)
5. **Analyze** Calculate the acceleration of the elevator at the beginning of your elevator trip using the equation $F_{scale} = ma + mg$.
6. **Use Numbers** What is the acceleration of the elevator at the end of your trip?

Conclude and Apply

How can you develop an experiment to find the acceleration of an amusement park ride that either drops rapidly or climbs rapidly?

Going Further

How can a bathroom scale measure both pounds mass (lbm) and pounds force (lbf) at the same time?

Real-World Physics

Forces on pilots in high-performance jet airplanes are measured in g's or g-force. What does it mean if a pilot is pulling 6 g's in a power climb?

Share Your Data

Communicate You can visit **physicspp.com/internet_lab** to post the acceleration of your elevator and compare it to other elevators around the country, maybe even the world. Post a description of your elevator's ride so that a comparison of acceleration versus ride comfort can be evaluated.

Physics Online

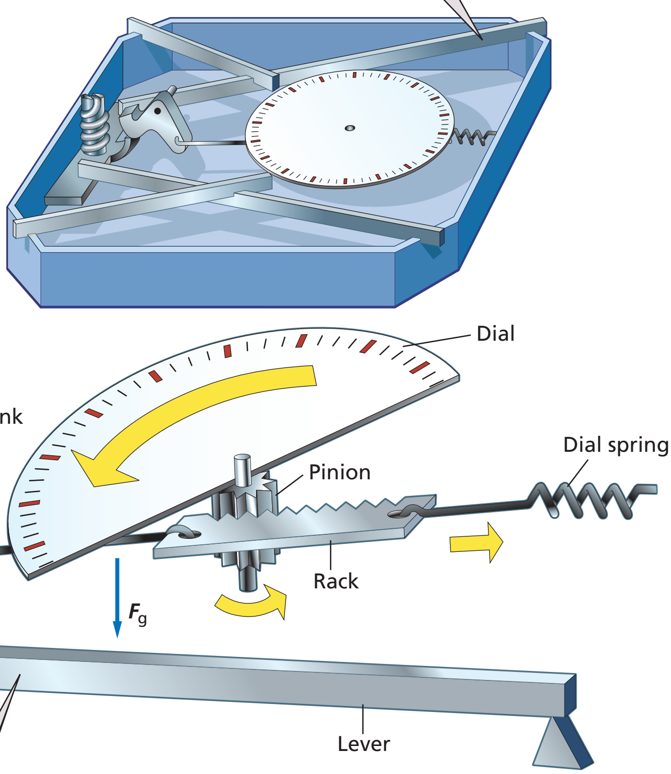
To find out more about forces and acceleration, visit the Web site: **physicspp.com**

How it Works Bathroom Scale

The portable weighing scale was patented in 1896 by John H. Hunter. People used coin-operated scales, usually located in stores, to weigh themselves until the advent of the home bathroom scale in 1946. How does a bathroom scale work?

1 There are two long and two short levers that are attached to each other. Brackets in the lid of the scale sit on top of the levers to help evenly distribute your weight on the levers.

3 As the calibrating plate is pushed down by weight on the scale, the crank pivots. This, in turn, moves the rack and rotates the pinion. As a result, the dial on the scale rotates.



4 When the spring force, F_{sp}, from the main spring being stretched is equal to F_g, the crank, rack, and pinion no longer move, and your weight is shown on the dial.

2 The long levers rest on top of a calibrating plate that has the main spring attached to it. When you step on the scale, your weight, F_g, is exerted on the levers, which, in turn, exert a force on the calibrating plate and cause the main spring to stretch.

Thinking Critically

1. **Hypothesize** Most springs in bathroom scales cannot exert a force larger than 20 lbs (89 N). How is it possible that you don't break the scale every time you step on it? *(Hint: Think about exerting a large force near the pivot of a see-saw.)*
2. **Solve** If the largest reading on most scales is 240 lbs (1068 N) and the spring can exert a maximum of 20 lbs (89 N), what ratio does the lever use?

Chapter 4

Study Guide

4.1 Force and Motion

Vocabulary

- force (p. 88)
- free-body diagram (p. 89)
- net force (p. 92)
- Newton's second law (p. 93)
- Newton's first law (p. 94)
- inertia (p. 95)
- equilibrium (p. 95)

Key Concepts

- An object that experiences a push or a pull has a force exerted on it.
- Forces have both direction and magnitude.
- Forces may be divided into contact and field forces.
- In a free-body diagram, always draw the force vectors leading away from the object, even if the force is a push.
- The forces acting upon an object can be added using vector addition to find the net force.
- Newton's second law states that the acceleration of a system equals the net force acting on it, divided by its mass.

$$\boldsymbol{a} = \frac{\boldsymbol{F}_{\text{net}}}{m}$$

- 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 no net force acting on it is in equilibrium.

4.2 Using Newton's Laws

Vocabulary

- apparent weight (p. 98)
- weightlessness (p. 98)
- drag force (p. 100)
- terminal velocity (p. 101)

Key Concepts

- The weight of an object depends upon the acceleration due to gravity and the mass of the object.
- An object's apparent weight is the force an object experiences as a result of the contact forces acting on it, giving the object an acceleration.
- An object with no apparent weight experiences weightlessness.
- The effect of drag on an object's motion is determined by the object's weight, size, and shape.
- If a falling object reaches a velocity such that the drag force is equal to the object's weight, it maintains that velocity, called the terminal velocity.

4.3 Interaction Forces

Vocabulary

- interaction pair (p. 102)
- Newton's third law (p. 102)
- tension (p. 105)
- normal force (p. 107)

Key Concepts

- All forces result from interactions between objects.
- 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.

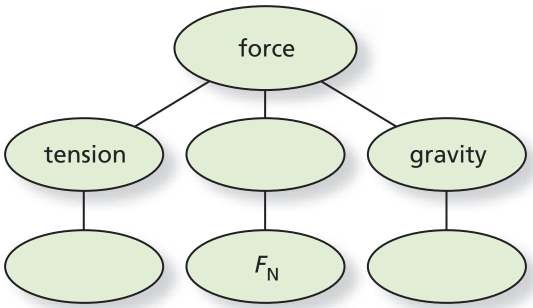
$$\boldsymbol{F}_{\text{A on B}} = -\boldsymbol{F}_{\text{B on A}}$$

- 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.
- Tension is the specific name for the force exerted by a rope or string.
- The normal force is a support force resulting from the contact of two objects. It is always perpendicular to the plane of contact between the two objects.

Chapter 4 Assessment

Concept Mapping

40. Complete the following concept map using the following term and symbols: *normal*, F_T, F_g.



Mastering Concepts

41. A physics book is motionless on the top of a table. If you give it a hard push with your hand, it slides across the table and slowly comes to a stop. Use Newton's laws to answer the following questions. (4.1)

a. Why does the book remain motionless before the force of your hand is applied?

b. Why does the book begin to move when your hand pushes hard enough on it?

c. Under what conditions would the book remain in motion at a constant speed?

42. **Cycling** Why do you have to push harder on the pedals of a single-speed bicycle to start it moving than to keep it moving at a constant velocity? (4.1)

43. Suppose that the acceleration of an object is zero. Does this mean that there are no forces acting on it? Give an example supporting your answer. (4.2)

44. **Basketball** When a basketball player dribbles a ball, it falls to the floor and bounces up. Is a force required to make it bounce? Why? If a force is needed, what is the agent involved? (4.2)

45. Before a sky diver opens her parachute, she may be falling at a velocity higher than the terminal velocity that she will have after the parachute opens. (4.2)

a. Describe what happens to her velocity as she opens the parachute.

b. Describe the sky diver's velocity from when her parachute has been open for a time until she is about to land.

46. If your textbook is in equilibrium, what can you say about the forces acting on it? (4.2)

47. A rock is dropped from a bridge into a valley. Earth pulls on the rock and accelerates it downward. According to Newton's third law, the rock must also be pulling on Earth, yet Earth does not seem to accelerate. Explain. (4.3)

48. Ramon pushes on a bed that has been pushed against a wall, as in **Figure 4-17.** Draw a free-body diagram for the bed and identify all the forces acting on it. Make a separate list of all the forces that the bed applies to other objects. (4.3)

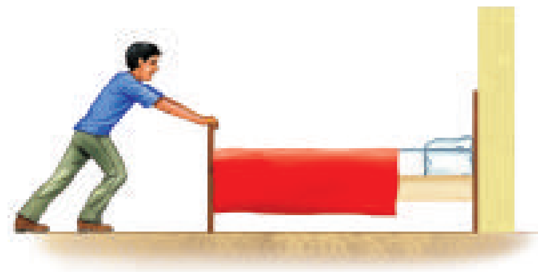


Figure 4-17

49. **Figure 4-18** shows a block in four different situations. Rank them according to the magnitude of the normal force between the block and the surface, greatest to least. Specifically indicate any ties. (4.3)

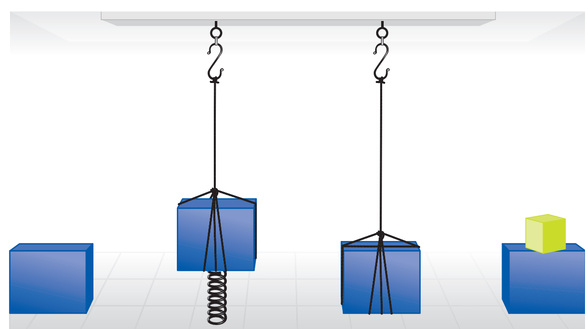


Figure 4-18

50. Explain why the tension in a massless rope is constant throughout it. (4.3)

51. A bird sits on top of a statue of Einstein. Draw free-body diagrams for the bird and the statue. Specifically indicate any interaction pairs between the two diagrams. (4.3)

52. **Baseball** A slugger swings his bat and hits a baseball pitched to him. Draw free-body diagrams for the baseball and the bat at the moment of contact. Specifically indicate any interaction pairs between the two diagrams. (4.3)

Applying Concepts

53. **Whiplash** If you are in a car that is struck from behind, you can receive a serious neck injury called whiplash.

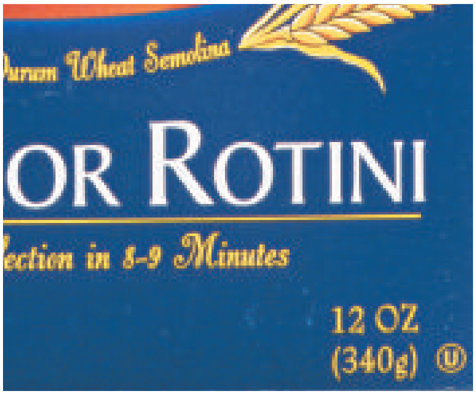
a. Using Newton's laws, explain what happens to cause such an injury.

b. How does a headrest reduce whiplash?

For more problems, go to Additional Problems, Appendix B.

54. Space Should astronauts choose pencils with hard or soft lead for making notes in space? Explain.

55. When you look at the label of the product in **Figure 4-19** to get an idea of how much the box contains, does it tell you its mass, weight, or both? Would you need to make any changes to this label to make it correct for consumption on the Moon?



■ **Figure 4-19**

56. From the top of a tall building, you drop two table-tennis balls, one filled with air and the other with water. Both experience air resistance as they fall. Which ball reaches terminal velocity first? Do both hit the ground at the same time?

57. It can be said that 1 kg equals 2.2 lb. What does this statement mean? What would be the proper way of making the comparison?

58. You toss a ball straight up into the air.
  a. Draw a free-body diagram for the ball at three points during its motion: on the way up, at the very top, and on the way down. Specifically identify the forces acting on the ball and their agents.
  b. What is the velocity of the ball at the very top of the motion?
  c. What is the acceleration of the ball at this same point?

Mastering Problems

4.1 Force and Motion

59. What is the net force acting on a 1.0-kg ball in free-fall?

60. Skating Joyce and Efua are skating. Joyce pushes Efua, whose mass is 40.0-kg, with a force of 5.0 N. What is Efua's resulting acceleration?

61. A car of mass 2300 kg slows down at a rate of 3.0 m/s^2 when approaching a stop sign. What is the magnitude of the net force causing it to slow down?

62. Breaking the Wishbone After Thanksgiving, Kevin and Gamal use the turkey's wishbone to make a wish. If Kevin pulls on it with a force 0.17 N larger than the force Gamal pulls with in the opposite direction, and the wishbone has a mass of 13 g, what is the wishbone's initial acceleration?

4.2 Using Newton's Laws

63. What is your weight in newtons?

64. Motorcycle Your new motorcycle weighs 2450 N. What is its mass in kilograms?

65. Three objects are dropped simultaneously from the top of a tall building: a shot put, an air-filled balloon, and a basketball.
  a. Rank the objects in the order in which they will reach terminal velocity, from first to last.
  b. Rank the objects according to the order in which they will reach the ground, from first to last.
  c. What is the relationship between your answers to parts a and b?

66. What is the weight in pounds of a 100.0-N wooden shipping case?

67. You place a 7.50-kg television on a spring scale. If the scale reads 78.4 N, what is the acceleration due to gravity at that location?

68. Drag Racing A 873-kg (1930-lb) dragster, starting from rest, attains a speed of 26.3 m/s (58.9 mph) in 0.59 s.
  a. Find the average acceleration of the dragster during this time interval.
  b. What is the magnitude of the average net force on the dragster during this time?
  c. Assume that the driver has a mass of 68 kg. What horizontal force does the seat exert on the driver?

69. Assume that a scale is in an elevator on Earth. What force would the scale exert on a 53-kg person standing on it during the following situations?
  a. The elevator moves up at a constant speed.
  b. It slows at 2.0 m/s^2 while moving upward.
  c. It speeds up at 2.0 m/s^2 while moving downward.
  d. It moves downward at a constant speed.
  e. It slows to a stop while moving downward with a constant acceleration.

70. 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?

71. A 0.50-kg guinea pig is lifted up from the ground. What is the smallest force needed to lift it? Describe its resulting motion.

Aaron Haupt

72. **Astronomy** On the surface of Mercury, the gravitational acceleration is 0.38 times its value on Earth.
- **a.** What would a 6.0-kg mass weigh on Mercury?
- **b.** If the gravitational acceleration on the surface of Pluto is 0.08 times that of Mercury, what would a 7.0-kg mass weigh on Pluto?

73. A 65-kg diver jumps off of a 10.0-m tower.
- **a.** Find the diver's velocity when he hits the water.
- **b.** The diver comes to a stop 2.0 m below the surface. Find the net force exerted by the water.

74. **Car Racing** A race car has a mass of 710 kg. It starts from rest and travels 40.0 m in 3.0 s. The car is uniformly accelerated during the entire time. What net force is exerted on it?

4.3 Interaction Forces

75. A 6.0-kg block rests on top of a 7.0-kg block, which rests on a horizontal table.
- **a.** What is the force (magnitude and direction) exerted by the 7.0-kg block on the 6.0-kg block?
- **b.** What is the force (magnitude and direction) exerted by the 6.0-kg block on the 7.0-kg block?

76. **Rain** A raindrop, with mass 2.45 mg, falls to the ground. As it is falling, what magnitude of force does it exert on Earth?

77. A 90.0-kg man and a 55-kg man have a tug-of-war. The 90.0-kg man pulls on the rope such that the 55-kg man accelerates at 0.025 m/s^2. What force does the rope exert on the 90.0-kg man?

78. Male lions and human sprinters can both accelerate at about 10.0 m/s^2. If a typical lion weighs 170 kg and a typical sprinter weighs 75 kg, what is the difference in the force exerted on the ground during a race between these two species?

79. A 4500-kg helicopter accelerates upward at 2.0 m/s^2. What lift force is exerted by the air on the propellers?

80. Three blocks are stacked on top of one another, as in **Figure 4-20.** The top block has a mass of 4.6 kg, the middle one has a mass of 1.2 kg, and the bottom one has a mass of 3.7 kg. Identify and calculate any normal forces between the objects.

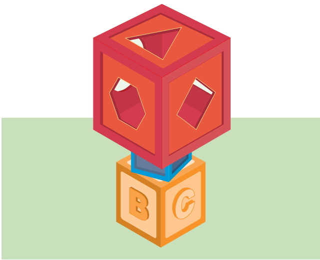


Figure 4-20

Mixed Review

81. The dragster in problem 68 completed a 402.3-m (0.2500-mi) run in 4.936 s. If the car had a constant acceleration, what was its acceleration and final velocity?

82. **Jet** A 2.75×10^6-N catapult jet plane is ready for takeoff. If the jet's engines supply a constant thrust of 6.35×10^6 N, how much runway will it need to reach its minimum takeoff speed of 285 km/h?

83. The dragster in problem 68 crossed the finish line going 126.6 m/s. Does the assumption of constant acceleration hold true? What other piece of evidence could you use to determine if the acceleration was constant?

84. Suppose a 65-kg boy and a 45-kg girl use a massless rope in a tug-of-war on an icy, resistance-free surface as in **Figure 4-21.** If the acceleration of the girl toward the boy is 3.0 m/s^2, find the magnitude of the acceleration of the boy toward the girl.

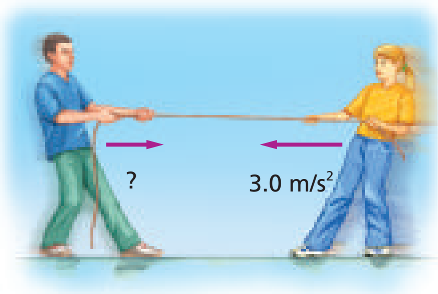


Figure 4-21

85. **Space Station** Pratish weighs 588 N and is weightless in a space station. If she pushes off the wall with a vertical acceleration of 3.00 m/s^2, determine the force exerted by the wall during her push off.

86. **Baseball** As a baseball is being caught, its speed goes from 30.0 m/s to 0.0 m/s in about 0.0050 s. The mass of the baseball is 0.145 kg.
- **a.** What is the baseball's acceleration?
- **b.** What are the magnitude and direction of the force acting on it?
- **c.** What are the magnitude and direction of the force acting on the player who caught it?

87. **Air Hockey** An air-hockey table works by pumping air through thousands of tiny holes in a table to support light pucks. This allows the pucks to move around on cushions of air with very little resistance. One of these pucks has a mass of 0.25 kg and is pushed along by a 12.0-N force for 9.0 s.
- **a.** What is the puck's acceleration?
- **b.** What is the puck's final velocity?

 For more problems, go to Additional Problems, Appendix B.

88. A student stands on a bathroom scale in an elevator at rest on the 64th floor of a building. The scale reads 836 N.

a. As the elevator moves up, the scale reading increases to 936 N. Find the acceleration of the elevator.

b. As the elevator approaches the 74th floor, the scale reading drops to 782 N. What is the acceleration of the elevator?

c. Using your results from parts a and b, explain which change in velocity, starting or stopping, takes the longer time.

89. Weather Balloon The instruments attached to a weather balloon in **Figure 4-22** have a mass of 5.0 kg. The balloon is released and exerts an upward force of 98 N on the instruments.

a. What is the acceleration of the balloon and instruments?

b. After the balloon has accelerated for 10.0 s, the instruments are released. What is the velocity of the instruments at the moment of their release?

c. What net force acts on the instruments after their release?

d. When does the direction of the instruments' velocity first become downward?

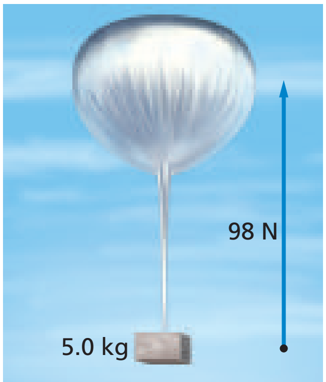


Figure 4-22

90. When a horizontal force of 4.5 N acts on a block on a resistance-free surface, it produces an acceleration of 2.5 m/s^2. Suppose a second 4.0-kg block is dropped onto the first. What is the magnitude of the acceleration of the combination if the same force continues to act? Assume that the second block does not slide on the first block.

91. Two blocks, masses 4.3 kg and 5.4 kg, are pushed across a frictionless surface by a horizontal force of 22.5 N, as shown in **Figure 4-23.**

a. What is the acceleration of the blocks?

b. What is the force of the 4.3-kg block on the 5.4-kg block?

c. What is the force of the 5.4-kg block on the 4.3-kg block?

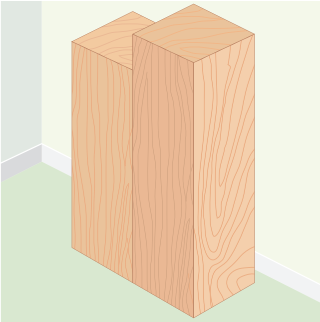


Figure 4-23

92. Two blocks, one of mass 5.0 kg and the other of mass 3.0 kg, are tied together with a massless rope as in **Figure 4-24.** This rope is strung over a massless, resistance-free pulley. The blocks are released from rest. Find the following.

a. the tension in the rope

b. the acceleration of the blocks

Hint: you will need to solve two simultaneous equations.

Figure 4-24

Thinking Critically

93. Formulate Models A 2.0-kg mass, m_A, and a 3.0-kg mass, m_B, are connected to a lightweight cord that passes over a frictionless pulley. The pulley only changes the direction of the force exerted by the rope. The hanging masses are free to move. Choose coordinate systems for the two masses with the positive direction being up for m_A and down for m_B.

a. Create a pictorial model.

b. Create a physical model with motion and free-body diagrams.

c. What is the acceleration of the smaller mass?

94. Use Models Suppose that the masses in problem 93 are now 1.00 kg and 4.00 kg. Find the acceleration of the larger mass.

95. Infer The force exerted on a 0.145-kg baseball by a bat changes from 0.0 N to 1.0×10^4 N in 0.0010 s, then drops back to zero in the same amount of time. The baseball was going toward the bat at 25 m/s.

a. Draw a graph of force versus time. What is the average force exerted on the ball by the bat?

b. What is the acceleration of the ball?

c. What is the final velocity of the ball, assuming that it reverses direction?

96. Observe and Infer Three blocks that are connected by massless strings are pulled along a frictionless surface by a horizontal force, as shown in **Figure 4-25.**

a. What is the acceleration of each block?

b. What are the tension forces in each of the strings?

Hint: Draw a separate free-body diagram for each block.

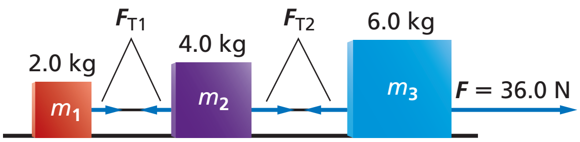


Figure 4-25

97. Critique Using the Example Problems in this chapter as models, write a solution to the following problem. A block of mass 3.46 kg is suspended from two vertical ropes attached to the ceiling. What is the tension in each rope?

98. Think Critically Because of your physics knowledge, you are serving as a scientific consultant for a new science-fiction TV series about space exploration. In episode 3, the heroine, Misty Moonglow, has been asked to be the first person to ride in a new interplanetary transport for use in our solar system. She wants to be sure that the transport actually takes her to the planet she is supposed to be going to, so she needs to take a testing device along with her to measure the force of gravity when she arrives. The script writers don't want her to just drop an object, because it will be hard to depict different accelerations of falling objects on TV. They think they'd like something involving a scale. It is your job to design a quick experiment Misty can conduct involving a scale to determine which planet in our solar system she has arrived on. Describe the experiment and include what the results would be for Pluto (g = 0.30 m/s^2), which is where she is supposed to go, and Mercury (g = 3.70 m/s^2), which is where she actually ends up.

99. Apply Concepts Develop a CBL lab, using a motion detector, that graphs the distance a free-falling object moves over equal intervals of time. Also graph velocity versus time. Compare and contrast your graphs. Using your velocity graph, determine the acceleration. Does it equal g?

Writing in Physics

100. Research Newton's contributions to physics and write a one-page summary. Do you think his three laws of motion were his greatest accomplishments? Explain why or why not.

101. Review, analyze, and critique Newton's first law. Can we prove this law? Explain. Be sure to consider the role of resistance.

102. Physicists classify all forces into four fundamental categories: gravitational, electromagnetic, strong nuclear, and weak nuclear. Investigate these four forces and describe the situations in which they are found.

Cumulative Review

103. Cross-Country Skiing Your friend is training for a cross-country skiing race, and you and some other friends have agreed to provide him with food and water along his training route. It is a bitterly cold day, so none of you wants to wait outside longer than you have to. Taro, whose house is the stop before yours, calls you at 8:25 A.M. to tell you that the skier just passed his house and is planning to move at an average speed of 8.0 km/h. If it is 5.2 km from Taro's house to yours, when should you expect the skier to pass your house? (Chapter 2)

104. Figure 4-26 is a position-time graph of the motion of two cars on a road. (Chapter 3)

a. At what time(s) does one car pass the other?

b. Which car is moving faster at 7.0 s?

c. At what time(s) do the cars have the same velocity?

d. Over what time interval is car B speeding up all the time?

e. Over what time interval is car B slowing down all the time?

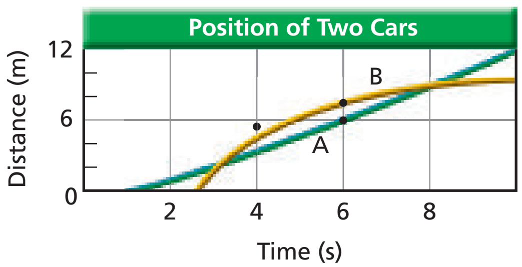


Figure 4-26

105. Refer to Figure 4-26 to find the instantaneous speed for the following: (Chapter 3)

a. car B at 2.0 s

b. car B at 9.0 s

c. car A at 2.0 s

 For more problems, go to Additional Problems, Appendix B.

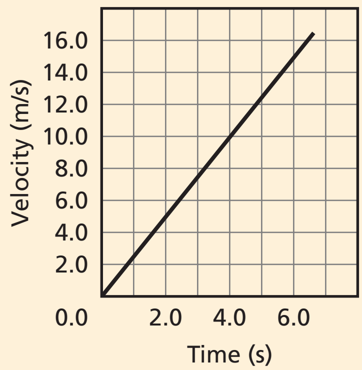
Standardized Test Practice

Multiple Choice

1. What is the acceleration of the car described by the graph below?

Ⓐ 0.20 m/s^2 Ⓒ 1.0 m/s^2

Ⓑ 0.40 m/s^2 Ⓓ 2.5 m/s^2



2. What distance will the car described by the above graph have traveled after 4.0 s?

Ⓐ 13 m Ⓒ 80 m

Ⓑ 40 m Ⓓ 90 m

3. If the car in the above graph maintains a constant acceleration, what will its velocity be after 10 s?

Ⓐ 10 km/h Ⓒ 90 km/h

Ⓑ 25 km/h Ⓓ 120 km/h

4. In a tug-of-war, 13 children, with an average mass of 30 kg each, pull westward on a rope with an average force of 150 N per child. Five parents, with an average mass of 60 kg each, pull eastward on the other end of the rope with an average force of 475 N per adult. Assuming that the whole mass accelerates together as a single entity, what is the acceleration of the system?

Ⓐ 0.62 m/s^2 E Ⓒ 3.4 m/s^2 E

Ⓑ 2.8 m/s^2 W Ⓓ 6.3 m/s^2 W

5. What is the weight of a 225-kg space probe on the Moon? The acceleration of gravity on the Moon is 1.62 m/s^2.

Ⓐ 139 N Ⓒ 1.35×10^3 N

Ⓑ 364 N Ⓓ 2.21×10^3 N

6. A 45-kg child sits on a 3.2-kg tire swing. What is the tension in the rope that hangs from a tree branch?

Ⓐ 310 N Ⓒ 4.5×10^2 N

Ⓑ 4.4×10^2 N Ⓓ 4.7×10^2 N

7. The tree branch in problem 6 sags and the child's feet rest on the ground. If the tension in the rope is reduced to 220 N, what is the value of the normal force being exerted on the child's feet?

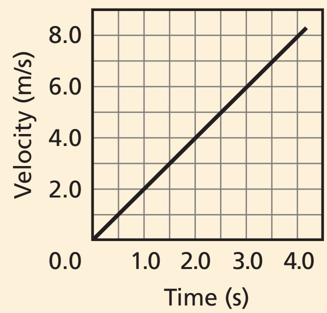
Ⓐ 2.2×10^2 N Ⓒ 4.3×10^2 N

Ⓑ 2.5×10^2 N Ⓓ 6.9×10^2 N

8. According the graph below, what is the force being exerted on the 16-kg cart?

Ⓐ 4 N Ⓒ 16 N

Ⓑ 8 N Ⓓ 32 N



Extended Answer

9. Draw a free-body diagram of a dog sitting on a scale in an elevator. Using words and mathematical formulas, describe what happens to the apparent weight of the dog when: the elevator accelerates upward, the elevator travels at a constant speed downward, and the elevator falls freely downward.

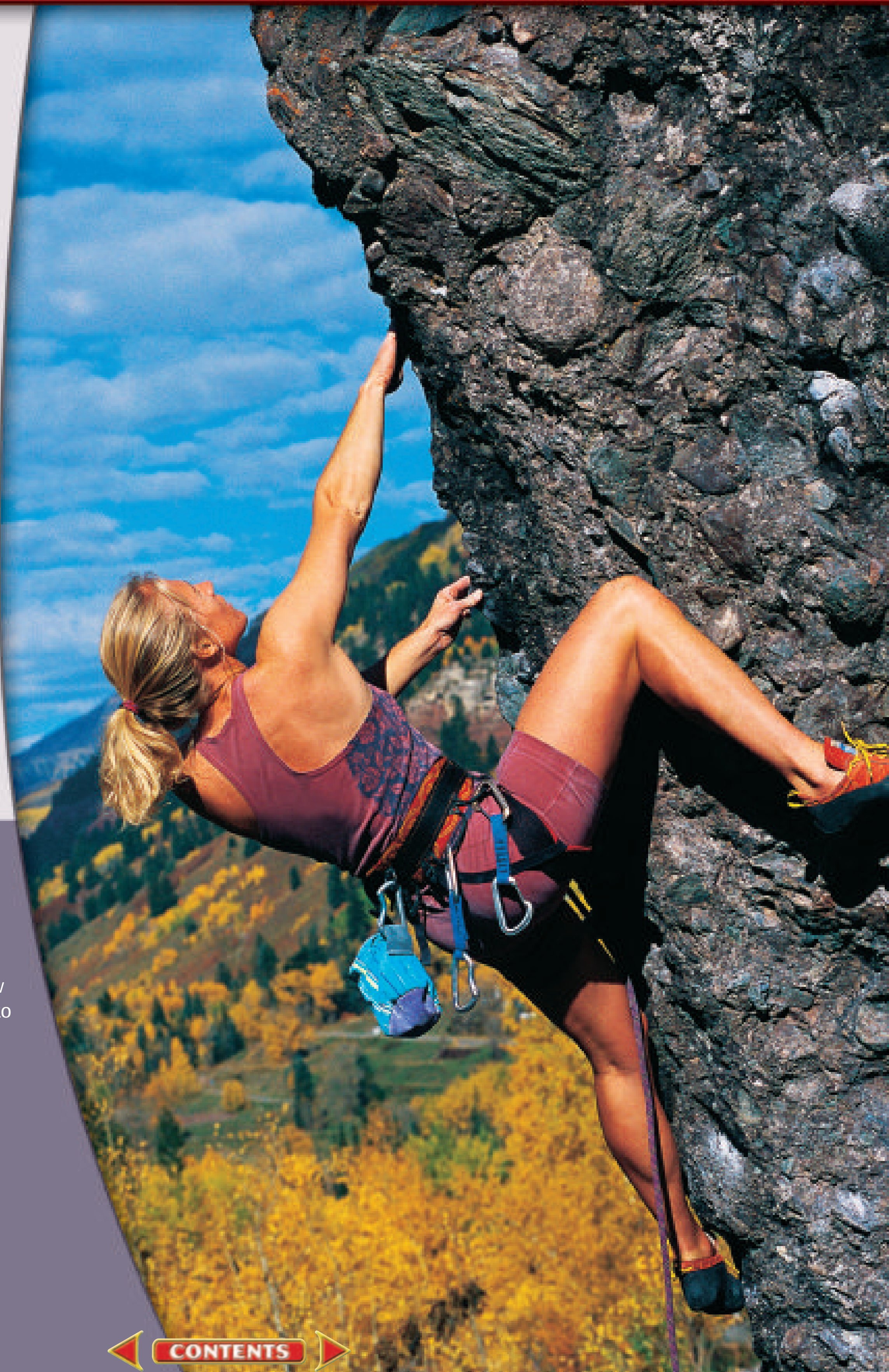
✓ Test-Taking TIP

Maximize Your Score

If possible, find out how your standardized test will be scored. In order to do your best, you need to know if there is a penalty for guessing, and if so, what the penalty is. If there is no random-guessing penalty at all, you should always fill in an answer, even if you have not read the question.

Chapter 5

Forces in Two Dimensions



What You'll Learn

- You will represent vector quantities both graphically and algebraically.
- You will use Newton's laws to analyze motion when friction is involved.
- You will use Newton's laws and your knowledge of vectors to analyze motion in two dimensions.

Why It's Important

Most objects experience forces in more than one dimension. A car being towed, for example, experiences upward and forward forces from the tow truck and the downward force of gravity.

Rock Climbing How do rock climbers keep from falling? This climber has more than one support point, and there are multiple forces acting on her in multiple directions.

Think About This ▶

A rock climber approaches a portion of the rock face that forces her to hang with her back to the ground. How will she use her equipment to apply the laws of physics in her favor and overcome this obstacle?

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LAUNCH Lab

Can 2 N + 2 N = 2 N?

Question

Under what conditions can two different forces equal one other force?

Procedure

1. **Measure** Use a spring scale to measure and record the weight of a 200-g object.
2. Obtain another spring scale, and attach one end of a 35-cm-long piece of string to the hooks on the bottom of each spring scale.
3. Tie one end of a 15-cm-long piece of string to the 200-g object. Loop the other end over the 35-cm-long piece of string and tie the end to the 200-g object. ***CAUTION: Avoid falling masses.***
4. Hold the spring scales parallel to each other so that the string between them forms a 120° angle. Move the string with the hanging object until both scales have the same reading. Record the readings on each scale.
5. **Collect and Organize Data** Slowly pull the string more and more horizontal while it is still supporting the 200-g object. Describe your observations.

Analysis

Does the sum of the forces measured by the two spring scales equal the weight of the hanging object? Is the sum greater than the weight? Less than the weight?

Critical Thinking Draw an equilateral triangle, with one side vertical, on a sheet of paper. If the two sides of the triangle are 2.0 N, explain the size of the third side. How is it possible that 2 N + 2 N = 2 N?

5.1 Vectors

How do rock climbers keep from falling in situations like the one shown on the preceding page? Notice that the climber has more than one support point and that there are multiple forces acting on her. She tightly grips crevices in the rock and has her feet planted on the rock face, so there are two contact forces acting on her. Gravity is pulling on her as well, so there are three total forces acting on the climber. One aspect of this situation that is different from the ones that you have studied in earlier chapters is that the forces exerted by the rock face on the climber are not horizontal or vertical forces. You know from previous chapters that you can pick your coordinate system and orient it in the way that is most useful to analyzing the situation. But what happens when the forces are not at right angles to each other? How can you set up a coordinate system and find for a net force when you are dealing with more than one dimension?

Objectives

- **Evaluate** the sum of two or more vectors in two dimensions graphically.
- **Determine** the components of vectors.
- **Solve** for the sum of two or more vectors algebraically by adding the components of the vectors.

Vocabulary

components
vector resolution

Vectors Revisited

Consider an example with force vectors. Recall the case in Chapter 4 in which you and a friend both pushed on a table together. Suppose that you each exerted 40 N of force to the right. **Figure 5-1** represents these vectors in a free-body diagram with the resultant vector, the net force, shown below it. The net force vector is 80 N, which is what you probably expected. But how was this net force vector obtained?

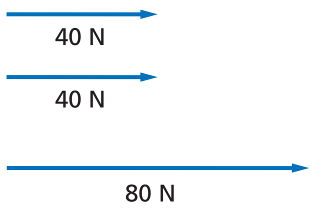
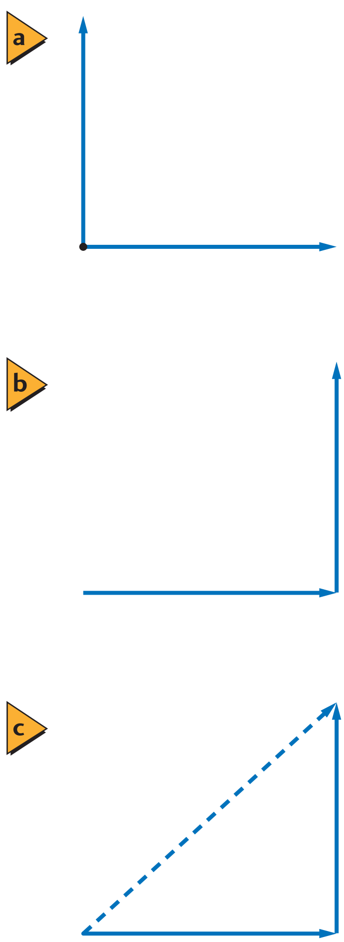


Figure 5-1 The sum of the two 40-N forces is shown by the resultant vector below them.

Vectors in Multiple Dimensions

The process for adding vectors works even when the vectors do not point along the same straight line. If you are solving one of these two-dimensional problems graphically, you will need to use a protractor, both to draw the vectors at the correct angles and also to measure the direction and magnitude of the resultant vector. You can add vectors by placing them tip-to-tail and then drawing the resultant of the vector by connecting the tail of the first vector to the tip of the second vector, as shown in **Figure 5-2**. **Figure 5-2a** shows the two forces in the free-body diagram. In **Figure 5-2b,** one of the vectors has been moved so that its tail is at the same place as the tip of the other vector. Notice that its length and direction have not changed. Because the length and direction are the only important characteristics of the vector, the vector is unchanged by this movement. This is always true: if you move a vector so that its length and direction are unchanged, the vector is unchanged. Now, as in **Figure 5-2c,** you can draw the resultant vector pointing from the tail of the first vector to the tip of the last vector and measure it to obtain its magnitude. Use a protractor to measure the direction of the resultant vector. Sometimes you will need to use trigonometry to determine the length or direction of resultant vectors. Remember that the length of the hypotenuse of a right triangle can be found by using the Pythagorean theorem. If you were adding together two vectors at right angles, vector $\boldsymbol{A}$ pointing north and vector $\boldsymbol{B}$ pointing east, you could use the Pythagorean theorem to find the magnitude of the resultant, R.

Figure 5-2 Add vectors by placing them tip-to-tail and drawing the resultant from the tail of the first vector to the tip of the last vector.



Pythagorean Theorem $R^2 = A^2 + B^2$

If vector A is at a right angle to vector B, then the sum of the squares of the magnitudes is equal to the square of the magnitude of the resultant vector.

If the two vectors to be added are at an angle other than 90°, then you can use the law of cosines or the law of sines.

Law of Cosines $R^2 = A^2 + B^2 - 2AB \cos \theta$

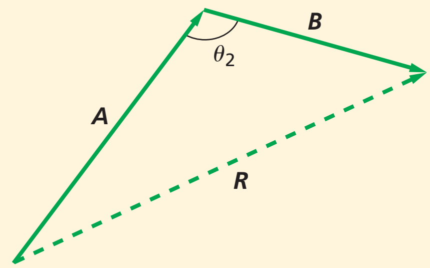
The square of the magnitude of the resultant vector is equal to the sum of the magnitudes of the squares of the two vectors, minus two times the product of the magnitudes of the vectors, multiplied by the cosine of the angle between them.

Law of Sines $\dfrac{R}{\sin \theta} = \dfrac{A}{\sin a} = \dfrac{B}{\sin b}$

The magnitude of the resultant, divided by the sine of the angle between two vectors, is equal to the magnitude of one of the vectors divided by the angle between that component vector and the resultant vector.

▶ EXAMPLE Problem 1

Finding the Magnitude of the Sum of Two Vectors Find the magnitude of the sum of a 15-km displacement and a 25-km displacement when the angle between them is 90° and when the angle between them is 135°.



1 Analyze and Sketch the Problem

- Sketch the two displacement vectors, $\mathbf{A}$ and $\mathbf{B}$, and the angle between them.

Known:		Unknown:
$A = 25$ km	$\theta_1 = 90°$	$R = ?$
$B = 15$ km	$\theta_2 = 135°$	

2 Solve for the Unknown

When the angle is 90°, use the Pythagorean theorem to find the magnitude of the resultant vector.

$$R^2 = A^2 + B^2$$
$$R = \sqrt{A^2 + B^2}$$
$$= \sqrt{(25\text{ km})^2 + (15\text{ km})^2} \quad \text{Substitute } A = 25\text{ km}, B = 15\text{ km}$$
$$= 29\text{ km}$$

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Square and Cube Roots
pages 839–840

When the angle does not equal 90°, use the law of cosines to find the magnitude of the resultant vector.

$$R^2 = A^2 + B^2 - 2AB(\cos\theta_2)$$
$$R = \sqrt{A^2 + B^2 - 2AB(\cos\theta_2)}$$
$$= \sqrt{(25\text{ km})^2 + (15\text{ km})^2 - 2(25\text{ km})(15\text{ km})(\cos 135°)} \quad \text{Substitute } A = 25\text{ km}, B = 15\text{ km}, \theta_2 = 135°$$
$$= 37\text{ km}$$

3 Evaluate the Answer

- **Are the units correct?** Each answer is a length measured in kilometers.
- **Do the signs make sense?** The sums are positive.
- **Are the magnitudes realistic?** The magnitudes are in the same range as the two combined vectors, but longer. This is because each resultant is the side opposite an obtuse angle. The second answer is larger than the first, which agrees with the graphical representation.

▶ PRACTICE Problems

Additional Problems, Appendix B

1. A car is driven 125.0 km due west, then 65.0 km due south. What is the magnitude of its displacement? Solve this problem both graphically and mathematically, and check your answers against each other.
2. Two shoppers walk from the door of the mall to their car, which is 250.0 m down a lane of cars, and then turn 90° to the right and walk an additional 60.0 m. What is the magnitude of the displacement of the shoppers' car from the mall door? Solve this problem both graphically and mathematically, and check your answers against each other.
3. A hiker walks 4.5 km in one direction, then makes a 45° turn to the right and walks another 6.4 km. What is the magnitude of her displacement?
4. An ant is crawling on the sidewalk. At one moment, it is moving south a distance of 5.0 mm. It then turns southwest and crawls 4.0 mm. What is the magnitude of the ant's displacement?

Components of Vectors

Choosing a coordinate system, such as the one in **Figure 5-3a,** is similar to laying a grid drawn on a sheet of transparent plastic on top of a vector problem. You have to choose where to put the center of the grid (the origin) and establish the directions in which the axes point. Notice that in the coordinate system shown in Figure 5-3a, the *x*-axis is drawn through the origin with an arrow pointing in the positive direction. The positive *y*-axis is located 90° counterclockwise from the positive *x*-axis and crosses the *x*-axis at the origin.

How do you choose the direction of the *x*-axis? There is never a single correct answer, but some choices make the problem easier to solve than others. When the motion you are describing is confined to the surface of Earth, it is often convenient to have the *x*-axis point east and the *y*-axis point north. When the motion involves an object moving through the air, the positive *x*-axis is often chosen to be horizontal and the positive *y*-axis vertical (upward). If the motion is on a hill, it's convenient to place the positive *x*-axis in the direction of the motion and the *y*-axis perpendicular to the *x*-axis.

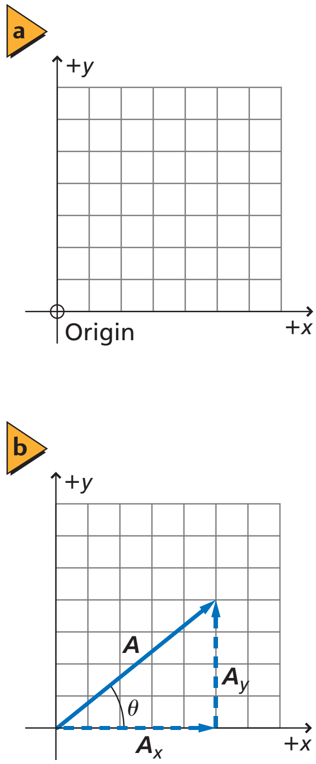


Figure 5-3 A coordinate system has an origin and two perpendicular axes **(a)**. The direction of a vector, ***A***, is measured counterclockwise from the *x*-axis **(b)**.

Component vectors Defining a coordinate system allows you to describe a vector in a different way. Vector ***A*** shown in **Figure 5-3b,** for example, could be described as going 5 units in the positive *x*-direction and 4 units in the positive *y*-direction. You can represent this information in the form of two vectors like the ones labeled $\boldsymbol{A}_x$ and $\boldsymbol{A}_y$ in the diagram. Notice that $\boldsymbol{A}_x$ is parallel to the *x*-axis, and $\boldsymbol{A}_y$ is parallel to the *y*-axis. Further, you can see that if you add $\boldsymbol{A}_x$ and $\boldsymbol{A}_y$, the resultant is the original vector, ***A***. A vector can be broken into its **components,** which are a vector parallel to the *x*-axis and another parallel to the *y*-axis. This can always be done and the following vector equation is always true.

$$\boldsymbol{A} = \boldsymbol{A}_x + \boldsymbol{A}_y$$

This process of breaking a vector into its components is sometimes called **vector resolution.** Notice that the original vector is the hypotenuse of a right triangle. This means that the magnitude of the original vector will always be larger than the magnitudes of either component vector.

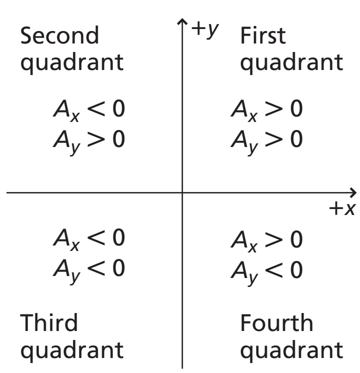
Another reason for choosing a coordinate system is that the direction of any vector can be specified relative to those coordinates. The direction of a vector is defined as the angle that the vector makes with the *x*-axis, measured counterclockwise. In Figure 5-3b, the angle, θ, tells the direction of the vector, ***A***. All algebraic calculations involve only the positive components of vectors, not the vectors themselves. In addition to measuring the lengths of the component vectors graphically, you can find the components by using trigonometry. The components are calculated using the equations below, where the angle, θ, is measured counterclockwise from the positive *x*-axis.

$$\cos\theta = \frac{\text{adjacent side}}{\text{hypotenuse}} = \frac{A_x}{A}; \text{ therefore, } A_x = A\cos\theta$$

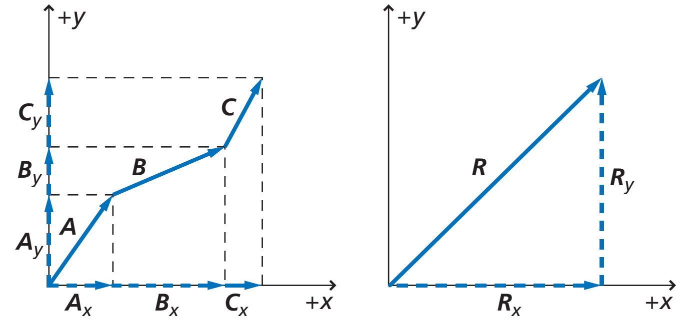
$$\sin\theta = \frac{\text{opposite side}}{\text{hypotenuse}} = \frac{A_y}{A}; \text{ therefore, } A_y = A\sin\theta$$

When the angle that a vector makes with the *x*-axis is larger than 90°, the sign of one or more components is negative, as shown in **Figure 5-4.**

Figure 5-4 The sign of a component depends upon which of the four quadrants the component is in.



Algebraic Addition of Vectors



■ **Figure 5-5** $\boldsymbol{R_x}$ is the sum of the x-components of $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$. $\boldsymbol{R_y}$ is the sum of the y-components. The vector sum of $\boldsymbol{R_x}$ and $\boldsymbol{R_y}$ is the vector sum of $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$.

You might be wondering why you need to resolve vectors into their components. The answer is that doing this often makes adding vectors together much easier mathematically. Two or more vectors (**A**, **B**, **C**, etc.) may be added by first resolving each vector into its x- and y-components. The x-components are added to form the x-component of the resultant: $R_x = A_x + B_x + C_x$. Similarly, the y-components are added to form the y-component of the resultant: $R_y = A_y + B_y + C_y$. This process is illustrated graphically in **Figure 5-5.** Because R_x and R_y are at a right angle (90°), the magnitude of the resultant vector can be calculated using the Pythagorean theorem, $R^2 = R_x^2 + R_y^2$. To find the angle or direction of the resultant, recall that the tangent of the angle that the vector makes with the x-axis is given by the following.

Angle of the Resultant Vector $\quad \theta = \tan^{-1}\left(\frac{R_y}{R_x}\right)$

The angle of the resultant vector is equal to the inverse tangent of the quotient of the y-component divided by the x-component of the resultant vector.

You can find the angle by using the $\tan^{-1}$ key on your calculator. Note that when $\tan\theta > 0$, most calculators give the angle between 0° and 90°, and when $\tan\theta < 0$, the angle is reported to be between 0° and −90°.

▶ PROBLEM-SOLVING **Strategies**

Vector Addition

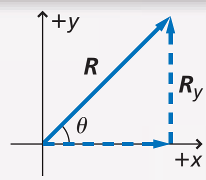
Use the following technique to solve problems for which you need to add or subtract vectors.

1. Choose a coordinate system.
2. Resolve the vectors into their x-components using $A_x = A\cos\theta$, and their y-components using $A_y = A\sin\theta$, where θ is the angle measured counterclockwise from the positive x-axis.
3. Add or subtract the component vectors in the x-direction.
4. Add or subtract the component vectors in the y-direction.
5. Use the Pythagorean theorem, $R = \sqrt{R_x^2 + R_y^2}$, to find the magnitude of the resultant vector.
6. Use $\theta = \tan^{-1}\left(\frac{R_y}{R_x}\right)$ to find the angle of the resultant vector.

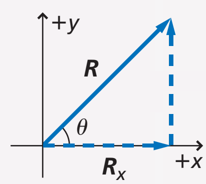
▶ Connecting **Math to Physics**

Math Review

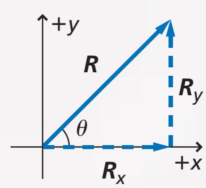
$$\sin\theta = \frac{\text{opposite side}}{\text{hypotenuse}} = \frac{R_y}{R}$$



$$\cos\theta = \frac{\text{adjacent side}}{\text{hypotenuse}} = \frac{R_x}{R}$$



$$\tan\theta = \frac{\text{opposite side}}{\text{adjacent side}} = \frac{R_y}{R_x}$$

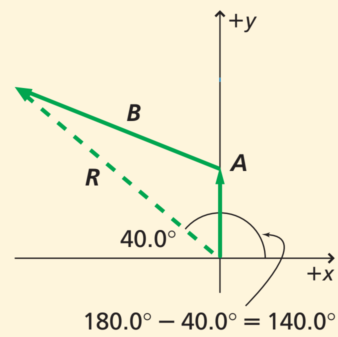


▶ EXAMPLE Problem 2

Finding Your Way Home A GPS receiver indicates that your home is 15.0 km and 40.0° north of west, but the only path through the woods leads directly north. If you follow the path 5.0 km before it opens into a field, how far, and in what direction, would you have to walk to reach your home?

1 Analyze and Sketch the Problem

- Draw the resultant vector, $\boldsymbol{R}$, from your original location to your home.
- Draw $\boldsymbol{A}$, the known vector, and draw $\boldsymbol{B}$, the unknown vector.



Known:

$\boldsymbol{A}$ = 5.0 km, due north

$\boldsymbol{R}$ = 15.0 km, 40.0° north of west

$\theta = 140.0°$

Unknown:

$\boldsymbol{B}$ = ?

2 Solve for the Unknown

Find the components of $\boldsymbol{R}$.

$R_x = R\cos\theta$

$= (15.0\text{ km})\cos 140.0°$ — Substitute $\boldsymbol{R} = 15.0$ km, $\theta = 140.0°$

$= -11.5\text{ km}$

$R_y = R\sin\theta$

$= (15.0\text{ km})\sin 140.0°$ — Substitute $\boldsymbol{R} = 15.0$ km, $\theta = 140.0°$

$= 9.64\text{ km}$

Because $\boldsymbol{A}$ is due north, $A_x = 0.0$ km and $A_y = 5.0$ km.

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Inverses of Sine, Cosine, and Tangent
page 856

Use the components of $\boldsymbol{R}$ and $\boldsymbol{A}$ to find the components of $\boldsymbol{B}$.

$B_x = R_x - A_x$

$= -11.5\text{ km} - 0.0\text{ km}$ — Substitute $R_x = -11.5$ km, $A_x = 0.0$ km

$= -11.5\text{ km}$ — The negative sign means that this component points west.

$B_y = R_y - A_y$

$= 9.64\text{ km} - 5.0\text{ km}$ — Substitute $R_y = 9.64$ km, $A_y = 5.0$ km

$= 4.6\text{ km}$ — This component points north.

Use the components of vector $\boldsymbol{B}$ to find the magnitude of vector $\boldsymbol{B}$.

$B = \sqrt{B_x^2 + B_y^2}$

$= \sqrt{(-11.5\text{ km})^2 + (4.6\text{ km})^2}$ — Substitute $B_y = -4.6$ km, $B_x = -11.5$ km

$= 12\text{ km}$

Use the tangent to find the direction of vector $\boldsymbol{B}$.

$\theta = \tan^{-1}\dfrac{B_y}{B_x}$

$= \tan^{-1}\dfrac{4.6\text{ km}}{-11.5\text{ km}}$ — Substitute $B_y = 4.6$ km, $B_x = -11.5$ km

$= -22°$ or $158°$ — Tangent of an angle is negative in quadrants II and IV, so two answers are possible.

Locate the tail of vector $\boldsymbol{B}$ at the origin of a coordinate system and draw the components B_x and B_y. The direction is in the third quadrant, at 158°, or 22° north of west. Thus, $\boldsymbol{B}$ = 12 km at 22° north of west.

3 Evaluate the Answer

- **Are the units correct?** Kilometers and degrees are correct.
- **Do the signs make sense?** They agree with the diagram.
- **Is the magnitude realistic?** The length of $\boldsymbol{B}$ should be longer than R_x because the angle between A and B is greater than 90°.

CONTENTS

PRACTICE Problems

Additional Problems, Appendix B

Solve problems 5–10 algebraically. You may also choose to solve some of them graphically to check your answers.

5. Sudhir walks 0.40 km in a direction 60.0° west of north, then goes 0.50 km due west. What is his displacement?

6. Afua and Chrissy are going to sleep overnight in their tree house and are using some ropes to pull up a box containing their pillows and blankets, which have a total mass of 3.20 kg. The girls stand on different branches, as shown in **Figure 5-6,** and pull at the angles and with the forces indicated. Find the *x*- and *y*-components of the net force on the box. *Hint: Draw a free-body diagram so that you do not leave out a force.*

7. You first walk 8.0 km north from home, then walk east until your displacement from home is 10.0 km. How far east did you walk?

8. A child's swing is held up by two ropes tied to a tree branch that hangs 13.0° from the vertical. If the tension in each rope is 2.28 N, what is the combined force (magnitude and direction) of the two ropes on the swing?

9. Could a vector ever be shorter than one of its components? Equal in length to one of its components? Explain.

10. In a coordinate system in which the *x*-axis is east, for what range of angles is the *x*-component positive? For what range is it negative?

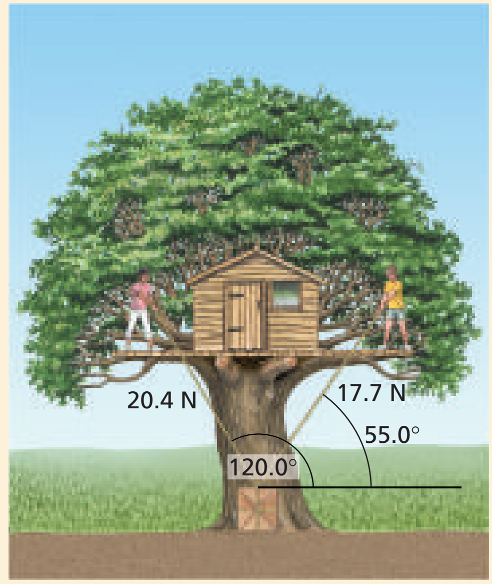


Figure 5-6 (Not to scale)

You will use these techniques to resolve vectors into their components throughout your study of physics. You will get more practice at it, particularly in the rest of this chapter and the next. Resolving vectors into components allows you to analyze complex systems of vectors without using graphical methods.

5.1 Section Review

11. Distance v. Displacement Is the distance that you walk equal to the magnitude of your displacement? Give an example that supports your conclusion.

12. Vector Difference Subtract vector ***K*** from vector ***L***, shown in **Figure 5-7.**

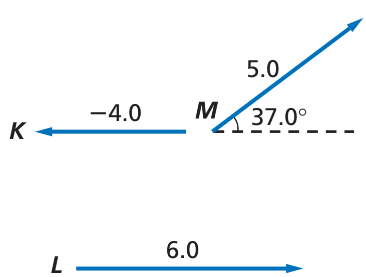


Figure 5-7

13. Components Find the components of vector ***M***, shown in Figure 5-7.

14. Vector Sum Find the sum of the three vectors shown in Figure 5-7.

15. Commutative Operations The order in which vectors are added does not matter. Mathematicians say that vector addition is commutative. Which ordinary arithmetic operations are commutative? Which are not?

16. Critical Thinking A box is moved through one displacement and then through a second displacement. The magnitudes of the two displacements are unequal. Could the displacements have directions such that the resultant displacement is zero? Suppose the box was moved through three displacements of unequal magnitude. Could the resultant displacement be zero? Support your conclusion with a diagram.

5.2 Friction

▸ **Objectives**

- **Define** the friction force.
- **Distinguish** between static and kinetic friction.

▸ **Vocabulary**

kinetic friction
static friction
coefficient of kinetic friction
coefficient of static friction

Push your hand across your desktop and feel the force called friction opposing the motion. Push your book across the desk. When you stop pushing, the book will continue moving for a little while, then it will slow down and stop. The frictional force acting on the book gave it an acceleration in the direction opposite to the one in which it was moving. So far, you have neglected friction in solving problems, but friction is all around you. You need it to both start and stop a bicycle and a car. If you have ever walked on ice, you understand the importance of friction.

Static and Kinetic Friction

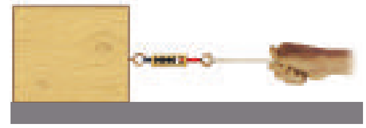
There are two types of friction. Both always oppose motion. When you pushed your book across the desk, it experienced a type of friction that acts on moving objects. This force is known as **kinetic friction,** and it is exerted on one surface by another when the two surfaces rub against each other because one or both of them are moving.

To understand the other kind of friction, imagine trying to push a heavy couch across the floor. You give it a push, but it does not move. Because it does not move, Newton's laws tell you that there must be a second horizontal force acting on the couch, one that opposes your force and is equal in size. This force is **static friction,** which is the force exerted on one surface by another when there is no motion between the two surfaces. You might push harder and harder, as shown in **Figures 5-8a** and **5-8b,** but if the couch still does not move, the force of friction must be getting larger. This is because the static friction force acts in response to other forces. Finally, when you push hard enough, as shown in **Figure 5-8c,** the couch will begin to move. Evidently, there is a limit to how large the static friction force can be. Once your force is greater than this maximum static friction, the couch begins moving and kinetic friction begins to act on it instead of static friction.

A model for friction forces On what does a frictional force depend? The materials that the surfaces are made of play a role. For example, there is more friction between skis and concrete than there is between skis and snow. It may seem reasonable to think that the force of friction also might depend on either the surface area in contact or the speed of the motion, but experiments have shown that this is not true. The normal force between the two objects does matter, however. The harder one object is pushed against the other, the greater the force of friction that results.

■ **Figure 5-8** There is a limit to the ability of the static friction force to match the applied force.

If you pull a block along a surface at a constant velocity, according to Newton's laws, the frictional force must be equal and opposite to the force with which you pull. You can pull a block of known mass along a table at a constant velocity and use a spring scale, as shown in **Figure 5-9,** to measure the force that you exert. You can then stack additional blocks on the block to increase the normal force and repeat the measurement.



■ **Figure 5-9** The spring scale pulls the block with a constant force.

Plotting the data will yield a graph like the one in **Figure 5-10.** There is a direct proportion between the kinetic friction force and the normal force. The different lines correspond to dragging the block along different surfaces. Note that the line corresponding to the sandpaper surface has a steeper slope than the line for the highly polished table. You would expect it to be much harder to pull the block along sandpaper than along a polished table, so the slope must be related to the magnitude of the resulting frictional force. The slope of this line, designated μ_k, is called the **coefficient of kinetic friction** between the two surfaces and relates the frictional force to the normal force, as shown below.

Kinetic Friction Force $F_{f,\ kinetic} = \mu_k F_N$

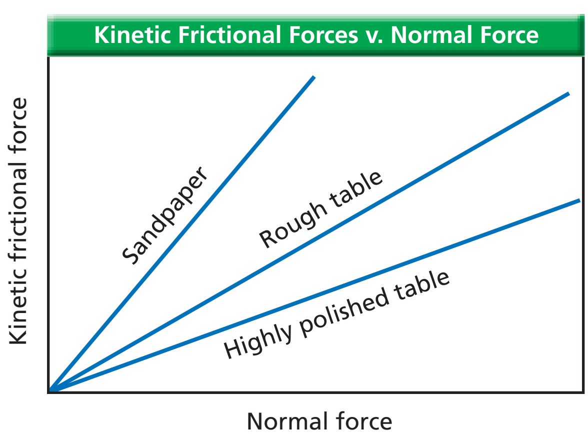
The kinetic friction force is equal to the product of the coefficient of the kinetic friction and the normal force.

The maximum static friction force is related to the normal force in a similar way as the kinetic friction force. Remember that the static friction force acts in response to a force trying to cause a stationary object to start moving. If there is no such force acting on an object, the static friction force is zero. If there is a force trying to cause motion, the static friction force will increase up to a maximum value before it is overcome and motion starts.

Static Friction Force $F_{f,\ static} \leq \mu_s F_N$

The static friction force is less than or equal to the product of the coefficient of the static friction and the normal force.

In the equation for the maximum static friction force, μ_s is the **coefficient of static friction** between the two surfaces, and $\mu_s F_N$ is the maximum static friction force that must be overcome before motion can begin. In Figure 5-8c, the static friction force is balanced the instant before the couch begins to move.



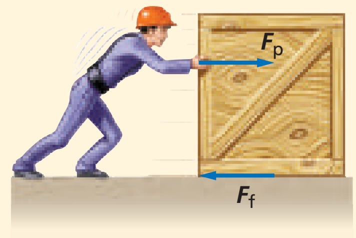
■ **Figure 5-10** There is a linear relationship between the frictional force and the normal force.

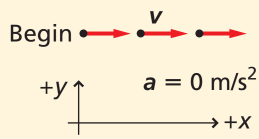
EXAMPLE Problem 3

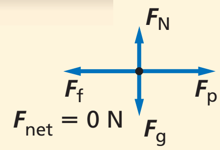
Balanced Friction Forces You push a 25.0-kg wooden box across a wooden floor at a constant speed of 1.0 m/s. How much force do you exert on the box?

1 Analyze and Sketch the Problem

- Identify the forces and establish a coordinate system.
- Draw a motion diagram indicating constant v and $a = 0$.
- Draw the free-body diagram.







Known:	**Unknown:**
$m = 25.0$ kg	$F_p = ?$
$v = 1.0$ m/s	
$a = 0.0$ m/s^2	
$\mu_k = 0.20$ (Table 5-1)	

2 Solve for the Unknown

The normal force is in the y-direction, and there is no acceleration.

$$\begin{aligned} F_N &= F_g \\ &= mg \\ &= (25.0\ \text{kg})(9.80\text{m/s}^2) \\ &= 245\ \text{N} \end{aligned}$$

Substitute $m = 25.0$ kg, $g = 9.80$ m/s^2

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Operations with Significant Digits
pages 835–836

The pushing force is in the x-direction; v is constant, thus there is no acceleration.

$$\begin{aligned} F_p &= \mu_k mg \\ &= (0.20)(25.0\ \text{kg})(9.80\ \text{m/s}^2) \\ &= 49\ \text{N} \end{aligned}$$

Substitute $\mu_k = 0.20$, $m = 25.0$ kg, $g = 9.80$ m/s^2

3 Evaluate the Answer

- **Are the units correct?** Performing dimensional analysis on the units verifies that force is measured in kg·m/s^2 or N.
- **Does the sign make sense?** The positive sign agrees with the sketch.
- **Is the magnitude realistic?** The force is reasonable for moving a 25.0-kg box.

PRACTICE Problems

Additional Problems, Appendix B

17. A girl exerts a 36-N horizontal force as she pulls a 52-N sled across a cement sidewalk at constant speed. What is the coefficient of kinetic friction between the sidewalk and the metal sled runners? Ignore air resistance.

18. You need to move a 105-kg sofa to a different location in the room. It takes a force of 102 N to start it moving. What is the coefficient of static friction between the sofa and the carpet?

19. Mr. Ames is dragging a box full of books from his office to his car. The box and books together have a combined weight of 134 N. If the coefficient of static friction between the pavement and the box is 0.55, how hard must Mr. Ames push the box in order to start it moving?

20. Suppose that the sled in problem 17 is resting on packed snow. The coefficient of kinetic friction is now only 0.12. If a person weighing 650 N sits on the sled, what force is needed to pull the sled across the snow at constant speed?

21. Suppose that a particular machine in a factory has two steel pieces that must rub against each other at a constant speed. Before either piece of steel has been treated to reduce friction, the force necessary to get them to perform properly is 5.8 N. After the pieces have been treated with oil, what will be the required force?

Table 5-1		
Typical Coefficients of Friction		
Surface	μ_s	μ_k
Rubber on dry concrete	0.80	0.65
Rubber on wet concrete	0.60	0.40
Wood on wood	0.50	0.20
Steel on steel (dry)	0.78	0.58
Steel on steel (with oil)	0.15	0.06

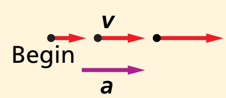
Note that the equations for the kinetic and maximum static friction forces involve only the magnitudes of the forces. The forces themselves, $\mathbf{F}_f$ and $\mathbf{F}_N$, are at right angles to each other. **Table 5-1** shows coefficients of friction between various surfaces. Although all the listed coefficients are less than 1.0, this does not mean that they must always be less than 1.0. For example, coefficients as large as 5.0 are experienced in drag racing.

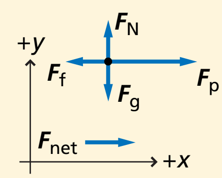
EXAMPLE Problem 4

Unbalanced Friction Forces If the force that you exert on the 25.0-kg box in Example Problem 3 is doubled, what is the resulting acceleration of the box?

1 Analyze and Sketch the Problem

- Draw a motion diagram showing v and a.
- Draw the free-body diagram with a doubled F_p.





Known:		Unknown:
$m = 25.0$ kg	$\mu_k = 0.20$	$a = ?$
$v = 1.0$ m/s	$F_p = 2(49\text{ N}) = 98\text{ N}$	

2 Solve for the Unknown

The normal force is in the y-direction, and there is no acceleration.

$$F_N = F_g \qquad \text{Substitute } F_g = mg$$
$$= mg$$

In the x-direction there is an acceleration. So the forces must be unequal.

$$F_{net} = F_p - F_f$$
$$ma = F_p - F_f \qquad \text{Substitute } F_{net} = ma$$
$$a = \frac{F_p - F_f}{m}$$

Find F_f and substitute it into the expression for a.

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$$F_f = \mu_k F_N$$
$$= \mu_k mg \qquad \text{Substitute } F_N = mg$$
$$a = \frac{F_p - \mu_k mg}{m} \qquad \text{Substitute } F_f = \mu_k mg$$
$$= \frac{98\text{ N} - (0.20)(25.0\text{ kg})(9.80\text{ m/s}^2)}{25.0\text{ kg}} \qquad \text{Substitute } F_p = 98\text{ N},\ m = 25.0\text{ kg},\ \mu_k = 0.20,\ g = 9.80\text{ m/s}^2$$
$$= 2.0\text{ m/s}^2$$

3 Evaluate the Answer

- **Are the units correct?** a is measured in m/s^2.
- **Does the sign make sense?** In this coordinate system, the sign should be positive.
- **Is the magnitude realistic?** If the force were cut in half, a would be zero.

PRACTICE Problems

Additional Problems, Appendix B

22. A 1.4-kg block slides across a rough surface such that it slows down with an acceleration of 1.25 m/s^2. What is the coefficient of kinetic friction between the block and the surface?

23. You help your mom move a 41-kg bookcase to a different place in the living room. If you push with a force of 65 N and the bookcase accelerates at 0.12 m/s^2, what is the coefficient of kinetic friction between the bookcase and the carpet?

24. A shuffleboard disk is accelerated to a speed of 5.8 m/s and released. If the coefficient of kinetic friction between the disk and the concrete court is 0.31, how far does the disk go before it comes to a stop? The courts are 15.8 m long.

25. Consider the force pushing the box in Example Problem 4. How long would it take for the velocity of the box to double to 2.0 m/s?

26. Ke Min is driving along on a rainy night at 23 m/s when he sees a tree branch lying across the road and slams on the brakes when the branch is 60.0 m in front of him. If the coefficient of kinetic friction between the car's locked tires and the road is 0.41, will the car stop before hitting the branch? The car has a mass of 2400 kg.

APPLYING PHYSICS

Causes of Friction All surfaces, even those that appear to be smooth, are rough at a microscopic level. If you look at a photograph of a graphite crystal magnified by a scanning tunneling microscope, the atomic level surface irregularities of the crystal are revealed. When two surfaces touch, the high points on each are in contact and temporarily bond. This is the origin of both static and kinetic friction. The details of this process are still unknown and are the subject of research in both physics and engineering.

Here are a few important things to remember when dealing with frictional situations. First, friction always acts in a direction opposite to the motion (or in the case of static friction, intended motion). Second, the magnitude of the force of friction depends on the magnitude of the normal force between the two rubbing surfaces; it does not necessarily depend on the weight of either object. Finally, multiplying the coefficient of static friction and the normal force gives you the maximum static friction force. Keep these things in mind as you review this section.

5.2 Section Review

27. Friction In this section, you learned about static and kinetic friction. How are these two types of friction similar? What are the differences between static and kinetic friction?

28. Friction At a wedding reception, you notice a small boy who looks like his mass is about 25 kg running part way across the dance floor, then sliding on his knees until he stops. If the kinetic coefficient of friction between the boy's pants and the floor is 0.15, what is the frictional force acting on him as he slides?

29. Velocity Derek is playing cards with his friends, and it is his turn to deal. A card has a mass of 2.3 g, and it slides 0.35 m along the table before it stops. If the coefficient of kinetic friction between the card and the table is 0.24, what was the initial speed of the card as it left Derek's hand?

30. Force The coefficient of static friction between a 40.0-kg picnic table and the ground below it is 0.43. What is the greatest horizontal force that could be exerted on the table while it remains stationary?

31. Acceleration Ryan is moving to a new apartment and puts a dresser in the back of his pickup truck. When the truck accelerates forward, what force accelerates the dresser? Under what circumstances could the dresser slide? In which direction?

32. Critical Thinking You push a 13-kg table in the cafeteria with a horizontal force of 20 N, but it does not move. You then push it with a horizontal force of 25 N, and it accelerates at 0.26 m/s^2. What, if anything, can you conclude about the coefficients of static and kinetic friction?

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