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CHAPTER 1

The Science of Physics

PHYSICS IN ACTION

The sails of this boat billow out round and full. As the boat begins moving forward faster and faster, a ball on the deck rolls toward the stern. The boat pitches back and forth gently as it slices through the waves. Water slaps against the hull, occasionally spraying the crew and keeping them cool in the hot sun.

At first, this scene seems to have little to do with physics. Many people associate physics with complicated concepts studied by white-coated scientists working in laboratories with intricate machinery.

But physics can be used to explain anything in the physical world—from why the ball moves to the back as the boat speeds up to why different parts of the sail have different colors.

- *How are the principles of physics applied to sailboat design?*
- *How can the principles of physics be used to predict how a sailboat will move under various conditions?*

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1-1
What is physics?

1-1 SECTION OBJECTIVES

- **Identify activities and fields that involve the major areas within physics.**
- **Describe the processes of the scientific method.**
- **Describe the role of models and diagrams in physics.**

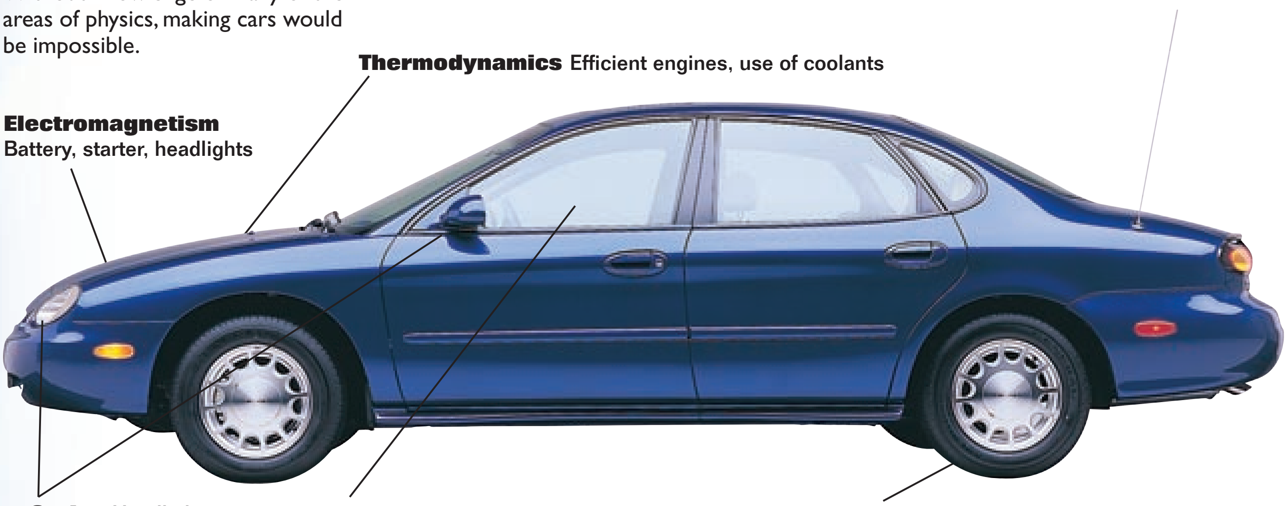
THE TOPICS OF PHYSICS

Many people consider physics to be a difficult science that is far removed from their lives. This may be because many of the world's most famous physicists study topics such as the structure of the universe or the incredibly small particles within an atom, often using complicated tools to observe and measure what they are studying.

But physics is simply the study of the physical world. Everything around you can be described using the tools of physics. The goal of physics is to use a small number of basic concepts, equations, and assumptions to describe the physical world. Once the physical world has been described this way, the physics principles involved can be used to make predictions about a broad range of phenomena. For example, the same physics principles that are used to describe the interaction between two planets can also be used to describe the motion of a satellite orbiting the Earth.

Many of the inventions, appliances, tools, and buildings we live with today are made possible by the application of physics principles. Every time you take a step, catch a ball, open a door, whisper, or check your image in a mirror, you are unconsciously using your knowledge of physics. **Figure 1-1** indicates how the areas of physics apply to building and operating a car. TEKS

Figure 1-1
Without knowledge of many of the areas of physics, making cars would be impossible.



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Physics is everywhere

We are surrounded by principles of physics in our everyday lives. In fact, most people know much more about physics than they realize. When you buy a carton of ice cream at the store and put it in the freezer at home, you do it because intuitively you know enough about the laws of physics to know that the ice cream will melt if you leave it on the counter.

Any problem that deals with temperature, size, motion, position, shape, or color involves physics. Physicists categorize the topics they study in a number of different ways. **Table 1-1** shows some of the major areas of physics that will be described in this book.

People who design, build, and operate sailboats need a working knowledge of the principles of physics. Designers figure out the best shape for the boat's hull so that it remains stable and floating yet quick-moving and maneuverable. This design requires knowledge of the physics of fluids. Determining the most efficient shapes for the sails and how to arrange them requires an understanding of the science of motion and its causes. Balancing loads in the construction of a sailboat requires knowledge of mechanics. Some of the same physics principles can also explain how the keel keeps the boat moving in one direction even when the wind is from a slightly different direction.

Table 1-1 Areas within physics

Name	Subjects	Examples
Mechanics	motion and its causes	falling objects, friction, weight, spinning objects
Thermodynamics	heat and temperature	melting and freezing processes, engines, refrigerators
Vibrations and wave phenomena	specific types of repetitive motions	springs, pendulums, sound
Optics	light	mirrors, lenses, color, astronomy
Electromagnetism	electricity, magnetism, and light	electrical charge, circuitry, permanent magnets, electromagnets
Relativity	particles moving at any speed, including very high speeds	particle collisions, particle accelerators, nuclear energy
Quantum mechanics	behavior of submicroscopic particles	the atom and its parts

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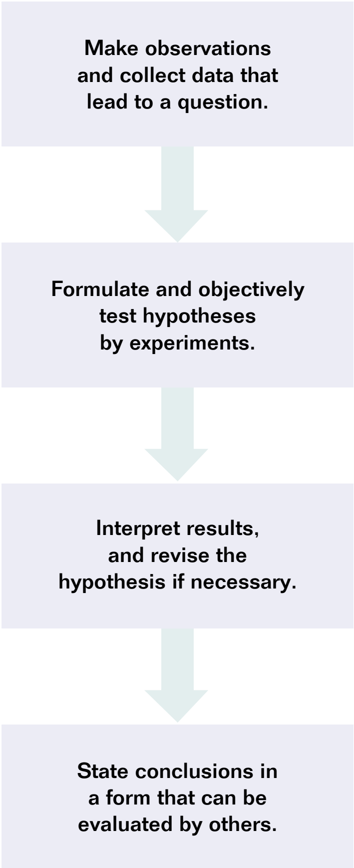


Figure 1-2
Physics, like all other sciences, is based on the scientific method.

THE SCIENTIFIC METHOD

When scientists look at the world, they see a network of rules and relationships that determine what will happen in a given situation. Everything you will study in this course was learned because someone looked out at the world and asked questions about how things work.

There is no single procedure that scientists follow in their work. However, there are certain steps common to all good scientific investigations. These steps, called the *scientific method,* are summarized in **Figure 1-2.** This simple chart is easy to understand; but, in reality, most scientific work is not so easily separated. Sometimes, exploratory experiments are performed as a part of the first step in order to generate observations that can lead to a focused question. A revised hypothesis may require more experiments.

Physics uses models that describe only part of reality

How is physics distinct from chemistry, biology, or the other sciences? One difference is the scope of the subject matter, as briefly referred to earlier in this section. Another difference is that although the physical world is very complex, physicists often use simple **models** to explain the most fundamental features of various phenomena. They use this approach because it is usually impossible to describe all aspects of a phenomenon at the same time. A common technique that physicists use to analyze an event or observation is to break it down into different parts. Then physicists decide which parts are important to what they want to study and which parts can be disregarded.

For example, let's say you wish to study the motion of the ball shown in **Figure 1-3.** There are many observations that can be made about the

model

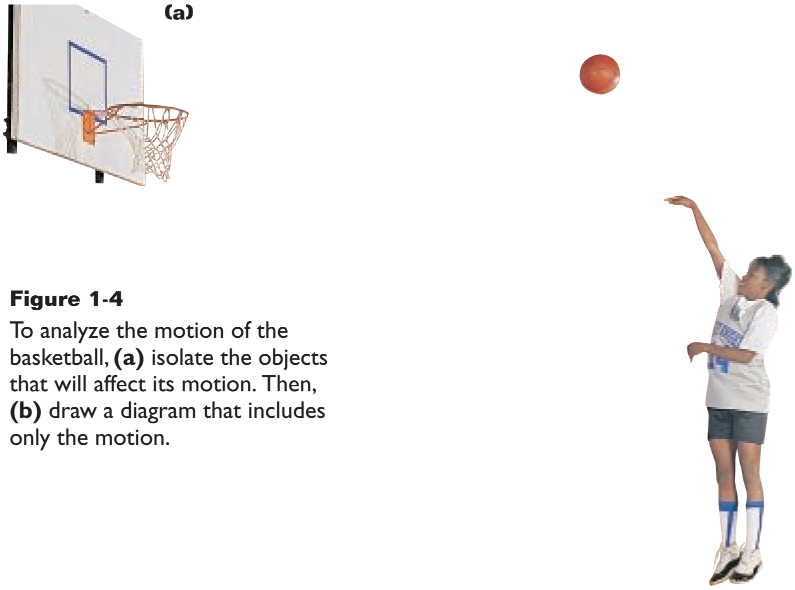
a replica or description designed to show the structure or workings of an object, system, or concept

Figure 1-3
This basketball game involves great complexity.

situation, including the ball's surroundings, size, spin, weight, color, time in the air, speed, and sound when hitting the ground. The first step toward simplifying this complicated situation is to decide what to study, the **system.** Typically, a single object and the items that immediately affect it are the focus of attention. Once you decide that the ball and its motion are what you want to study, you can eliminate all information about the surroundings of the ball except information that affects its motion, as indicated in **Figure 1-4(a).**

system

a set of items or interactions considered a distinct physical entity for the purpose of study



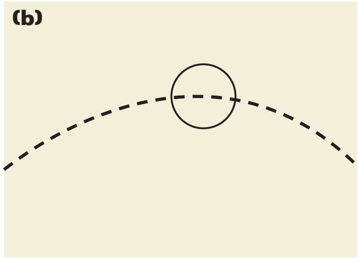


Figure 1-4
To analyze the motion of the basketball, **(a)** isolate the objects that will affect its motion. Then, **(b)** draw a diagram that includes only the motion.

You can disregard characteristics of the ball that have little or no effect on its motion, such as the ball's color and its sound when bouncing against the floor. In some studies of motion, even the ball's spin and size are disregarded, and the change in the ball's position will be the only quantity investigated, as shown in **Figure 1-4(b).**

In effect, the physicist studies the motion of a ball by first creating a simple model of the ball and its motion. Unlike the real ball, the model object is isolated; it has no color, spin, or size, and it makes no noise on impact. Frequently, a model can be summarized with a diagram, like the one in **Figure 1-4(b).** Another way to summarize these models is to build a computer simulation or small-scale replica of the situation.

Without models to simplify matters, situations such as building a car or sailing a boat would be too complex to study. For instance, analyzing the motion of the sailboat is made easier by imagining that the push on the boat from the wind is steady and consistent. The boat is also treated as an object with a certain mass being pushed through the water. In other words, the color of the boat, the model of the boat, and the details of its shape are left out of the analysis. Furthermore, the water the boat moves through is treated as if it were a perfectly smooth-flowing liquid with no internal friction. In spite of these simplifications, the analysis can still make useful predictions of how the sailboat will move.

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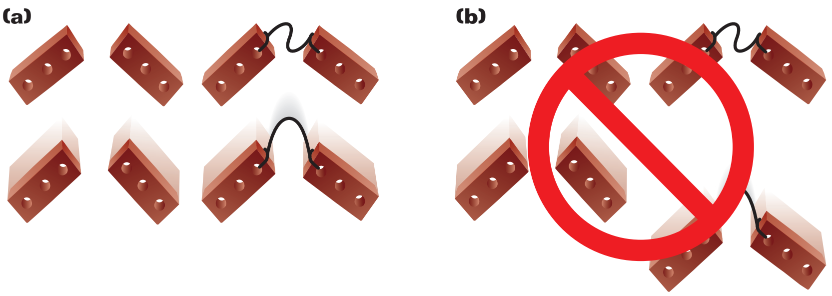
Models can help build hypotheses

A scientific hypothesis is a reasonable explanation for observations—one that can be tested with additional experiments. The process of simplifying and modeling a situation can help you identify the relevant variables and identify a hypothesis for testing.

Consider the example of Galileo's "thought experiment," in which he modeled the behavior of falling objects in order to develop a hypothesis about how objects fell. At the time Galileo published his work on falling objects, in 1638, scientists believed that a heavy object would fall faster than a lighter object.

In Galileo's thought experiment, he imagined two identical objects being released at the same time from the same height. They should fall with the same speed. Galileo then imagined tying the two objects together while they were falling. Both scenarios are represented in **Figure 1-5.**

If common belief were correct, the two objects tied together would suddenly fall faster than they had fallen before because they would be one heavy object instead of two lighter ones. But Galileo believed that tying the two objects together should not cause such a sudden change. As a result of this reasoning, Galileo hypothesized that all objects fall at the same rate in the absence of air resistance, no matter what size they are.



What does happen: Heavy objects fall as fast as lighter ones.

What does not happen: Heavy objects do *not* fall faster than lighter ones.

Figure 1-5
Galileo used the thought experiment represented by this diagram as a way to organize his thoughts about falling bodies. Heavy objects must fall as fast as lighter ones **(a),** or else two bricks tied together would fall faster than they would if kept separate **(b).**

Models help guide experimental design

Galileo performed many experiments to test his hypothesis. To be certain he was observing differences due to weight, he kept all other variables the same: the objects he tested had the same size (but different weights) and were measured falling from the same point.

The measuring devices at that time were not precise enough to measure the motion of objects falling in air, and there was no way to eliminate air resistance. So Galileo used the motion of a ball rolling down a series of smooth ramps as a model of the motion of a falling ball. The steeper the ramp, the closer the model came to representing a falling object. These ramp experiments provided data that matched the predictions Galileo made in his hypothesis.

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Like Galileo's hypothesis, any hypothesis must be tested in a **controlled experiment.** In an experiment to test a hypothesis, you must change one variable at a time to determine what influences the phenomenon you are observing. Galileo performed a series of experiments using balls of different weights on one ramp before determining the time they took to roll down a steeper ramp.

controlled experiment

experiment involving manipulation of a single variable or factor

The best physics hypotheses can make predictions in new situations

Until the invention of the air pump, it was not possible to perform direct tests of Galileo's hypothesis by observing objects falling in the absence of air resistance. But even though it was not completely testable, Galileo's hypothesis was used to make reasonably accurate predictions about the motion of many objects, from raindrops to boulders (even though they all experience air resistance).

Even if some experiments produce results that support a certain hypothesis, at any time another experiment may produce results that do not support the hypothesis. When this occurs, scientists repeat the experiment until they are sure that the results are not in error. If the unexpected results are confirmed, the hypothesis must be abandoned or revised. That is why the last step of the scientific method is so important. A conclusion is valid only if it can be verified by other people.

Did you know?

In addition to conducting experiments to test their hypotheses, scientists also research the work of other scientists. The steps of this type of research include:

- identifying reliable sources
- searching the sources to find references
- checking carefully for opposing views
- documenting sources
- presenting findings to other scientists for review and discussion

Section Review

1. Name the areas of physics.
2. Identify the area of physics that is most relevant to each of the following situations. Explain your reasoning.
   a. a high school football game
   b. food preparation for the prom
   c. playing in the school band
   d. lightning in a thunderstorm
   e. wearing a pair of sunglasses outside in the sun
3. What are the activities involved in the scientific method?
4. Give two examples of ways that physicists model the physical world.
5. **Physics in Action** Identify the area of physics involved in each of the following tests of a lightweight metal alloy proposed for use in sailboat hulls:
   a. testing the effects of a collision on the alloy
   b. testing the effects of extreme heat and cold on the alloy
   c. testing whether the alloy can affect a magnetic compass needle

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1-2
Measurements in experiments

1-2 SECTION OBJECTIVES

- **List basic SI units and the quantities they describe.**
- **Convert measurements into scientific notation.**
- **Distinguish between *accuracy* and *precision.***
- **Use significant figures in measurements and calculations.**

NUMBERS AS MEASUREMENTS

Physicists perform experiments to test hypotheses about how changing one variable in a situation affects another variable. An accurate analysis of such experiments requires numerical measurements.

Numerical measurements are different from the numbers used in a mathematics class. In mathematics, a number like 7 can stand alone and be used in equations. In science, measurements are more than just a number. For example, a measurement reported as 7 leads to several questions. What physical quantity is being measured—length, mass, time, or something else? If it is length that is being measured, what units were used for the measurement—meters, feet, inches, miles, or light-years?

The description of *what kind* of physical quantity is represented by a certain measurement is called *dimension.* In the next several chapters, you will encounter three basic dimensions: length, mass, and time. Many other measurements can be expressed in terms of these three dimensions. For example, physical quantities, such as force, velocity, energy, volume, and acceleration, can all be described as combinations of length, mass, and time. In later chapters, we will need to add two other dimensions to our list, for temperature and for electric current.

The description of *how much* of a physical quantity is represented by a certain numerical measurement depends on the *units* with which the quantity is measured. For example, small distances are more easily measured in millimeters than in kilometers or light-years.

SI is the standard measurement system for science

When scientists do research, they must communicate the results of their experiments with each other and agree on a system of units for their measurements. In 1960, an international committee agreed on a system of standards, such as the standard shown in **Figure 1-6,** and designations for the fundamental quantities needed for measurements. This system of units is called the Système International (SI). In SI, there are only seven base units, each describing a single dimension, such as length, mass, or time. The units of length, mass, and

Figure 1-6
The official standard kilogram mass is a platinum-iridium cylinder kept in a sealed container at the International Bureau of Weights and Measures at Sèvres, France.

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Table 1-2 SI standards

Unit	Original standard	Current standard
meter (length)	$\frac{1}{10\ 000\ 000}$ distance from equator to North Pole	the distance traveled by light in a vacuum in $3.33564095 \times 10^{-9}$ s
kilogram (mass)	mass of 0.001 cubic meters of water	the mass of a specific platinum-iridium alloy cylinder
second (time)	$\left(\frac{1}{60}\right)\left(\frac{1}{60}\right)\left(\frac{1}{24}\right) =$ 0.000 01574 average solar days	9 192 631 770 times the period of a radio wave emitted from a cesium-133 atom

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time are the meter, kilogram, and second, respectively. In most measurements, these units will be abbreviated as m, kg, and s, respectively.

These units are defined by the standards described in **Table 1-2** and are reproduced so that every meterstick, kilogram mass, and clock in the world is calibrated to give consistent results. We will use SI units throughout this book because they are almost universally accepted in science and industry.

Not every observation can be described using one of these units, but the units can be combined to form derived units. Derived units are formed by combining the seven base units with multiplication or division. For example, speeds are typically expressed in units of meters per second (m/s), with one unit divided by another unit.

In other cases, it may appear that a new unit that is not one of the base units is being introduced, but often these new units merely serve as shorthand ways to refer to combinations of units. For example, forces and weights are typically measured in units of newtons (N), but a newton is defined as being exactly equivalent to one kilogram multiplied by meters per second squared ($1 kg \bullet m/s^2$). Derived units, such as newtons, will be explained throughout this book as they are introduced.

Did you know?

NIST-7, an atomic clock at the National Institute of Standards and Technology in Colorado, is one of the most accurate timing devices in the world. As a public service, the Institute sends out radio transmissions 24 hours a day in order to broadcast the time given by the atomic clock.

SI uses prefixes to accommodate extremes

Physics is a science that describes a broad range of topics and requires a wide range of measurements, from very large to very small. For example, distance measurements can range from the distances between stars (about 100 000 000 000 000 000 m) to the distances between atoms in a solid (0.000 000 001 m). Because these numbers can be extremely difficult to read and write, they are often expressed in powers of 10, such as 1×10^{17} m or 1×10^{-9} m.

Another approach commonly used in SI is to combine the units with prefixes that symbolize certain powers of 10, as shown in **Figure 1-7.** The most

Figure 1-7
The mass of this mosquito can be expressed several different ways: 1×10^{-5} kg, 0.01 g, or 10 mg.

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Table 1-3
Some prefixes for powers of 10 used with metric units

Power	Prefix	Abbreviation	Power	Prefix	Abbreviation
10^{-18}	atto-	a	10^{-1}	deci-	d
10^{-15}	femto-	f	10^{1}	deka-	da
10^{-12}	pico-	p	10^{3}	kilo-	k
10^{-9}	nano-	n	10^{6}	mega-	M
10^{-6}	micro-	μ (Greek letter *mu*)	10^{9}	giga-	G
			10^{12}	tera-	T
10^{-3}	milli-	m	10^{15}	peta-	P
10^{-2}	centi-	c	10^{18}	exa-	E

Quick Lab

Metric Prefixes

MATERIALS LIST

- ✔ balance (0.01 g precision or better)
- ✔ 50 sheets of loose-leaf paper

Record the following measurements (with appropriate units and metric prefixes):

- the mass of a single sheet of paper
- the mass of exactly 10 sheets of paper
- the mass of exactly 50 sheets of paper

Use each of these measurements to determine the mass of a single sheet of paper. How many different ways can you express each of these measurements? Use your results to estimate the mass of one ream (500 sheets) of paper. How many ways can you express this mass? Which is the most practical approach? Give reasons for your answer.

common prefixes and their symbols are shown in **Table 1-3.** For example, the length of a housefly, 5×10^{-3} m, is equivalent to 5 millimeters (mm), and the distance of a satellite 8.25×10^{5} m from Earth's surface can be expressed as 825 kilometers (km). A year, which is 3.2×10^{7} s, can also be expressed as 32 megaseconds (Ms).

Converting a measurement from its prefix form is easy to do. You can build conversion factors from any equivalent relationship, including those in **Table 1-3,** such as 1.609 km = 1 mi and 3600 s = 1 h. Just put the quantity on one side of the equation in the numerator and the quantity on the other side in the denominator, as shown below for the case of the conversion 1 mm = 1×10^{-3} m. Because these two quantities are equal, the following equations are also true:

$$\frac{1\ \text{mm}}{10^{-3}\ \text{m}} = 1 \quad \text{and} \quad \frac{10^{-3}\ \text{m}}{1\ \text{mm}} = 1$$

Thus, any measurement multiplied by either one of these fractions will be multiplied by 1. The number and the unit will change, but the quantity described by the measurement will stay the same.

To convert measurements, use the conversion factor that will cancel with the units you are given to provide the units you need, as shown in the example below. Typically, the units to which you are converting should be placed in the numerator. It is useful to cross out units that cancel to help keep track of them.

$$\text{Units } \textit{don't} \text{ cancel: } 37.2\ \text{mm} \times \frac{1\ \text{mm}}{10^{-3}\ \text{m}} = 3.72 \times 10^{4}\ \frac{\text{mm}^2}{\text{m}}$$

$$\text{Units } \textit{do} \text{ cancel: } 37.2\ \cancel{\text{mm}} \times \frac{10^{-3}\ \text{m}}{1\ \cancel{\text{mm}}} = 3.72 \times 10^{-2}\ \text{m}$$

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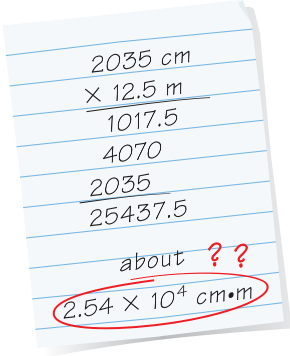
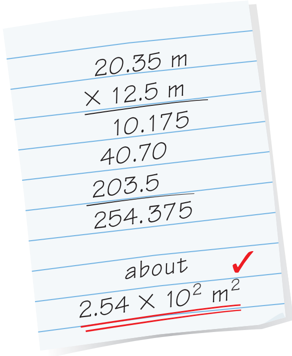
(a)

Figure 1-8
When determining area by multiplying measurements of length and width, be sure the measurements are expressed in the same units.

(b)



(c)



Both dimension and units must agree

Measurements of physical quantities must be expressed in units that match the dimensions of that quantity. For example, measurements of length cannot be expressed in units of kilograms because units of kilograms describe the dimension of mass. It is very important to be certain that a measurement is expressed in units that refer to the correct dimension. One good technique for avoiding errors in physics is to check the units in an answer to be certain they are appropriate for the dimension of the physical quantity that is being sought in a problem or calculation.

If several people make independent measurements of the same physical quantity, they may each use different units. As an example, consider **Figure 1-8(a),** which shows two people measuring a room to determine the area of carpet necessary to cover the floor. It is possible for one person to measure the length of the room in meters and for the other person to measure the width of the room in centimeters. When the numbers are multiplied to find the area, they will give a difficult-to-interpret answer in units of cm•m, as shown in **Figure 1-8(b).** On the other hand, if both measurements are made using the same units, the calculated area is much easier to intepret because it is expressed in units of m^2, as shown in **Figure 1-8(c).** Suppose that the measurements were made in different units, as in the example above. Because centimeters and meters are both units of length, one unit can be easily converted to the other. In order to avoid confusion, it is better to make the conversion to the same units before doing any more arithmetic.

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SAMPLE PROBLEM 1A

Metric prefixes

PROBLEM

A typical bacterium has a mass of about 2.0 fg. Express this measurement in terms of grams and kilograms.

SOLUTION

Given: mass = 2.0 fg

Unknown: mass = ? g mass = ? kg

Build conversion factors from the relationships given in **Table 1-3.** Two possibilities are shown below.

$$\frac{1 \times 10^{-15}\ \text{g}}{1\ \text{fg}} \text{ and } \frac{1\ \text{fg}}{1 \times 10^{-15}\ \text{g}}$$

Only the first one will cancel the units of femtograms to give units of grams.

$$(2.0\ \cancel{\text{fg}})\left(\frac{1 \times 10^{-15}\ \text{g}}{1\ \cancel{\text{fg}}}\right) = \boxed{2.0 \times 10^{-15}\ \text{g}}$$

Then, take this answer and use a similar process to cancel the units of grams to give units of kilograms.

$$(2.0 \times 10^{-15}\ \cancel{\text{g}})\left(\frac{1\ \text{kg}}{1 \times 10^{3}\ \cancel{\text{g}}}\right) = \boxed{2.0 \times 10^{-18}\ \text{kg}}$$

PRACTICE 1A

Metric prefixes

1. A human hair is approximately 50 μm in diameter. Express this diameter in meters.

2. A typical radio wave has a period of 1 μs. Express this period in seconds.

3. A hydrogen atom has a diameter of about 10 nm.

a. Express this diameter in meters.
b. Express this diameter in millimeters.
c. Express this diameter in micrometers.

4. The distance between the sun and the Earth is about 1.5×10^{11} m. Express this distance with an SI prefix and in kilometers.

5. The average mass of an automobile in the United States is about 1.440×10^{6} g. Express this mass in kilograms.

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ACCURACY AND PRECISION

Because theories are based on observation and experiment, careful measurements are very important in physics. But in reality, no measurement is perfect. In describing the imperfection, there are two factors to consider: a measurement's **accuracy** and a measurement's **precision.** Although these terms are often used interchangeably in everyday speech, they have specific meanings in a scientific discussion.

accuracy

describes how close a measured value is to the true value of the quantity measured

precision

refers to the degree of exactness with which a measurement is made and stated

Problems with accuracy are due to error

Experimental work is never free of error, but it is important to minimize error in order to obtain accurate results. Human error can occur, for example, if a mistake is made in reading an instrument or recording the results. One way to avoid human error is to take repeated measurements to be certain they are consistent.

If some measurements are taken using one method and some are taken using a different method, another type of error, called method error, will result. Method error can be greatly reduced by standardizing the method of taking measurements. For example, when measuring a length with a meterstick, choose a line of sight directly over what is being measured, as shown in **Figure 1-9(a).** If you are too far to one side, you are likely to overestimate or underestimate the measurement, as shown in **Figure 1-9(b)** and **(c).** This problem is due to the phenomenon known as *parallax.* Another example of parallax is the fact that the speedometer reading reported by a car's driver is more accurate than the speedometer reading as seen from the passenger seat in an automobile.

Another type of error is instrument error. If a meterstick or balance is not in good working order, this will introduce error into any measurements made with the device. For this reason, it is important to be careful with lab equipment. Rough handling can damage balances. If a wooden meterstick gets wet, it can warp, making accurate measurements difficult.

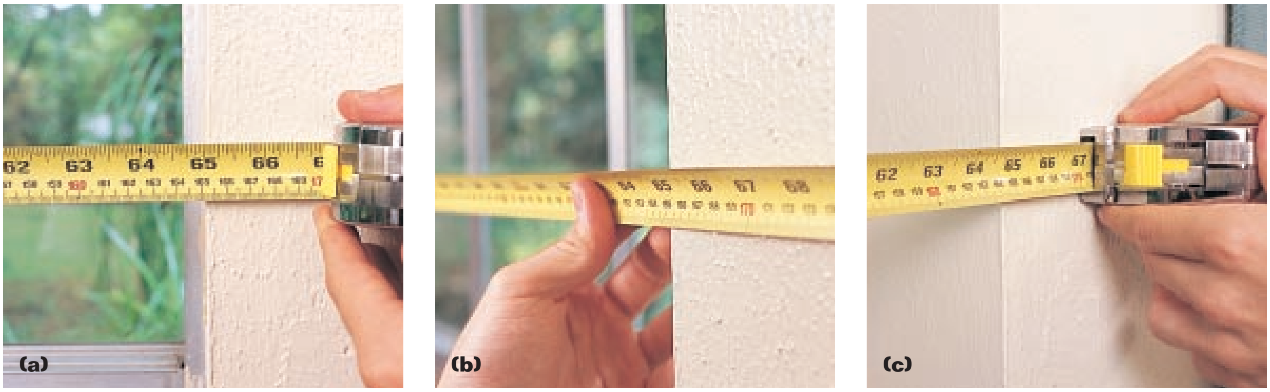

Figure 1-9
If you measure this window by keeping your line of sight directly over the measurement **(a),** you will find that it is 165.2 cm long. If you do not keep your eye directly above the mark, **(b)** and **(c),** you may report a measurement with some error.

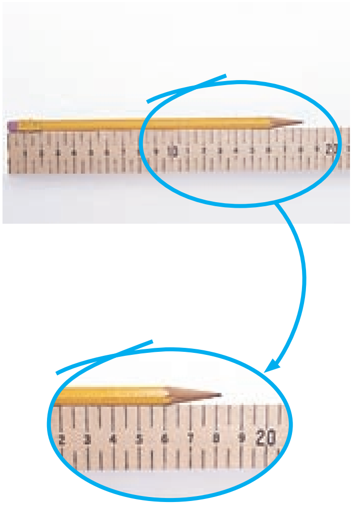

Figure 1-10
Even though this ruler is marked in only centimeters and half-centimeters, if you estimate, you can use it to report measurements to a precision of a millimeter.

Because the ends of a meterstick can be easily damaged or worn, it is best to minimize instrument error by making measurements with a portion of the scale that is in the middle of the meterstick. Instead of measuring from the end (0 cm), try measuring from the 10 cm line.

Precision describes the limitations of the measuring instrument

Poor accuracy involves errors that can often be corrected. On the other hand, precision describes how exact a measurement can possibly be. For example, a measurement of 1.325 m is more precise than a measurement of 1.3 m. A lack of precision is typically due to limitations of the measuring instrument and is not the result of human error or lack of calibration. For example, if a meterstick is divided only into centimeters, it will be difficult to measure something only a few millimeters thick with it.

In many situations, you can improve the precision of a measurement. This can be done by making a reasonable estimation of where the mark on the instrument would have been. Suppose that in a laboratory experiment you are asked to measure the length of a pencil with a meterstick marked in centimeters, as shown in **Figure 1-10.** The end of the pencil lies somewhere between 18 cm and 18.5 cm. The length you have actually measured is slightly more than 18 cm. You can make a reasonable estimation of how far between the two marks the end of the pencil is and add a digit to the end of the actual measurement. In this case, the end of the pencil seems to be less than half way between the two marks, so you would report the measurement as 18.2 cm.

Significant figures help keep track of imprecision

significant figures

those digits in a measurement that are known with certainty plus the first digit that is uncertain

It is important to record the precision of your measurements so that other people can understand and interpret your results. A common convention used in science to indicate precision is known as **significant figures.**

In the case of the measurement of the pencil as about 18.2 cm, the measurement has three significant figures. The significant figures of a measurement include all the digits that are actually measured (18 cm), plus one *estimated* digit. Note that the number of significant figures is determined by the precision of the markings on the measuring scale.

The last digit is reported as a 0.2 (for the estimated 0.2 cm past the 18 cm mark). Because this digit is an estimate, the true value for the measurement is actually somewhere between 18.15 cm and 18.25 cm.

When the last digit in a recorded measurement is a zero, it is difficult to tell whether the zero is there as a place holder or as a significant digit. For example, if a length is recorded as 230 mm, it is impossible to tell whether this number has two or three significant digits. In other words, it can be difficult to know whether the measurement of 230 mm means the measurement is known to be between 225 mm and 235 mm or is known more precisely to be between 229.5 mm and 230.5 mm.

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One way to solve such problems is to report all values using scientific notation. In scientific notation, the measurement is recorded to a power of 10, and all of the figures given are significant. For example, if the length of 230 cm has two significant figures, it would be recorded in scientific notation as 2.3×10^2 cm. If it has three significant figures, it would be recorded as 2.30×10^2 cm.

Scientific notation is also helpful when the zero in a recorded measurement appears in front of the measured digits. For example, a measurement such as 0.000 15 cm should be expressed in scientific notation as 1.5×10^{-4} cm if it has two significant figures. The three zeros between the decimal point and the digit 1 are not counted as significant figures because they are present only to locate the decimal point and to indicate the order of magnitude. The rules for determining how many significant figures are in a measurement that includes zeros are shown in **Table 1-4.**

Figure 1-11
If a mountain's height is known with an uncertainty of 5 m, the addition of 0.20 m of rocks will not appreciably change the height.

Significant figures in calculations require special rules

In calculations, the number of significant figures in your result depends on the number of significant figures in each measurement. For example, if someone reports that the height of a mountaintop, like the one shown in **Figure 1-11,** is 1710 m, that implies that its actual height is between 1705 and 1715 m. If another person builds a pile of rocks 0.20 m high on top of the mountain, that would not suddenly make the mountain's new height known accurately enough to be measured as 1710.20 m. The final answer cannot be more precise than the least precise measurement used to find the answer. Therefore, the answer should be rounded off to 1710 m even if the pile of rocks is included.

Table 1-4 Rules for determining whether zeros are significant figures

Rule	Examples
1. Zeros between other nonzero digits are significant.	**a.** 50.3 m has three significant figures. **b.** 3.0025 s has five significant figures.
2. Zeros in front of nonzero digits are not significant.	**a.** 0.892 kg has three significant figures. **b.** 0.0008 ms has one significant figure.
3. Zeros that are at the end of a number and also to the right of the decimal are significant.	**a.** 57.00 g has four significant figures. **b.** 2.000 000 kg has seven significant figures.
4. Zeros at the end of a number but to the left of a decimal are significant if they have been measured or are the first estimated digit; otherwise, they are *not* significant. In this book, they will be treated as *not* significant.	**a.** 1000 m may contain from one to four significant figures, depending on the precision of the measurement, but in this book it will be assumed that measurements like this have one significant figure. **b.** 20 m may contain one or two significant figures, but in this book it will be assumed to have one significant figure.

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Similar rules apply to multiplication. Suppose that you calculate the area of a room by multiplying the width and length. If the room's dimensions are 4.6 m by 6.7 m, the product of these values would be 30.82 m^2. However, this answer contains four significant figures, which implies that it is more precise than the measurements of the length and width. Because the room could be as small as 4.55 m by 6.65 m or as large as 4.65 m by 6.75 m, the area of the room is known only to be between 30.26 m^2 and 31.39 m^2. The area of the room can have only two significant figures because each measurement has only two. So it must be rounded off to 31 m^2. **Table 1-5** summarizes the two basic rules for determining significant figures when you are performing calculations.

Table 1-5 Rules for calculating with significant figures

Type of calculation	Rule	Example
addition or subtraction	The final answer should have the same number of digits to the right of the decimal as the measurement with the *smallest* number of digits *to the right of the decimal.*	97.3 + 5.85 = 103.15 $\xrightarrow{\text{round off}}$ 103.2
multiplication or division	The final answer has the same number of significant figures as the measurement having the *smallest* number of *significant figures.*	123 × 5.35 = 658.05 $\xrightarrow{\text{round off}}$ 658

Calculators do not pay attention to significant figures

When you use a calculator to analyze problems or measurements, you may be able to save time because the calculator can do the math more quickly than you. However, the calculator does not keep track of the significant figures in your measurements.

Calculators often exaggerate the precision of your final results by returning answers with as many digits as the display can show. To reinforce the correct approach, the answers to the sample problems in this book will always show only the number of significant figures that the measurements justify.

In order to provide answers with the correct number of significant figures, it will sometimes be necessary to round the results of a calculation. The rules described in **Table 1-6** will be used. In this book, the results of a calculation will be rounded after each type of mathematical operation. For example, the result of a series of multiplications should be rounded using the multiplication/division rule before it is added to another number. Similarly, the sum of several numbers should be rounded according to the addition/subtraction rule before the sum is multiplied by another number. You should consult your teacher to find out whether to round this way or to delay rounding until the end of all calculations.

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Table 1-6 Rules for rounding

What to do	When to do it	Examples
round down	• whenever the digit following the last significant figure is a 0, 1, 2, 3, or 4	30.24 becomes 30.2
	• if the last significant figure is an even number and the next digit is a 5, with no other nonzero digits	32.25 becomes 32.2 32.65000 becomes 32.6
round up	• whenever the digit following the last significant figure is a 6, 7, 8, or 9	22.49 becomes 22.5
	• if the digit following the last significant figure is a 5 followed by a nonzero digit	54.7511 becomes 54.8
	• if the last significant figure is an odd number and the next digit is a 5, with no other nonzero digits	54.75 becomes 54.8 79.3500 becomes 79.4

Section Review

1. Which SI units would you use for the following measurements?

a. the length of a swimming pool

b. the mass of the water in the pool

c. the time it takes a swimmer to swim a lap

2. Express the following measurements as indicated.

a. 6.20 mg in kilograms

b. 3×10^{-9} s in milliseconds

c. 88.0 km in meters

3. The following students measure the density of a piece of lead three times. The density of lead is actually 11.34 g/cm^3. Considering all of the results, which person's results were accurate? Which were precise? Were any both accurate and precise?

a. Rachel: 11.32 g/cm^3, 11.35 g/cm^3, 11.33 g/cm^3

b. Daniel: 11.43 g/cm^3, 11.44 g/cm^3, 11.42 g/cm^3

c. Leah: 11.55 g/cm^3, 11.34 g/cm^3, 11.04 g/cm^3

4. Perform these calculations, following the rules for significant figures.

a. $26 \times 0.02584 = ?$

b. $15.3 \div 1.1 = ?$

c. $782.45 - 3.5328 = ?$

d. $63.258 + 734.2 = ?$

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1-3
The language of physics

1-3 SECTION OBJECTIVES

- **Interpret data in tables and graphs, and recognize equations that summarize data.**
- **Distinguish between conventions for abbreviating units and quantities.**
- **Use dimensional analysis to check the validity of expressions.**
- **Perform order-of-magnitude calculations.**

MATHEMATICS AND PHYSICS

Just as physicists create simplified models to better understand the real world, they use the tools of mathematics to analyze and summarize their observations. Then they can use the mathematical relationships among physical quantities to help predict what will happen in new situations.

Tables, graphs, and equations can make data easier to understand

There are many ways to organize data. Consider the experiment shown in **Figure 1-12,** which tests Galileo's hypothesis by dropping a table-tennis ball and a golf ball in a vacuum and measuring how far each ball falls during a certain time interval. The results are recorded as a set of numbers corresponding to the times of the fall and the distance each ball falls. A convenient way to analyze the data is to form a table like **Table 1-7.** A clear trend can be seen in the data. The more time that passes after each ball is dropped, the farther the ball falls.

Table 1-7 Data from dropped-ball experiment

Time (s)	Distance golf ball falls (cm)	Distance table-tennis ball falls (cm)
0.067	2.20	2.20
0.133	8.67	8.67
0.200	19.60	19.59
0.267	34.93	34.92
0.333	54.34	54.33
0.400	78.40	78.39

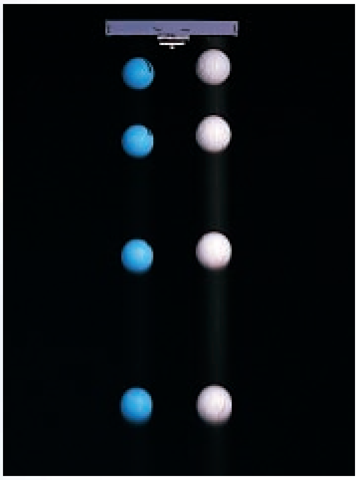

Figure 1-12
This experiment tests Galileo's hypothesis by having two balls with different masses dropped simultaneously.

A better method for analyzing the data is to construct a graph of the distance the balls fall in each time interval, as shown in **Figure 1-13** on the next page. Using the graph, you can reconstruct the table by noting the values along the distance and time axes for each of the points shown.

In addition, because the graph shows an obvious pattern, we can draw a smooth curve through the data points to make estimations for times when we have no data, such as 0.225 s. The shape of the graph also provides information about the relationship between time and distance.

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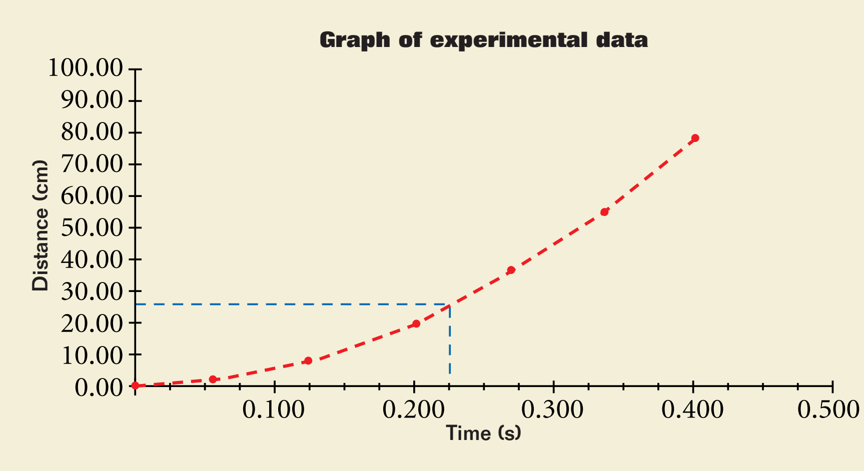

Figure 1-13
The graph of these data provides a convenient way to summarize the data and indicate the relationship between the time an object has been falling and the distance it has fallen.

We can also use the following equation to describe the relationship between the variables in the experiment:

$$\text{(change in position in meters)} = 4.9 \times \text{(time of fall in seconds)}^2$$

This equation allows you to reproduce the graph and make predictions about the change in position for any arbitrary time during the fall.

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Physics equations indicate relationships

While mathematicians use equations to describe relationships between variables, physicists use the tools of mathematics to describe measured or predicted relationships between physical quantities in a situation. For example, one or more variables may affect the outcome of an experiment. In the case of a prediction, the physical equation is a compact statement based on a model of the situation. It shows how two or more variables are thought to be related. Many of the most important equations in physics do not contain numbers. Instead, they represent a simple description of the relationship between physical quantities.

To make expressions as simple as possible, physicists often use letters to describe specific quantities in an equation. For example, the letter v is used to denote speed. Sometimes, Greek letters are used to describe mathematical operations. For example, the Greek letter Δ (delta) is often used to mean "difference or change in," and the Greek letter Σ (sigma) is used to mean "sum" or "total."

With these conventions, the word equation above can be written as follows:

$$\Delta y = 4.9(\Delta t)^2$$

The abbreviation Δy indicates the change in a ball's position from its starting point, and Δt indicates the time elapsed.

As you saw in Section 1-2, the units in which these quantities are measured are also often abbreviated with symbols consisting of a letter or two. Most physics books provide some clues to help you keep track of which letters refer to quantities and variables and which letters are used to indicate units. Typically,

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CONCEPT PREVIEW

The differences between quantities denoted with boldfaced symbols and those denoted with italicized symbols will be further described in Chapter 3.

variables and other specific quantities are abbreviated with letters that are **boldfaced** or *italicized.* Units are abbreviated with regular letters (sometimes called roman letters). Some examples of variable symbols and the abbreviations for the units that measure them are shown in **Table 1-8.**

As you continue to study physics, carefully note the introduction of new variable quantities, and recognize which units go with them. The tables provided in Appendix A can help you keep track of these abbreviations.

Table 1-8 Abbreviations for variables and units

Quantity	Symbol	Units	Unit abbreviations
change in position	Δx, Δy	meters	m
time interval	Δt	seconds	s
mass	m	kilograms	kg

EVALUATING PHYSICS EXPRESSIONS

Like most models physicists build to describe the world around them, physics equations are valid only if they can be used to make predictions about situations. Although an experiment is the best way to test the validity of a physics expression, several techniques can be used to evaluate whether expressions are likely to be valid.

Dimensional analysis can weed out invalid equations

Suppose a car, such as the one in **Figure 1-14,** is moving at a speed of 88 km/h and you want to know how long it will take it to travel 725 km. How can you decide a good way to solve the problem?

Figure 1-14
Dimensional analysis can be a useful check for many types of problems, including those involving the length of time it would take for this car to travel 725 km if it moves with a speed of 88 km/h.

You can use a powerful procedure called *dimensional analysis.* Dimensional analysis makes use of the fact that *dimensions can be treated as algebraic quantities.* For example, quantities can be added or subtracted only if they have the same dimensions, and the two sides of any given equation must have the same dimensions.

Let us apply this technique to the problem of the car moving at a speed of 88 km/h. This measurement is given in dimensions of length over time. The total distance traveled has the dimension of length. Multiplying these numbers together gives the dimensions indicated below. Clearly, the result of this calculation does not have the dimensions of time, which is what you are trying to calculate. That is,

$$\frac{\text{length}}{\text{time}} \times \text{length} = \frac{\text{length}^2}{\text{time}} \text{ or } \frac{88 \text{ km}}{1.0 \text{ h}} \times 725 \text{ km} = \frac{6.4 \times 10^4 \text{ km}^2}{1.0 \text{ h}}$$

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To calculate an answer that will have the dimension of time, you should take the distance and *divide* it by the speed of the car, as follows:

$$\text{length} \div \frac{\text{length}}{\text{time}} = \frac{\cancel{\text{length}} \times \text{time}}{\cancel{\text{length}}} = \text{time} \qquad \frac{725 \cancel{\text{km}} \times 1.0 \text{ h}}{88 \cancel{\text{km}}} = 8.2 \text{ h}$$

In a very simple example like this one, you might be able to solve the problem without dimensional analysis. But in more-complicated situations, dimensional analysis is a wise first step that can often save you a great deal of time.

Order-of-magnitude estimations check answers

Because the scope of physics is so wide and the numbers may be astronomically large or subatomically small, it is often useful to estimate an answer to a problem before trying to solve the problem exactly. This kind of estimate is called an *order-of-magnitude* calculation, which means determining the power of 10 that is closest to the actual numerical value of the quantity. Once you have done this, you will be in a position to judge whether the answer you get from a more exacting procedure is correct.

For example, consider the car trip described in the discussion of dimensional analysis. We must divide the distance by the speed to find the time. The distance, 725 km, is closer to 10^3 km (or 1000 km) than to 10^2 km (or 100 km), so we use 10^3 km. The speed, 88 km/h, is about 10^2 km/h (or 100 km/h).

$$\frac{10^3 \cancel{\text{km}}}{10^2 \cancel{\text{km}}/\text{h}} = 10 \text{ h}$$

This estimate indicates that the answer should be closer to 10 than to 1 or to 100 (or 10^2). If you perform the calculation, you will find that the correct answer is 8.2 h, which certainly fits this range.

Order-of-magnitude estimates can also be used to estimate numbers in situations in which little information is given. For example, how could you estimate how many gallons of gasoline are used annually by all of the cars in the United States?

First, consider that the United States has about 250 million people. Assuming that each family of about five people has a car, an estimate of the number of cars in the country is 50 million.

Next, decide the order of magnitude of the average distance each car travels every year. Some cars travel as few as 1000 mi per year, while others travel more than 100 000 mi per year. The appropriate order of magnitude to include in the estimate is 10 000 mi, or 10^4 mi, per year.

If we assume that cars average 20 mi for every gallon of gas, each car needs about 500 gal per year.

$$\left(\frac{10\ 000 \cancel{\text{mi}}}{1 \text{ year}}\right)\left(\frac{1 \text{ gal}}{20 \cancel{\text{mi}}}\right) = 500 \text{ gal/year for each car}$$

Did you know?

The physicist Enrico Fermi made the first nuclear reactor at the University of Chicago in 1942. Fermi was also well known for his ability to make quick order-of-magnitude calculations, such as estimating the number of piano tuners in New York City.

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Consumer Focus

A Billion Burgers, a Trillion M&M's?

You have seen the signs before. "Billions of Hamburgers Sold." "Over a Million Satisfied Customers." These are pretty large numbers. Who counted all of those burgers and customers? Can these claims be trusted?

For most large numbers, such as the number of stars in the universe, the exact quantity is not known. Nobody really needs the exact number of burgers, customers, or stars, so no one is paid to make an exact count. Typically, these numbers are estimates from other data, such as the amount of raw materials consumed, the sales income of a company, or the number of stars in a very small patch of sky.

To see how this works, consider M&M's™ chocolate candies. How many of these candies have been eaten over all of time? According to the head office of Mars, Inc., the manufacturer of M&M's candies, "well over 100 million candies a day have been consumed" for the last 10 years. To keep up with this rate of consumption, 10 years (3650 days) would require the production of the following number of candies:

$$\frac{10^8 \text{ candies}}{\text{day}} \times (3.6 \times 10^3 \text{ days}) = 3.6 \times 10^{11} \text{ candies}$$

M&M's candies have been produced in large quantities since 1942. Assuming that the average production rate for each decade is at least half the amount for the last 10 years, we can say that more than 1.3×10^{12}, or 1 trillion, M&M's candies have been eaten over time.

But if no one is counting, can you be sure these claims are reasonable? You can test the validity of these claims by making an order-of-magnitude estimate of what this would mean for a single person and deciding whether it seems reasonable.

Is it reasonable to assume that over 100 million M&M's candies are eaten every day? First consider how many people are likely to be consuming these candies. The population of the United States is about 250 million people. Not all people in the United States eat M&M's candies, but these candies are also sold in many other countries, so a number like 200 million potential consumers seems about right.

Next, examine these numbers on a per-person (or *per capita*) basis by dividing the number eaten per day by the number of people who do the eating.

$$\frac{10^8 \text{ candies/day}}{2 \times 10^8 \text{ people}} = 0.5 \text{ candies per day per person}$$

Is it likely that 200 million people would carefully cut their M&M's candies in half? No, this number is an average over the period of one day. Instead of considering the average per day, it may be more appropriate to consider a longer period of time, like a month. Certainly it is possible to imagine a typical consumer eating 15 candies during a month. This would mean that the average consumer would consume a regular-sized packet every three months or so.

Thus, the claim that 100 million M&M's candies are eaten daily seems reasonable based on the estimates. Breaking large numbers like this down in terms of *per capita* consumption can help identify whether they are reasonable.

Multiplying this by the estimate of the total number of cars in the United States gives an annual consumption of more than 2×10^{10} gallons.

$$(5 \times 10^7 \cancel{\text{cars}})\left(\frac{500 \text{ gal}}{1 \cancel{\text{car}}}\right) = 2.5 \times 10^{10} \text{ gal}$$

This corresponds to a yearly consumer expenditure of more than $20 billion! Even so, this estimate may be low because we haven't accounted for commercial consumption and two-car families.

Section Review

1. Which of the following graphs best matches the data shown below?

Volume of air (m^3)	Mass of air (kg)
0.50	0.644
1.50	1.936
2.25	2.899
4.00	5.159
5.50	7.096

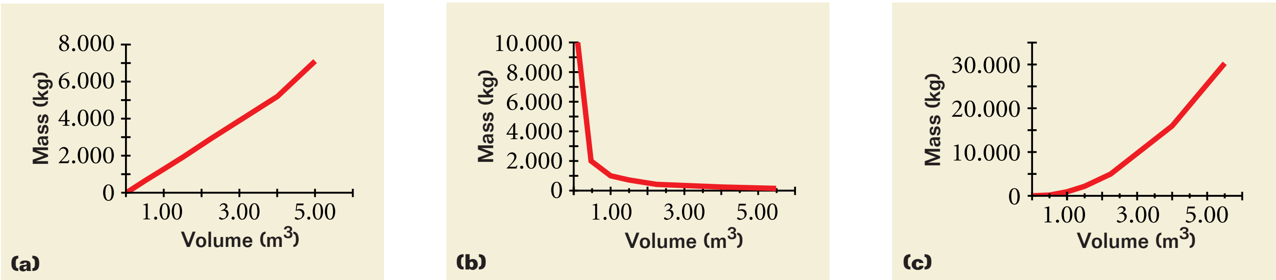

Figure 1-15

2. Which of the following equations best matches the data from item 1?

a. $(\text{mass})^2 = 1.29$ (volume) **b.** (mass)(volume) = 1.29
c. mass = 1.29 (volume) **d.** $\text{mass} = 1.29 (\text{volume})^2$

3. Indicate which of the following physics symbols denote units and which denote variables or quantities.

a. C **b.** *c* **c.** *C* **d.** *t* **e.** T **f.** *T*

4. Determine the units of the quantity described by the following combinations of units:

a. kg (m/s) (1/s) **b.** $(\text{kg/s})(\text{m/s}^2)$
c. $(\text{kg/s})(\text{m/s})^2$ **d.** (kg/s) (m/s)

5. Which of the following is the best order of magnitude estimate in meters of the height of a mountain?

a. 1 m **b.** 10 m **c.** 100 m **d.** 1000 m

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CHAPTER 1
Summary

KEY TERMS

accuracy (p. 15)

controlled experiment (p. 9)

model (p. 6)

precision (p. 15)

significant figures (p. 16)

system (p. 7)

KEY IDEAS

Section 1-1 What is physics?

- Physics is the study of the physical world, from motion and energy to light and electricity.
- Physics uses the scientific method to discover general laws that can be used to make predictions about a variety of situations.
- A common technique in physics for analyzing a complex situation is to disregard irrelevant factors and create a model that describes the essence of a system or situation.

Section 1-2 Measurements in experiments

- Physics measurements are typically made and expressed in SI, a system that uses a set of base units and prefixes to describe measurements of physical quantities.
- *Accuracy* describes how close a measurement is to reality. *Precision* results from the limitations of the measuring device used.
- Significant figures are used to indicate which digits in a measurement are actual measurements and which are estimates.
- Significant-figure rules provide a means to ensure that calculations do not report results that are more precise than the data used to make them.

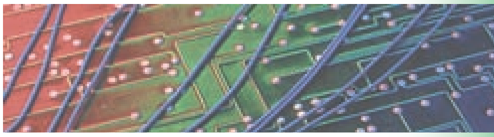
Section 1-3 The language of physics

- Physicists make their work easier by summarizing data in tables and graphs and by abbreviating quantities in equations.
- Dimensional analysis can help identify whether a physics expression is a valid one.
- Order-of-magnitude calculations provide a quick way to evaluate the appropriateness of an answer.

Variable symbols

Quantities		Units	
Δx, Δy	change in position	m	meters
Δt	time interval	s	seconds
m	mass	kg	kilograms

CHAPTER 1
Review and Assess



THE SCIENCE OF PHYSICS

Review questions

1. Refer to **Table 1-1** on page 5 to identify at least two areas of physics involved in the following:

- **a.** building a louder stereo system in your car
- **b.** bungee jumping
- **c.** judging how hot a stove burner is by looking at it
- **d.** cooling off on a hot day by diving into a swimming pool

2. Which of the following scenarios fit the approach of the scientific method?

- **a.** An auto mechanic listens to how a car runs and comes up with an idea of what might be wrong. The mechanic tests the idea by adjusting the idle speed. Then the mechanic decides his idea was wrong based on this evidence. Finally, the mechanic decides the only other problem could be the fuel pump, and he consults with the shop's other mechanics about his conclusion.
- **b.** Because of a difference of opinions about where to take the class trip, the class president holds an election. The majority of the students decide to go to the amusement park instead of to the shore.
- **c.** Your school's basketball team has advanced to the regional playoffs. A friend from another school says their team will win because their players want to win more than your school's team does.
- **d.** A water fountain does not squirt high enough. The handle on the fountain seems loose, so you try to push the handle in as you turn it. When you do this, the water squirts high enough that you can get a drink. You make sure to tell all your friends how you did it.

3. You have decided to select a new car by using the scientific method. How might you proceed?

4. Consider the phrase, "The quick brown fox jumped over the lazy dog." Which details of this situation would a physicist who is modeling the path of a fox ignore?

SI UNITS

Review questions

5. List an appropriate SI base unit (with a prefix as needed) for measuring the following:

- **a.** the time it takes to play a CD in your stereo
- **b.** the mass of a sports car
- **c.** the length of a soccer field
- **d.** the diameter of a large pizza
- **e.** the mass of a single slice of pepperoni
- **f.** a semester at your school
- **g.** the distance from your home to your school
- **h.** your mass
- **i.** the length of your physics lab room
- **j.** your height

6. If you square the speed expressed in meters per second, in what units will the answer be expressed?

7. If you divide a force measured in newtons (1 newton = 1 kg•m/s^2) by a speed expressed in meters per second, in what units will the answer be expressed?

Conceptual questions

8. The height of a horse is sometimes given in units of "hands." Why was this a poor standard of length before it was redefined to refer to exactly 4 in.?

9. Explain the advantages in having the meter officially defined in terms of the distance light travels in a given time rather than as the length of a specific metal bar.

10. Einstein's famous equation indicates that $E = mc^2$, where c is the speed of light and m is the object's mass. Given this, what is the SI unit for E?

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Practice problems

11. Express each of the following as indicated:

a. 2 dm expressed in millimeters
b. 2 h 10 min expressed in seconds
c. 16 g expressed in micrograms
d. 0.75 km expressed in centimeters
e. 0.675 mg expressed in grams
f. 462 μm expressed in centimeters
g. 35 km/h expressed in meters per second

(See Sample Problem 1A.)

12. Use the SI prefixes in **Table 1-3** on page 12 to convert these *hypothetical* units of measure into appropriate quantities:

a. 10 rations
b. 2000 mockingbirds
c. 10^{-6} phones
d. 10^{-9} goats
e. 10^{18} miners

(See Sample Problem 1A.)

13. Use the fact that the speed of light in a vacuum is about 3.00×10^8 m/s to determine how many kilometers a pulse from a laser beam travels in exactly one hour.
(See Sample Problem 1A.)

14. If a metric ton is 1.000×10^3 kg, how many 85 kg people can safely occupy an elevator that can hold a maximum mass of exactly 1 metric ton?
(See Sample Problem 1A.)

ACCURACY, PRECISION, AND SIGNIFICANT FIGURES

Review questions

15. Can a set of measurements be precise but not accurate? Explain.

16. How many significant figures are in the following measurements?

a. 300 000 000 m/s
b. 25.030°C
c. 0.006 070°C
d. 1.004 J
e. 1.305 20 MHz

17. **Figure 1-16** shows photographs of unit conversions on the labels of some grocery-store items. Check the accuracy of these conversions. Are the manufacturers using significant figures correctly?

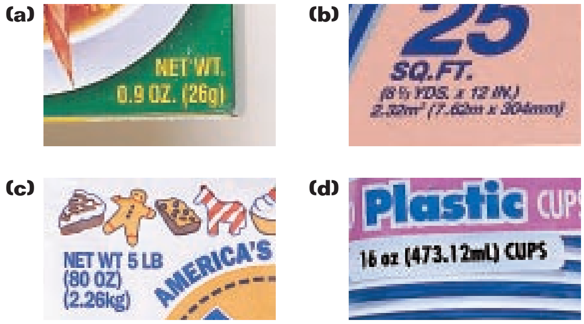

Figure 1-16

18. The value of the speed of light is now known to be $2.997\,924\,58 \times 10^8$ m/s. Express the speed of light in the following ways:

a. with three significant figures
b. with five significant figures
c. with seven significant figures

19. How many significant figures are there in the following measurements?

a. 78.9 ± 0.2 m
b. 3.788×10^9 s
c. 2.46×10^6 kg
d. 0.0032 mm

20. Carry out the following arithmetic operations:

a. find the sum of the measurements 756 g, 37.2 g, 0.83 g, and 2.5 g
b. find the quotient of 3.2 m/3.563 s
c. find the product of 5.67 mm $\times\ \pi$
d. find the difference of 27.54 s and 3.8 s

21. A fisherman catches two sturgeons. The smaller of the two has a measured length of 93.46 cm (two decimal places and four significant figures), and the larger fish has a measured length of 135.3 cm (one decimal place and four significant figures). What is the total length of the two fish?

22. A farmer measures the distance around a rectangular field. The length of each long side of the rectangle is found to be 38.44 m, and the length of each short side is found to be 19.5 m. What is the total distance around the field?

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DIMENSIONAL ANALYSIS AND ORDER-OF-MAGNITUDE ESTIMATES

Review questions

Note: In developing answers to order-of-magnitude calculations, you should state your important assumptions, including the numerical values assigned to parameters used in the solution. Since only order-of-magnitude results are expected, do not be surprised if your results differ from those of other students.

23. Suppose that two quantities, A and B, have different dimensions. Which of the following arithmetic operations *could* be physically meaningful?

a. $A + B$
b. A/B
c. $A \times B$
d. $A - B$

24. Estimate the order of magnitude of the length in meters of each of the following:

a. a ladybug
b. your leg
c. your school building
d. a giraffe
e. a city block

25. If an equation is dimensionally correct, does this mean that the equation is true?

26. The radius of a circle inscribed in any triangle whose sides are a, b, and c is given by the following equation, in which s is an abbreviation for $(a + b + c) \div 2$. Check this formula for dimensional consistency.

$$r = \sqrt{\frac{(s-a)(s-b)(s-c)}{s}}$$

27. The period of a simple pendulum, defined as the time necessary for one complete oscillation, is measured in time units and is given by the equation

$$T = 2\pi\sqrt{\frac{L}{g}}$$

where L is the length of the pendulum and g is the acceleration due to gravity, which has units of length divided by time squared. Check this equation for dimensional consistency.

Conceptual questions

28. In a desperate attempt to come up with an equation to solve a problem during an examination, a student tries the following: (velocity in m/s)^2 = (acceleration in m/s^2) × (time in s). Use dimensional analysis to determine whether this equation might be valid.

29. Estimate the number of breaths taken during 70 years, the average life span of a person.

30. Estimate the number of times your heart beats in an average day.

31. Estimate the magnitude of your age, as measured in units of seconds.

32. An automobile tire is rated to last for 50 000 mi. Estimate the number of revolutions the tire will make in its lifetime.

33. Imagine that you are the equipment manager of a professional baseball team. One of your jobs is to keep a supply of baseballs for games in your home ballpark. Balls are sometimes lost when players hit them into the stands as either home runs or foul balls. Estimate how many baseballs you have to buy per season in order to make up for such losses. Assume your team plays an 81-game home schedule in a season.

34. A chain of hamburger restaurants advertises that it has sold more than 50 billion hamburgers over the years. Estimate how many pounds of hamburger meat must have been used by the restaurant chain to make 50 billion hamburgers and how many head of cattle were required to furnish the meat for these hamburgers.

35. Estimate the number of piano tuners living in New York City (The population of New York City is approximately 8 million). This problem was first proposed by the physicist Enrico Fermi, who was well known for his ability to quickly make order-of-magnitude calculations.

36. Estimate the number of table-tennis balls that would fit (without being crushed) into a room that is 4 m long, 4 m wide, and 3 m high. Assume that the diameter of a ball is 3.8 cm.

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MIXED REVIEW PROBLEMS

37. Calculate the circumference and area for the following circles. (Use the following formulas: circumference = $2\pi r$ and area = πr^2.)

a. a circle of radius 3.5 cm

b. a circle of radius 4.65 cm

38. A billionaire offers to give you \$5 billion if you will count out the amount in \$1 bills or a lump sum of \$5000. Which offer should you accept? Explain your answer. (Assume that you can count at an average rate of one bill per second, and be sure to allow for the fact that you need about 10 hours a day for sleeping and eating. Your answer does not need to be limited to one significant figure.)

39. Exactly 1 quart of ice cream is to be made in the form of a cube. What should be the length of one side in meters for the container to have the appropriate volume? (Use the following conversion: 4 qt = 3.786×10^{-3} m^3)

40. You can obtain a rough estimate of the size of a molecule with the following simple experiment: Let a droplet of oil spread out on a fairly large but smooth water surface. The resulting "oil slick" that forms on the surface of the water will be approximately one molecule thick. Given an oil droplet with a mass of 9.00×10^{-7} kg and a density of 918 kg/m^3 that spreads out to form a circle with a radius of 41.8 cm on the water surface, what is the approximate diameter of an oil molecule?

Technology & Learning

Graphing calculators

Refer to Appendix B for instructions on downloading programs for your calculator. The program "Chap1" allows you to analyze the relationship between the mass and length of three wires, each made of a different substance.

All three wires have a diameter of 0.50 cm. Because the wires have the same diameter, their cross-sectional areas are the same. As for any circle, this area is equal to πr^2. Using this area, the wires can be described by the following equations:

$$Y_1 = 8.96X^* \pi(0.25)^2$$
$$Y_2 = 2.70X^* \pi(0.25)^2$$
$$Y_3 = 10.49X^* \pi(0.25)^2$$

In these equations, X represents the length of the wire in centimeters. Note that X is multiplied by a different factor in each equation. This factor signifies the mass per unit volume, or *density,* of the substance.

a. Assuming the density is in units of grams per centimeter, use dimensional analysis to determine the units of Y.

Press [PRGM], and scroll down to "Chap1" by pressing [▼]. Press [ENTER] to execute the program.

Press [ENTER] twice to begin graphing. The calculator will display three lines. Each line represents one type of wire. The mass of the wire in grams is plotted on the *y*-axis, and the length of the wire in centimeters is plotted on the *x*-axis.

The calculator is already in [TRACE] mode; a blinking cursor should be visible on the central line. Press [◄] to move along this line. Press [►] to move from one line to another. The equation for the line being traced appears in the top left corner of the screen. The values corresponding to the placement of the cursor appear at the bottom left corner. Use these values to complete the following exercises.

Find the approximate masses of each kind of wire at the following lengths:

b. 0.3 cm

c. 5.2 cm

d. 7.3 cm

e. Assuming equal size, does a larger or smaller density correspond to a larger mass?

Press [ENTER] and [CLEAR] to end.

41. An ancient unit of length called the cubit was equal to approximately 50 centimeters, which is, of course, approximately .50 meters. It has been said that Noah's ark was 300 cubits long, 50 cubits wide, and 30 cubits high. Estimate the volume of the ark in cubic meters. Also estimate the volume of a typical home, and compare it with the ark's volume.

42. If one micrometeorite (a sphere with a diameter of 1.0×10^{-6} m) struck each square meter of the moon each second, it would take many years to cover the moon with micrometeorites to a depth of 1.0 m. Consider a cubic box, 1.0 m on a side, on the moon. Find how long it would take to completely fill the box with micrometeorites.

43. One cubic centimeter ($1.0\ cm^3$) of water has a mass of 1.0×10^{-3} kg at 25°C. Determine the mass of $1.0\ m^3$ of water at 25°C.

44. Assuming biological substances are 90 percent water and the density of water is $1.0 \times 10^3\ kg/m^3$, estimate the masses (density multiplied by volume) of the following:

a. a spherical cell with a diameter of 1.0 μm (volume $= \frac{4}{3}\pi r^3$)

b. a fly, which can be approximated by a cylinder 4.0 mm long and 2.0 mm in diameter (volume $= \ell \pi r^2$)

45. The radius of the planet Saturn is 5.85×10^7 m, and its mass is 5.68×10^{26} kg.

a. Find the density of Saturn (its mass divided by its volume) in grams per cubic centimeter. (The volume of a sphere is given by $\frac{4}{3}\pi r^3$.)

b. Find the surface area of Saturn in square meters. (The surface area of a sphere is given by $4\pi r^2$.)

Alternative Assessment

Performance assessment

1. Imagine that you are a member of your state's highway board. In order to comply with a bill passed in the state legislature, all of your state's highway signs must show distances in miles and kilometers. Two plans are before you. One plan suggests adding metric equivalents to all highway signs as follows: Dallas 300 mi (483 km). Proponents of the other plan say that the first plan makes the metric system seem more cumbersome, so they propose replacing the old signs with new signs every 50 km as follows: Dallas 300 km (186 mi). Participate in a class debate about which plan should be followed.

2. Can you measure the mass of a five-cent coin with a bathroom scale? Record the mass in grams displayed by your scales as you place coins on the scales, one at a time. Then divide each measurement by the number of coins to determine the approximate mass of a single five-cent coin, but remember to follow the rules for significant figures in calculations. Which estimate do you think is the most accurate? Which is the most precise?

Portfolio projects

3. Find out who were the Nobel laureates for physics last year, and research their work. Alternatively, explore the history of the Nobel Prizes. Who founded the awards? Why? Who delivers the award? Where? Document your sources and present your findings in a brochure, poster, or presentation.

4. You have a clock with a second hand, a ruler marked in millimeters, a graduated cylinder marked in milliliters, and scales sensitive to 1 mg. How would you measure the mass of a drop of water? How would you measure the period of a swing? How would you measure the volume of a paper clip? How can you improve the accuracy of your measurements? Write the procedures clearly so that a partner can follow them and obtain reasonable results.

5. Create a poster or other presentation depicting the possible ranges of measurement for a dimension, such as distance, time, temperature, speed, or mass. Depict examples ranging from the very large to the very small. Include several examples that are typical of your own experiences.

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CHAPTER 1
Laboratory Exercise A

OBJECTIVES

- Use typical laboratory equipment to make accurate measurements.
- Measure length and mass in SI units.
- Determine the appropriate number of significant figures for various measurements and calculations.
- Examine the relationships between measured physical quantities using graphs and data analysis.

MATERIALS LIST

- ✔ **2 rectangular wooden blocks**
- ✔ **15 cm metric ruler**
- ✔ **balance**
- ✔ **meterstick**

PHYSICS AND MEASUREMENT

In this laboratory exercise, you will gain experience making measurements as a physicist does. All measurements will be made using units to the precision allowed by your instruments.

SAFETY

- **Review lab safety guidelines. Always follow correct procedures in the lab.**

PREPARATION

1. Read the entire lab procedure, and plan the steps you will take.
2. Prepare a data table in your lab notebook with seven columns and five rows, as shown below. In the first row, label the second through seventh columns *Trial 1, Trial 2, Trial 3, Trial 4, Trial 5,* and *Trial 6.* In the first column, label the second through fifth rows *Length (cm), Width (cm), Thickness (cm),* and *Mass (kg).*

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Length (cm)						
Width (cm)						
Thickness (cm)						
Mass (kg)						

PROCEDURE

Measuring length, width, thickness, and mass

3. Use a meterstick to measure the length of the wood block. Record all measured digits plus one estimated digit.

4. Follow the same procedure to measure the width and thickness of the block. Repeat all measurements two more times. Record your data.

5. Carefully adjust the balance to obtain an average zero reading when there is no mass on it. Your teacher will show you how to adjust the balances in your classroom to obtain an average zero reading. Use the balance to find the mass of the block, as shown in **Figure 1-17.** Record the measurement in your data table.

6. Repeat the mass measurement three more times, and record the values in your data table. Each time, place the block on a different side.

7. For trials 4–6, repeat steps 3 through 6 with the second wood block.

Figure 1-17
Step 3: Always record measurements to the precision allowed by your instruments.
Step 5: Make sure you know how to use the balances in your classroom. The balance should read zero when there is no mass on it. The number of significant figures in your measurement will be determined by your instrument, the object being measured, and the purpose of your measurement.

ANALYSIS AND INTERPRETATION

Calculations and data analysis

1. **Organizing data** Using your data, calculate the volume of the wood block for each trial. The equation for the volume of a rectangular block is *volume* = *length* × *width* × *thickness*.

2. **Analyzing data** Use your measurements from different trials to answer the following questions.
   a. For each block, what is the difference between the smallest length measurement and the largest length measurement?
   b. For each block, what is the difference between the smallest calculated volume and the largest calculated volume?
   c. Based on your answers to (a) and (b), how does multiplying several length measurements together to find the volume affect the precision of the result?

Conclusions

3. **Interpreting results** For each trial, find the ratio between the mass and the volume. Based on your data, what is the relationship between the mass and volume?

4. **Evaluating methods** For each type of measurement you made, explain how error could have affected your results. Consider method error and instrument error. How could you find out whether error had a significant effect on your results for each part of the lab?

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CHAPTER 1

Laboratory Exercise B

OBJECTIVES

- Use typical laboratory equipment to measure the distance and time of an observed motion.
- Measure distance and time in SI units.
- Determine the appropriate number of significant figures for various measurements.
- Use graphs and data analysis to examine the relationships between measured physical quantities.

MATERIALS LIST

- ✔ meterstick
- ✔ rectangular wooden block

PROCEDURE

CBL AND SENSORS

- ✔ C-clamp
- ✔ CBL
- ✔ CBL motion detector
- ✔ graphing calculator with link cable
- ✔ support stand and clamp
- ✔ thin foam pad

STOPWATCH

- ✔ stopwatch

TIME AND MEASUREMENT

Many fields of physics require experimenters to study events that take place over time. In this laboratory exercise, you will become familiar with the kinds of equipment used to make these measurements, such as metersticks and stopwatches; or motion detectors, CBL, and graphing calculators. All measurements will be made using SI units to the precision allowed by your instruments.

SAFETY

- **Perform this lab in a clear area. Falling or dropped masses can cause serious injury.**

PREPARATION

1. Determine whether you will be using the CBL and sensors or the stopwatch. Read the entire lab for the appropriate procedure, and plan the steps you will take.
2. Prepare a data table in your lab notebook with three columns and seven rows. In the first row, label the columns *Trial*, *Distance (m)*, and *Time (s)*. Label the second through seventh rows *1, 2, 3, 4, 5,* and *6.*

Trial	Distance (m)	Time (s)
1		
2		
3		
4		
5		
6		

Stopwatch procedure begins on page 36.

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PROCEDURE

CBL AND SENSORS

Measuring distance and time

3. This exercise should be performed with a partner. Perform this in a clear area away from other groups. Connect the CBL to the calculator with the unit-to-unit link cable using the ports located on each unit. Connect the motion detector to the SONIC port.

4. Set up the apparatus as shown in **Figure 1-18.** Securely clamp the motion detector to the support stand so that it faces downward, over the edge of the table. Make sure the motion detector is far enough away from the edge of the table that the signal will not hit the tabletop, clamp, or table leg.

5. Use a meterstick to measure a distance 0.5 m below the motion detector, and mark the point with tape on the table or stand. This is the starting position from which the blocks will be dropped from rest. Measure the height of the tape mark above the floor. Record this distance in your data table.

6. Start the program PHYSICS on your graphing calculator. Select option *SET UP PROBES* from the MAIN MENU. Enter 1 for the number of probes. Select *MOTION DETECTOR* from the list.

7. Select the *MONITOR INPUT* option from the DATA COLLECTION menu. Test to be sure the motion detector is positioned properly.

- **a.** Read the CBL measurement for the distance between the motion detector and the floor. Measure the distance with a meterstick to confirm the CBL value. If the CBL reading is too low, adjust the motion detector to make sure the signal is not hitting the table instead of the floor.
- **b.** Cover the floor under the motion detector with a foam pad to reduce feedback.
- **c.** Hold the wooden block directly beneath the motion detector, move the block up and down, and read the CBL measurements. Make sure the motion detector is not detecting other objects, such as the stand base, the tabletop, or the table leg. When the probe is functioning correctly, press + on the calculator to return to the MAIN MENU.

8. Select the *COLLECT DATA* option. Enter 0.02 for the time between samples. Enter 99 for the number of samples.

- **a.** Check the values you entered, and press ENTER. If the values are correct, select *USE TIME SETUP* to continue. If you made a mistake entering the time values, select *MODIFY SETUP*, reenter the values, and continue.

Figure 1-18
Step 4: The motion detector should be clamped securely to the stand, and the base of the stand should be clamped to the table if possible. Tape the cord to the stand to keep it out of the way.
Step 7: With the CBL in MONITOR INPUT mode, move the wooden block up and down below the motion detector to check the readings.

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b. If you are given a choice on the TIME GRAPH menu, select *NON-LIVE DISPLAY.* Otherwise, continue to the next step.

9. One student should hold the block horizontally between flat hands, as shown in **Figure 1-19** on the next page. Position the block directly below the motion detector and level with the 0.5 m mark.

10. Turn on the CBL and the graphing calculator. When the area is clear of people and objects, one student should press ENTER on the graphing calculator. As soon as the motion detector begins to click, the student holding the block should release the block by pulling both hands out to the side. Releasing the block this way will prevent the block from twisting as it falls, which could affect the results of this experiment.

11. When the motion detector has stopped clicking and the CBL displays DONE, press ENTER on the graphing calculator to get to the SELECT CHANNELS menu. Select the *SONIC* option, and then select *DISTANCE* to plot a graph of distance in meters against time in seconds. The graph should have a smooth shape. If it has spikes or black lines, repeat the trial to obtain a smooth graph, and continue on to the next step.

12. Examine the graph to find the section of the curve that represents the block's motion. On the far left and far right, the curve represents the position of the block before and after its motion. The middle section of the curve represents the motion of the falling block. Sketch the graph in your lab notebook.

13. Use the arrow keys to trace the graph. The *x*- and *y*-coordinates will be displayed as the cursor moves along the graph. Select a point from the beginning of the block's motion and another point from the end. Find the time interval between the two points by finding the difference between their *x*-values. Record this in your data table as the time in seconds. Find the distance moved by the block during that time by finding the difference between the *y*-values of the two points. Record this in your data table as the distance. Press ENTER on the graphing calculator.

14. Repeat for two more trials, recording all data in your data table. Try to drop the block from exactly the same height each time.

15. Switch roles so that the student who dropped the block is now operating the CBL, and repeat the experiment. Perform three trials. Record all data in your data table.

Analysis and Interpretation begins on page 37.

PROCEDURE

STOPWATCH

Measuring distance and time

3. Perform this exercise with a partner. One partner will drop the wooden block from a measured height, and the other partner will measure the time it takes the block to fall to the floor. Perform this in a clear area away from other groups.

4. One student should hold the wooden block held straight out in front of him or her at shoulder height. Hold the block between your hands, as shown in **Figure 1-19** on the next page. Use the meterstick to measure the height of the wood block. Record this distance in your data table.

5. Use the stopwatch to time the fall of the block. Make sure the area is clear, and inform nearby groups that you are about to begin. The student holding the block should release it by pulling both hands straight out to the sides. The student with the stopwatch should begin timing the instant the block is released and stop timing as soon as the block hits the floor. In your data table, record the time required for the block to fall.

6. Repeat for two more trials, recording all data in your data table. Try to drop the block from exactly the same height each time.

7. Switch roles, and repeat steps 4 through 6. Perform three trials. Record all data in your data table.

Figure 1-19
Step 4: Hold the block between your hands.
Step 5: Release the block by pulling both hands straight out to the sides. It may take some practice to release the block so that it falls straight down without turning.

ANALYSIS AND INTERPRETATION

Calculations and data analysis

1. **Organizing data** Did the block always fall from the same height in the same amount of time? Explain how you found the answer to this question.

2. **Graphing data** Using the data from all trials, make a scatter plot of the distance versus the time of the block's fall. Use a graphing calculator, computer, or graph paper.

Conclusions

3. **Evaluating methods** For each type of measurement you made, explain how error could have affected your results. Consider method error and instrument error. How could you find out whether error had a significant effect on your results for each part of the lab?

Extensions

4. **Evaluating data** If there is time and your teacher approves, conduct the following experiment. Have one student drop the wooden block from shoulder height while all other class members time the fall. Perform three trials. Compare results each time. What does this exercise suggest about accuracy and precision in the laboratory?