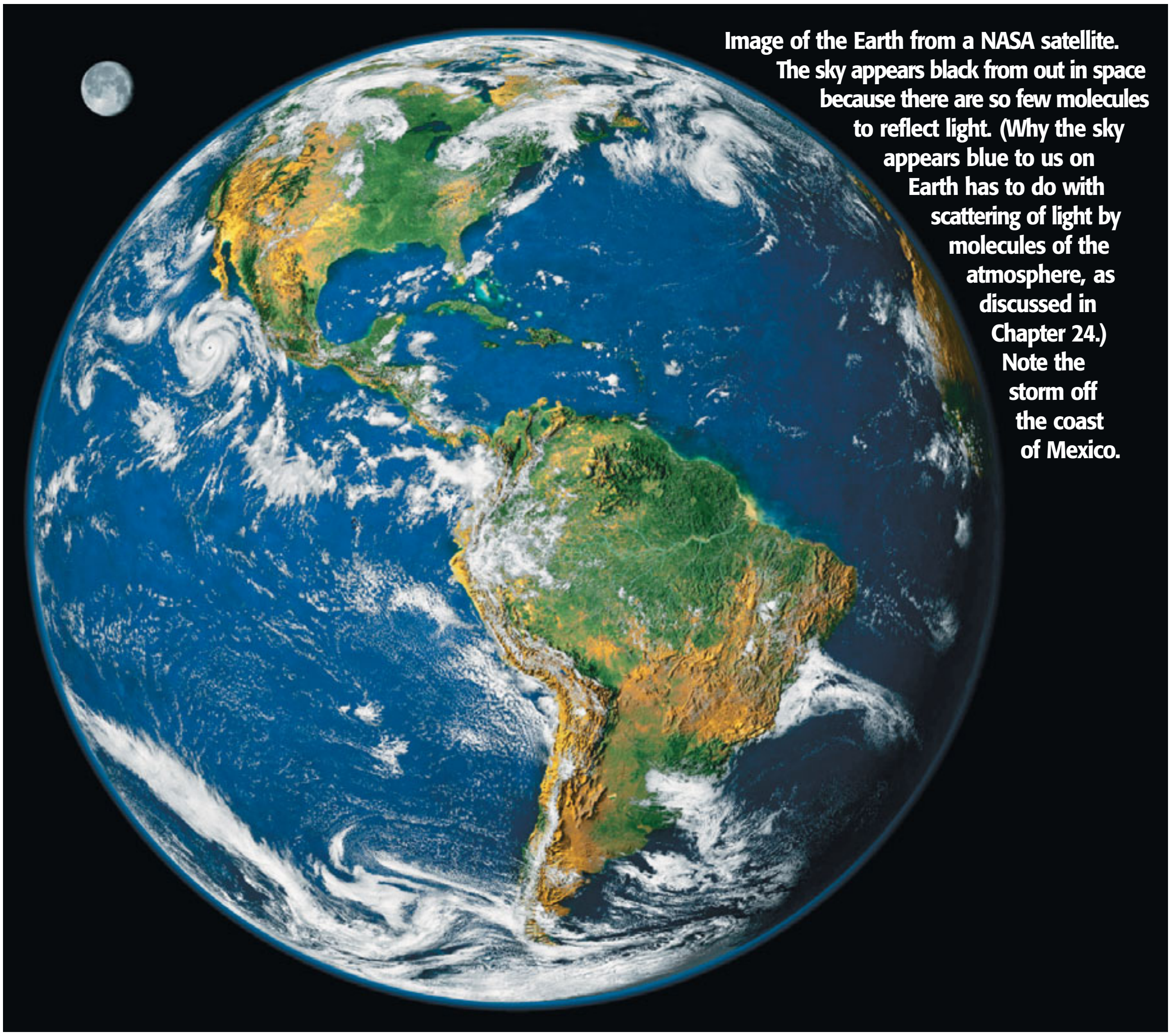


Image of the Earth from a NASA satellite. The sky appears black from out in space because there are so few molecules to reflect light. (Why the sky appears blue to us on Earth has to do with scattering of light by molecules of the atmosphere, as discussed in Chapter 24.) Note the storm off the coast of Mexico.

CHAPTER 1

Introduction, Measurement, Estimating

CHAPTER-OPENING QUESTIONS—Guess now!

1. How many cm^3 are in $1.0\ m^3$?

(a) 10. **(b)** 100. **(c)** 1000. **(d)** 10,000. **(e)** 100,000. **(f)** 1,000,000.

2. Suppose you wanted to actually measure the radius of the Earth, at least roughly, rather than taking other people's word for what it is. Which response below describes the best approach?

(a) Use an extremely long measuring tape.
(b) It is only possible by flying high enough to see the actual curvature of the Earth.
(c) Use a standard measuring tape, a step ladder, and a large smooth lake.
(d) Use a laser and a mirror on the Moon or on a satellite.
(e) Give up; it is impossible using ordinary means.

[*We start each Chapter with a Question—sometimes two. Try to answer right away. Don't worry about getting the right answer now—the idea is to get your preconceived notions out on the table. If they are misconceptions, we expect them to be cleared up as you read the Chapter. You will usually get another chance at the Question(s) later in the Chapter when the appropriate material has been covered. These Chapter-Opening Questions will also help you see the power and usefulness of physics.*]

CONTENTS

Physics is the most basic of the sciences. It deals with the behavior and structure of matter. The field of physics is usually divided into *classical physics* which includes motion, fluids, heat, sound, light, electricity, and magnetism; and *modern physics* which includes the topics of relativity, atomic structure, quantum theory, condensed matter, nuclear physics, elementary particles, and cosmology and astrophysics. We will cover all these topics in this book, beginning with motion (or mechanics, as it is often called) and ending with the most recent results in fundamental particles and the cosmos. But before we begin on the physics itself, we take a brief look at how this overall activity called "science," including physics, is actually practiced.

1–1 The Nature of Science

The principal aim of all sciences, including physics, is generally considered to be the search for order in our observations of the world around us. Many people think that science is a mechanical process of collecting facts and devising theories. But it is not so simple. Science is a creative activity that in many respects resembles other creative activities of the human mind.

One important aspect of science is **observation** of events, which includes the design and carrying out of experiments. But observation and experiments require imagination, because scientists can never include everything in a description of what they observe. Hence, scientists must make judgments about what is relevant in their observations and experiments.

Consider, for example, how two great minds, Aristotle (384–322 B.C.; Fig. 1–1) and Galileo (1564–1642; Fig. 2–18), interpreted motion along a horizontal surface. Aristotle noted that objects given an initial push along the ground (or on a tabletop) always slow down and stop. Consequently, Aristotle argued, the natural state of an object is to be at rest. Galileo, the first true experimentalist, reexamined horizontal motion in the 1600s. He imagined that if friction could be eliminated, an object given an initial push along a horizontal surface would continue to move indefinitely without stopping. He concluded that for an object to be in motion was just as natural as for it to be at rest. By inventing a new way of thinking about the same data, Galileo founded our modern view of motion (Chapters 2, 3, and 4), and he did so with a leap of the imagination. Galileo made this leap conceptually, without actually eliminating friction.

FIGURE 1–1 Aristotle is the central figure (dressed in blue) at the top of the stairs (the figure next to him is Plato) in this famous Renaissance portrayal of *The School of Athens*, painted by Raphael around 1510. Also in this painting, considered one of the great masterpieces in art, are Euclid (drawing a circle at the lower right), Ptolemy (extreme right with globe), Pythagoras, Socrates, and Diogenes.

Observation, with careful experimentation and measurement, is one side of the scientific process. The other side is the invention or creation of **theories** to explain and order the observations. Theories are never derived directly from observations. Observations may help inspire a theory, and theories are accepted or rejected based on the results of observation and experiment.

Theories are inspirations that come from the minds of human beings. For example, the idea that matter is made up of atoms (the atomic theory) was not arrived at by direct observation of atoms—we can't see atoms directly. Rather, the idea sprang from creative minds. The theory of relativity, the electromagnetic theory of light, and Newton's law of universal gravitation were likewise the result of human imagination.

The great theories of science may be compared, as creative achievements, with great works of art or literature. But how does science differ from these other creative activities? One important difference is that science requires **testing** of its ideas or theories to see if their predictions are borne out by experiment. But theories are not "proved" by testing. First of all, no measuring instrument is perfect, so exact confirmation is not possible. Furthermore, it is not possible to test a theory for every possible set of circumstances. Hence a theory cannot be absolutely verified. Indeed, the history of science tells us that long-held theories can sometimes be replaced by new ones, particularly when new experimental techniques provide new or contradictory data.

A new theory is accepted by scientists in some cases because its predictions are quantitatively in better agreement with experiment than those of the older theory. But in many cases, a new theory is accepted only if it explains a greater *range* of phenomena than does the older one. Copernicus's Sun-centered theory of the universe (Fig. 1–2b), for example, was originally no more accurate than Ptolemy's Earth-centered theory (Fig. 1–2a) for predicting the motion of heavenly bodies (Sun, Moon, planets). But Copernicus's theory had consequences that Ptolemy's did not, such as predicting the moonlike phases of Venus. A simpler and richer theory, one which unifies and explains a greater variety of phenomena, is more useful and beautiful to a scientist. And this aspect, as well as quantitative agreement, plays a major role in the acceptance of a theory.

FIGURE 1–2 (a) Ptolemy's geocentric view of the universe. Note at the center the four elements of the ancients: Earth, water, air (clouds around the Earth), and fire; then the circles, with symbols, for the Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, the fixed stars, and the signs of the zodiac. (b) An early representation of Copernicus's heliocentric view of the universe with the Sun at the center. (See Chapter 5.)

(a)

(b)

An important aspect of any theory is how well it can quantitatively predict phenomena, and from this point of view a new theory may often seem to be only a minor advance over the old one. For example, Einstein's theory of relativity gives predictions that differ very little from the older theories of Galileo and Newton in nearly all everyday situations. Its predictions are better mainly in the extreme case of very high speeds close to the speed of light. But quantitative prediction is not the only important outcome of a theory. Our view of the world is affected as well. As a result of Einstein's theory of relativity, for example, our concepts of space and time have been completely altered, and we have come to see mass and energy as a single entity (via the famous equation $E = mc^2$).

1–2 Physics and its Relation to Other Fields

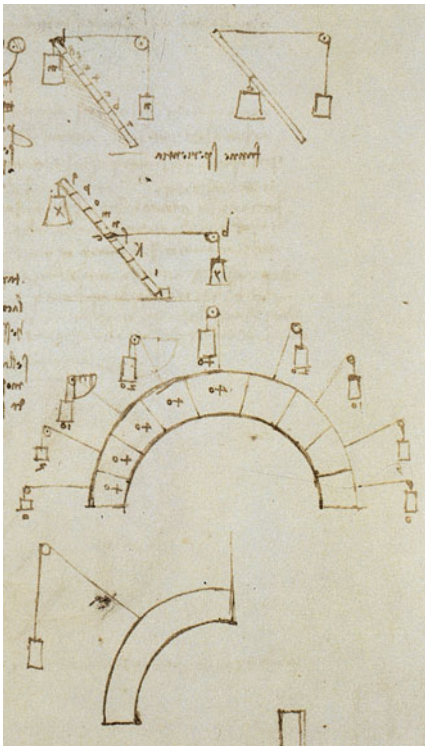


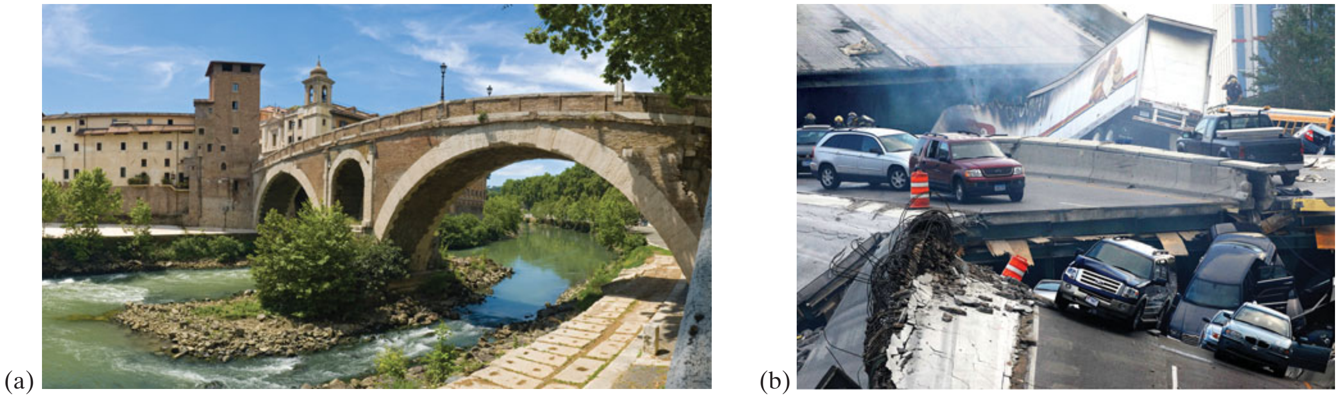
FIGURE 1–3 Studies on the forces in structures by Leonardo da Vinci (1452–1519).

For a long time science was more or less a united whole known as natural philosophy. Not until a century or two ago did the distinctions between physics and chemistry and even the life sciences become prominent. Indeed, the sharp distinction we now see between the arts and the sciences is itself only a few centuries old. It is no wonder then that the development of physics has both influenced and been influenced by other fields. For example, the notebooks (Fig. 1–3) of Leonardo da Vinci, the great Renaissance artist, researcher, and engineer, contain the first references to the forces acting within a structure, a subject we consider as physics today; but then, as now, it has great relevance to architecture and building.

Early work in electricity that led to the discovery of the electric battery and electric current was done by an eighteenth-century physiologist, Luigi Galvani (1737–1798). He noticed the twitching of frogs' legs in response to an electric spark and later that the muscles twitched when in contact with two dissimilar metals (Chapter 18). At first this phenomenon was known as "animal electricity," but it shortly became clear that electric current itself could exist in the absence of an animal.

Physics is used in many fields. A zoologist, for example, may find physics useful in understanding how prairie dogs and other animals can live underground without suffocating. A physical therapist will be more effective if aware of the principles of center of gravity and the action of forces within the human body. A knowledge of the operating principles of optical and electronic equipment is helpful in a variety of fields. Life scientists and architects alike will be interested in the nature of heat loss and gain in human beings and the resulting comfort or discomfort. Architects may have to calculate the dimensions of the pipes in a heating system or the forces involved in a given structure to determine if it will remain standing (Fig. 1–4). They must know physics principles in order to make realistic designs and to communicate effectively with engineering consultants and other specialists.

FIGURE 1–4 (a) This bridge over the River Tiber in Rome was built 2000 years ago and still stands. (b) The 2007 collapse of a Mississippi River highway bridge built only 40 years before.



From the aesthetic or psychological point of view, too, architects must be aware of the forces involved in a structure—for example instability, even if only illusory, can be discomforting to those who must live or work in the structure.

The list of ways in which physics relates to other fields is extensive. In the Chapters that follow we will discuss many such applications as we carry out our principal aim of explaining basic physics.

1–3 Models, Theories, and Laws

When scientists are trying to understand a particular set of phenomena, they often make use of a **model**. A model, in the scientific sense, is a kind of analogy or mental image of the phenomena in terms of something else we are already familiar with. One example is the wave model of light. We cannot see waves of light as we can water waves. But it is valuable to think of light as made up of waves, because experiments indicate that light behaves in many respects as water waves do.

The purpose of a model is to give us an approximate mental or visual picture—something to hold on to—when we cannot see what actually is happening. Models often give us a deeper understanding: the analogy to a known system (for instance, the water waves above) can suggest new experiments to perform and can provide ideas about what other related phenomena might occur.

You may wonder what the difference is between a theory and a model. Usually a model is relatively simple and provides a structural similarity to the phenomena being studied. A **theory** is broader, more detailed, and can give quantitatively testable predictions, often with great precision. It is important, however, not to confuse a model or a theory with the real system or the phenomena themselves.

Scientists have given the title **law** to certain concise but general statements about how nature behaves (that electric charge is conserved, for example). Often the statement takes the form of a relationship or equation between quantities (such as Newton's second law, $F = ma$).

Statements that we call laws are usually experimentally valid over a wide range of observed phenomena. For less general statements, the term **principle** is often used (such as Archimedes' principle). We use "theory" for a more general picture of the phenomena dealt with.

Scientific laws are different from political laws in that the latter are *prescriptive*: they tell us how we ought to behave. Scientific laws are *descriptive*: they do not say how nature *should* behave, but rather are meant to describe how nature *does* behave. As with theories, laws cannot be tested in the infinite variety of cases possible. So we cannot be sure that any law is absolutely true. We use the term "law" when its validity has been tested over a wide range of cases, and when any limitations and the range of validity are clearly understood.

Scientists normally do their research as if the accepted laws and theories were true. But they are obliged to keep an open mind in case new information should alter the validity of any given law or theory.

1–4 Measurement and Uncertainty; Significant Figures

In the quest to understand the world around us, scientists seek to find relationships among physical quantities that can be measured.

Uncertainty

Reliable measurements are an important part of physics. But no measurement is absolutely precise. There is an uncertainty associated with every measurement.

FIGURE 1–5 Measuring the width of a board with a centimeter ruler. Accuracy is about ± 1 mm.

Among the most important sources of uncertainty, other than blunders, are the limited accuracy of every measuring instrument and the inability to read an instrument beyond some fraction of the smallest division shown. For example, if you were to use a centimeter ruler to measure the width of a board (Fig. 1–5), the result could be claimed to be precise to about 0.1 cm (1 mm), the smallest division on the ruler, although half of this value might be a valid claim as well. The reason is that it is difficult for the observer to estimate (or "interpolate") between the smallest divisions. Furthermore, the ruler itself may not have been manufactured to an accuracy very much better than this.

When giving the result of a measurement, it is important to state the **estimated uncertainty** in the measurement. For example, the width of a board might be written as 8.8 ± 0.1 cm. The ± 0.1 cm ("plus or minus 0.1 cm") represents the estimated uncertainty in the measurement, so that the actual width most likely lies between 8.7 and 8.9 cm. The **percent uncertainty** is the ratio of the uncertainty to the measured value, multiplied by 100. For example, if the measurement is 8.8 cm and the uncertainty about 0.1 cm, the percent uncertainty is

$$\frac{0.1}{8.8} \times 100\% \approx 1\%,$$

where ≈ means "is approximately equal to."

Often the uncertainty in a measured value is not specified explicitly. In such cases, the

> **uncertainty in a numerical value is assumed to be *one or a few units* in the last digit specified.**

For example, if a length is given as 8.8 cm, the uncertainty is assumed to be about 0.1 cm or 0.2 cm. It is important in this case that you do not write 8.80 cm, because this implies an uncertainty on the order of 0.01 cm; it assumes that the length is probably between 8.79 cm and 8.81 cm, when actually you believe it is between 8.7 and 8.9 cm.

CONCEPTUAL EXAMPLE 1–1 **Is the diamond yours?** A friend asks to borrow your precious diamond for a day to show her family. You are a bit worried, so you carefully have your diamond weighed on a scale which reads 8.17 grams. The scale's accuracy is claimed to be ± 0.05 gram. The next day you weigh the returned diamond again, getting 8.09 grams. Is this your diamond?

RESPONSE The scale readings are measurements and are not perfect. They do not necessarily give the "true" value of the mass. Each measurement could have been high or low by up to 0.05 gram or so. The actual mass of your diamond lies most likely between 8.12 grams and 8.22 grams. The actual mass of the returned diamond is most likely between 8.04 grams and 8.14 grams. These two ranges overlap, so the data do not give you a strong reason to doubt that the returned diamond is yours.

Significant Figures

The number of reliably known digits in a number is called the number of **significant figures**. Thus there are four significant figures in the number 23.21 cm and two in the number 0.062 cm (the zeros in the latter are merely place holders that show where the decimal point goes). The number of significant figures may not always be clear. Take, for example, the number 80. Are there one or two significant figures? We need words here: If we say it is *roughly* 80 km between two cities, there is only one significant figure (the 8) since the zero is merely a place holder. If there is no suggestion that the 80 is a rough approximation, then we can often assume (as we will in this book) that it is 80 km within an accuracy of about 1 or 2 km, and then the 80 has two significant figures. If it is precisely 80 km, to within ± 0.1 km, then we write 80.0 km (three significant figures).

When making measurements, or when doing calculations, you should avoid the temptation to keep more digits in the final answer than is justified: see boldface statement on previous page. For example, to calculate the area of a rectangle 11.3 cm by 6.8 cm, the result of multiplication would be $76.84\ \text{cm}^2$. But this answer can not be accurate to the implied $0.01\ \text{cm}^2$ uncertainty, because (using the outer limits of the assumed uncertainty for each measurement) the result could be between $11.2\ \text{cm} \times 6.7\ \text{cm} = 75.04\ \text{cm}^2$ and $11.4\ \text{cm} \times 6.9\ \text{cm} = 78.66\ \text{cm}^2$. At best, we can quote the answer as $77\ \text{cm}^2$, which implies an uncertainty of about 1 or $2\ \text{cm}^2$. The other two digits (in the number $76.84\ \text{cm}^2$) must be dropped (rounded off) because they are not significant. As a rough general rule we can say that

> *the final result of a multiplication or division should have no more digits than the numerical value with the fewest significant figures.*

In our example, 6.8 cm has the least number of significant figures, namely two. Thus the result $76.84\ \text{cm}^2$ needs to be rounded off to $77\ \text{cm}^2$.

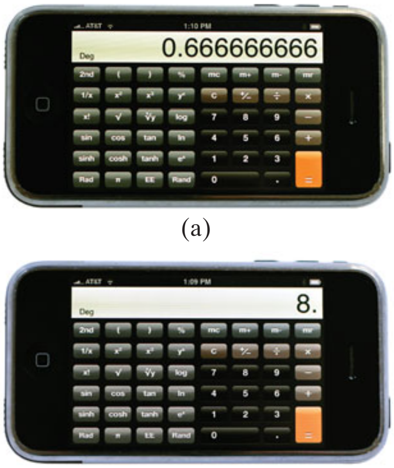
EXERCISE A The area of a rectangle 4.5 cm by 3.25 cm is correctly given by (*a*) $14.625\ \text{cm}^2$; (*b*) $14.63\ \text{cm}^2$; (*c*) $14.6\ \text{cm}^2$; (*d*) $15\ \text{cm}^2$.

When adding or subtracting numbers, the final result should contain no more decimal places than the number with the fewest decimal places. For example, the result of subtracting 0.57 from 3.6 is 3.0 (not 3.03). Similarly $36 + 8.2 = 44$, not 44.2.

Be careful not to confuse significant figures with the number of decimal places.

EXERCISE B For each of the following numbers, state the number of significant figures and the number of decimal places: (*a*) 1.23; (*b*) 0.123; (*c*) 0.0123.

Keep in mind when you use a calculator that all the digits it produces may not be significant. When you divide 2.0 by 3.0, the proper answer is 0.67, and not 0.666666666 as calculators give (Fig. 1–6a). Digits should not be quoted in a result unless they are truly significant figures. However, to obtain the most accurate result, you should normally *keep one or more extra significant figures throughout a calculation, and round off only in the final result.* (With a calculator, you can keep all its digits in intermediate results.) Note also that calculators sometimes give too few significant figures. For example, when you multiply 2.5×3.2, a calculator may give the answer as simply 8. But the answer is accurate to two significant figures, so the proper answer is 8.0. See Fig. 1–6b.



(a)

(b)

FIGURE 1–6 These two calculations show the wrong number of significant figures. In (a), 2.0 was divided by 3.0. The correct final result would be 0.67. In (b), 2.5 was multiplied by 3.2. The correct result is 8.0.

PROBLEM SOLVING

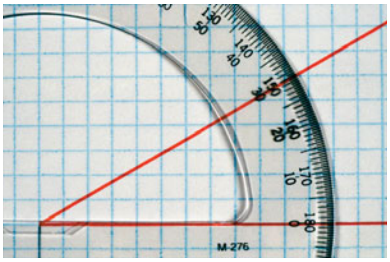
Report only the proper number of significant figures in the final result. But keep extra digits during the calculation

CONCEPTUAL EXAMPLE 1–2 **Significant figures.** Using a protractor (Fig. 1–7), you measure an angle to be 30°. (*a*) How many significant figures should you quote in this measurement? (*b*) Use a calculator to find the cosine of the angle you measured.

RESPONSE (*a*) If you look at a protractor, you will see that the precision with which you can measure an angle is about one degree (certainly not 0.1°). So you can quote two significant figures, namely 30° (not 30.0°). (*b*) If you enter cos 30° in your calculator, you will get a number like 0.866025403. But the angle you entered is known only to two significant figures, so its cosine is correctly given by 0.87; you must round your answer to two significant figures.

NOTE Trigonometric functions, like cosine, are reviewed in Chapter 3 and Appendix A.

FIGURE 1–7 Example 1–2. A protractor used to measure an angle.



Scientific Notation

We commonly write numbers in "powers of ten," or "scientific" notation—for instance 36,900 as 3.69×10^4, or 0.0021 as 2.1×10^{-3}. One advantage of scientific notation (reviewed in Appendix A) is that it allows the number of significant figures to be clearly expressed. For example, it is not clear whether 36,900 has three, four, or five significant figures. With powers of 10 notation the ambiguity can be avoided: if the number is known to three significant figures, we write 3.69×10^4, but if it is known to four, we write 3.690×10^4.

EXERCISE C Write each of the following in scientific notation and state the number of significant figures for each: (*a*) 0.0258; (*b*) 42,300; (*c*) 344.50.

* Percent Uncertainty vs. Significant Figures

The significant figures rule is only approximate, and in some cases may underestimate the accuracy (or uncertainty) of the answer. Suppose for example we divide 97 by 92:

$$\frac{97}{92} = 1.05 \approx 1.1.$$

Both 97 and 92 have two significant figures, so the rule says to give the answer as 1.1. Yet the numbers 97 and 92 both imply an uncertainty of ± 1 if no other uncertainty is stated. Both 92 ± 1 and 97 ± 1 imply an uncertainty of about 1% $(1/92 \approx 0.01 = 1\%)$. But the final result to two significant figures is 1.1, with an implied uncertainty of ± 0.1, which is an uncertainty of about 10% $(0.1/1.1 \approx 0.1 \approx 10\%)$. It is better in this case to give the answer as 1.05 (which is three significant figures). Why? Because 1.05 implies an uncertainty of ± 0.01 which is $0.01/1.05 \approx 0.01 \approx 1\%$, just like the uncertainty in the original numbers 92 and 97.

SUGGESTION: Use the significant figures rule, but consider the % uncertainty too, and add an extra digit if it gives a more realistic estimate of uncertainty.

Approximations

Much of physics involves approximations, often because we do not have the means to solve a problem precisely. For example, we may choose to ignore air resistance or friction in doing a Problem even though they are present in the real world, and then our calculation is only an approximation. In doing Problems, we should be aware of what approximations we are making, and be aware that the precision of our answer may not be nearly as good as the number of significant figures given in the result.

Accuracy vs. Precision

There is a technical difference between “precision” and “accuracy.” **Precision** in a strict sense refers to the repeatability of the measurement using a given instrument. For example, if you measure the width of a board many times, getting results like 8.81 cm, 8.85 cm, 8.78 cm, 8.82 cm (interpolating between the 0.1 cm marks as best as possible each time), you could say the measurements give a *precision* a bit better than 0.1 cm. **Accuracy** refers to how close a measurement is to the true value. For example, if the ruler shown in Fig. 1–5 was manufactured with a 2% error, the accuracy of its measurement of the board’s width (about 8.8 cm) would be about 2% of 8.8 cm or about ± 0.2 cm. Estimated uncertainty is meant to take both accuracy and precision into account.

1–5 Units, Standards, and the SI System

The measurement of any quantity is made relative to a particular standard or **unit**, and this unit must be specified along with the numerical value of the quantity. For example, we can measure length in British units such as inches, feet, or miles, or in the metric system in centimeters, meters, or kilometers. To specify that the length of a particular object is 18.6 is insufficient. The unit *must* be given, because 18.6 meters is very different from 18.6 inches or 18.6 millimeters.

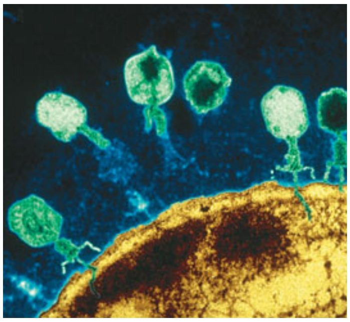
For any unit we use, such as the meter for distance or the second for time, we need to define a **standard** which defines exactly how long one meter or one second is. It is important that standards be chosen that are readily reproducible so that anyone needing to make a very accurate measurement can refer to the standard in the laboratory and communicate with other people.

Length

The first truly international standard was the **meter** (abbreviated m) established as the standard of **length** by the French Academy of Sciences in the 1790s. The standard meter was originally chosen to be one ten-millionth of the distance from the Earth's equator to either pole,[†] and a platinum rod to represent this length was made. (One meter is, very roughly, the distance from the tip of your nose to the tip of your finger, with arm and hand stretched out horizontally.) In 1889, the meter was defined more precisely as the distance between two finely engraved marks on a particular bar of platinum–iridium alloy. In 1960, to provide even greater precision and reproducibility, the meter was redefined as 1,650,763.73 wavelengths of a particular orange light emitted by the gas krypton-86. In 1983 the meter was again redefined, this time in terms of the speed of light (whose best measured value in terms of the older definition of the meter was 299,792,458 m/s, with an uncertainty of 1 m/s). The new definition reads: "The meter is the length of path traveled by light in vacuum during a time interval of 1/299,792,458 of a second."[‡]

British units of length (inch, foot, mile) are now defined in terms of the meter. The inch (in.) is defined as exactly 2.54 centimeters (cm; 1 cm = 0.01 m). Other conversion factors are given in the Table on the inside of the front cover of this book. Table 1–1 presents some typical lengths, from very small to very large, rounded off to the nearest power of 10. See also Fig. 1–8. [Note that the abbreviation for inches (in.) is the only one with a period, to distinguish it from the word "in".]

FIGURE 1–8 Some lengths: (a) viruses (about 10^{-7} m long) attacking a cell; (b) Mt. Everest's height is on the order of 10^4 m (8850 m above sea level, to be precise).



(a)

(b)

Time

The standard unit of **time** is the **second** (s). For many years, the second was defined as 1/86,400 of a mean solar day (24 h/day × 60 min/h × 60 s/min = 86,400 s/day). The standard second is now defined more precisely in terms of the frequency of radiation emitted by cesium atoms when they pass between two particular states. [Specifically, one second is defined as the time required for 9,192,631,770 oscillations of this radiation.] There are, by definition, 60 s in one minute (min) and 60 minutes in one hour (h). Table 1–2 presents a range of measured time intervals, rounded off to the nearest power of 10.

[†] Modern measurements of the Earth's circumference reveal that the intended length is off by about one-fiftieth of 1%. Not bad!

[‡] The new definition of the meter has the effect of giving the speed of light the exact value of 299,792,458 m/s.

TABLE 1–1 Some Typical Lengths or Distances (order of magnitude)

Length (or Distance)	Meters (approximate)
Neutron or proton (diameter)	10^{-15} m
Atom (diameter)	10^{-10} m
Virus [see Fig. 1–8a]	10^{-7} m
Sheet of paper (thickness)	10^{-4} m
Finger width	10^{-2} m
Football field length	10^{2} m
Height of Mt. Everest [see Fig. 1–8b]	10^{4} m
Earth diameter	10^{7} m
Earth to Sun	10^{11} m
Earth to nearest star	10^{16} m
Earth to nearest galaxy	10^{22} m
Earth to farthest galaxy visible	10^{26} m

TABLE 1–2 Some Typical Time Intervals (order of magnitude)

Time Interval	Seconds (approximate)
Lifetime of very unstable subatomic particle	10^{-23} s
Lifetime of radioactive elements	10^{-22} s to 10^{28} s
Lifetime of muon	10^{-6} s
Time between human heartbeats	10^{0} s (= 1 s)
One day	10^{5} s
One year	3×10^{7} s
Human life span	2×10^{9} s
Length of recorded history	10^{11} s
Humans on Earth	10^{13} s
Age of Earth	10^{17} s
Age of Universe	4×10^{17} s

TABLE 1–3 Some Masses

Object	Kilograms (approximate)
Electron	10^{-30} kg
Proton, neutron	10^{-27} kg
DNA molecule	10^{-17} kg
Bacterium	10^{-15} kg
Mosquito	10^{-5} kg
Plum	10^{-1} kg
Human	10^{2} kg
Ship	10^{8} kg
Earth	6×10^{24} kg
Sun	2×10^{30} kg
Galaxy	10^{41} kg

Mass

The standard unit of **mass** is the **kilogram** (kg). The standard mass is a particular platinum–iridium cylinder, kept at the International Bureau of Weights and Measures near Paris, France, whose mass is defined as exactly 1 kg. A range of masses is presented in Table 1–3. [For practical purposes, 1 kg weighs about 2.2 pounds on Earth.]

When dealing with atoms and molecules, we usually use the **unified atomic mass unit** (u or amu). In terms of the kilogram,

$$1\ \text{u} = 1.6605 \times 10^{-27}\ \text{kg}.$$

The definitions of other standard units for other quantities will be given as we encounter them in later Chapters. (Precise values of this and other useful numbers are given inside the front cover.)

Unit Prefixes

In the metric system, the larger and smaller units are defined in multiples of 10 from the standard unit, and this makes calculation particularly easy. Thus 1 kilometer (km) is 1000 m, 1 centimeter is $\frac{1}{100}$ m, 1 millimeter (mm) is $\frac{1}{1000}$ m or $\frac{1}{10}$ cm, and so on. The prefixes "centi-," "kilo-," and others are listed in Table 1–4 and can be applied not only to units of length but to units of volume, mass, or any other unit. For example, a centiliter (cL) is $\frac{1}{100}$ liter (L), and a kilogram (kg) is 1000 grams (g). An 8.2-megapixel camera has a detector with 8,200,000 pixels (individual "picture elements").

In common usage, $1\ \mu\text{m}\ (= 10^{-6}\ \text{m})$ is called 1 **micron**.

PROBLEM SOLVING

Always use a consistent set of units

Systems of Units

When dealing with the laws and equations of physics it is very important to use a consistent set of units. Several systems of units have been in use over the years. Today the most important is the **Système International** (French for International System), which is abbreviated SI. In SI units, the standard of length is the meter, the standard for time is the second, and the standard for mass is the kilogram. This system used to be called the MKS (meter-kilogram-second) system.

A second metric system is the **cgs system**, in which the centimeter, gram, and second are the standard units of length, mass, and time, as abbreviated in the title. The **British engineering system** (although more used in the U.S. than Britain) has as its standards the foot for length, the pound for force, and the second for time.

We use SI units almost exclusively in this book.

TABLE 1–4 Metric (SI) Prefixes

Prefix	Abbreviation	Value
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deka	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro[†]	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

[†] μ is the Greek letter "mu."

* Base vs. Derived Quantities

Physical quantities can be divided into two categories: *base quantities* and *derived quantities*. The corresponding units for these quantities are called *base units* and *derived units*. A **base quantity** must be defined in terms of a standard. Scientists, in the interest of simplicity, want the smallest number of base quantities possible consistent with a full description of the physical world. This number turns out to be seven, and those used in the SI are given in Table 1–5.

TABLE 1–5 SI Base Quantities and Units

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

All other quantities can be defined in terms of these seven base quantities,[†] and hence are referred to as **derived quantities**. An example of a derived quantity is speed, which is defined as distance divided by the time it takes to travel that distance. A Table inside the front cover lists many derived quantities and their units in terms of base units. To define any quantity, whether base or derived, we can specify a rule or procedure, and this is called an **operational definition**.

1–6 Converting Units

Any quantity we measure, such as a length, a speed, or an electric current, consists of a number *and* a unit. Often we are given a quantity in one set of units, but we want it expressed in another set of units. For example, suppose we measure that a shelf is 21.5 inches wide, and we want to express this in centimeters. We must use a **conversion factor**, which in this case is, *by definition*, exactly

$$1\text{ in.} = 2.54\text{ cm}$$

or, written another way,

$$1 = 2.54\text{ cm/in.}$$

Since multiplying by the number one does not change anything, the width of our shelf, in cm, is

$$21.5\text{ inches} = (21.5\ \cancel{\text{in.}}) \times \left(2.54\,\frac{\text{cm}}{\cancel{\text{in.}}}\right) = 54.6\text{ cm}.$$

Note how the units (inches in this case) cancelled out (thin red lines). A Table containing many unit conversions is found inside the front cover of this book. Let's consider some Examples.

EXAMPLE 1–3 **The 8000-m peaks.** There are only 14 peaks whose summits are over 8000 m above sea level. They are the tallest peaks in the world (Fig. 1–9 and Table 1–6) and are referred to as "eight-thousanders." What is the elevation, in feet, of an elevation of 8000 m?

APPROACH We need to convert meters to feet, and we can start with the conversion factor $1\text{ in.} = 2.54\text{ cm}$, which is exact. That is, $1\text{ in.} = 2.5400\text{ cm}$ to any number of significant figures, because it is *defined* to be.

SOLUTION One foot is 12 in., so we can write

$$1\text{ ft} = (12\ \cancel{\text{in.}})\left(2.54\,\frac{\text{cm}}{\cancel{\text{in.}}}\right) = 30.48\text{ cm} = 0.3048\text{ m},$$

which is exact. Note how the units cancel (colored slashes). We can rewrite this equation to find the number of feet in 1 meter:

$$1\text{ m} = \frac{1\text{ ft}}{0.3048} = 3.28084\text{ ft}.$$

(We could carry the result to 6 significant figures because 0.3048 is exact, 0.304800….) We multiply this equation by 8000.0 (to have five significant figures):

$$8000.0\text{ m} = (8000.0\ \cancel{\text{m}})\left(3.28084\,\frac{\text{ft}}{\cancel{\text{m}}}\right) = 26{,}247\text{ ft}.$$

An elevation of 8000 m is 26,247 ft above sea level.

NOTE We could have done the conversion all in one line:

$$8000.0\text{ m} = (8000.0\ \cancel{\text{m}})\left(\frac{100\ \cancel{\text{cm}}}{1\ \cancel{\text{m}}}\right)\left(\frac{1\ \cancel{\text{in.}}}{2.54\ \cancel{\text{cm}}}\right)\left(\frac{1\text{ ft}}{12\ \cancel{\text{in.}}}\right) = 26{,}247\text{ ft}.$$

The key is to multiply conversion factors, each equal to one $(= 1.0000)$, and to make sure which units cancel.

FIGURE 1–9 The world's second highest peak, K2, whose summit is considered the most difficult of the "8000-ers." K2 is seen here from the south (Pakistan). Example 1–3.

PHYSICS APPLIED
The world's tallest peaks

TABLE 1–6 The 8000-m Peaks

Peak	Height (m)
Mt. Everest	8850
K2	8611
Kangchenjunga	8586
Lhotse	8516
Makalu	8462
Cho Oyu	8201
Dhaulagiri	8167
Manaslu	8156
Nanga Parbat	8125
Annapurna	8091
Gasherbrum I	8068
Broad Peak	8047
Gasherbrum II	8035
Shisha Pangma	8013

[†] Some exceptions are for angle (radians—see Chapter 8), solid angle (steradian), and sound level (bel or decibel, Chapter 12). No general agreement has been reached as to whether these are base or derived quantities.

EXAMPLE 1–4 **Apartment area.** You have seen a nice apartment whose floor area is 880 square feet (ft^2). What is its area in square meters?

APPROACH We use the same conversion factor, 1 in. = 2.54 cm, but this time we have to use it twice.

SOLUTION Because $1\text{ in.} = 2.54\text{ cm} = 0.0254\text{ m}$, then

$$1\text{ ft}^2 = (12\text{ in.})^2(0.0254\text{ m/in.})^2 = 0.0929\text{ m}^2.$$

So

$$880\text{ ft}^2 = (880\text{ ft}^2)(0.0929\text{ m}^2/\text{ft}^2) \approx 82\text{ m}^2.$$

NOTE As a rule of thumb, an area given in ft^2 is roughly 10 times the number of square meters (more precisely, about $10.8\times$).

EXAMPLE 1–5 **Speeds.** Where the posted speed limit is 55 miles per hour (mi/h or mph), what is this speed (*a*) in meters per second (m/s) and (*b*) in kilometers per hour (km/h)?

APPROACH We again use the conversion factor $1\text{ in.} = 2.54\text{ cm}$, and we recall that there are 5280 ft in a mile and 12 inches in a foot; also, one hour contains $(60\text{ min/h}) \times (60\text{ s/min}) = 3600\text{ s/h}$.

SOLUTION (*a*) We can write 1 mile as

$$\begin{aligned} 1\text{ mi} &= (5280\ \cancel{\text{ft}})\left(12\,\frac{\cancel{\text{in.}}}{\cancel{\text{ft}}}\right)\left(2.54\,\frac{\cancel{\text{cm}}}{\cancel{\text{in.}}}\right)\left(\frac{1\text{ m}}{100\ \cancel{\text{cm}}}\right) \\ &= 1609\text{ m}. \end{aligned}$$

We also know that 1 hour contains 3600 s, so

$$\begin{aligned} 55\,\frac{\text{mi}}{\text{h}} &= \left(55\,\frac{\cancel{\text{mi}}}{\cancel{\text{h}}}\right)\left(1609\,\frac{\text{m}}{\cancel{\text{mi}}}\right)\left(\frac{1\ \cancel{\text{h}}}{3600\text{ s}}\right) \\ &= 25\,\frac{\text{m}}{\text{s}}, \end{aligned}$$

where we rounded off to two significant figures.

(*b*) Now we use $1\text{ mi} = 1609\text{ m} = 1.609\text{ km}$; then

$$\begin{aligned} 55\,\frac{\text{mi}}{\text{h}} &= \left(55\,\frac{\cancel{\text{mi}}}{\text{h}}\right)\left(1.609\,\frac{\text{km}}{\cancel{\text{mi}}}\right) \\ &= 88\,\frac{\text{km}}{\text{h}}. \end{aligned}$$

PROBLEM SOLVING
Conversion factors = 1

NOTE Each conversion factor is equal to one. You can look up most conversion factors in the Table inside the front cover.

EXERCISE D Return to the first Chapter-Opening Question, page 1, and answer it again now. Try to explain why you may have answered differently the first time.

EXERCISE E Would a driver traveling at 15 m/s in a 35 mi/h zone be exceeding the speed limit? Why or why not?

PROBLEM SOLVING
Unit conversion is wrong if units do not cancel

When changing units, you can avoid making an error in the use of conversion factors by checking that units cancel out properly. For example, in our conversion of 1 mi to 1609 m in Example 1–5(*a*), if we had incorrectly used the factor $\left(\frac{100\text{ cm}}{1\text{ m}}\right)$ instead of $\left(\frac{1\text{ m}}{100\text{ cm}}\right)$, the centimeter units would not have cancelled out; we would not have ended up with meters.

1–7 Order of Magnitude: Rapid Estimating

We are sometimes interested only in an approximate value for a quantity. This might be because an accurate calculation would take more time than it is worth or would require additional data that are not available. In other cases, we may want to make a rough estimate in order to check a calculation made on a calculator, to make sure that no blunders were made when the numbers were entered.

PROBLEM SOLVING
How to make a rough estimate

A rough estimate can be made by rounding off all numbers to one significant figure and its power of 10, and after the calculation is made, again keeping only one significant figure. Such an estimate is called an **order-of-magnitude estimate** and can be accurate within a factor of 10, and often better. In fact, the phrase "order of magnitude" is sometimes used to refer simply to the power of 10.

Let's do some Examples.

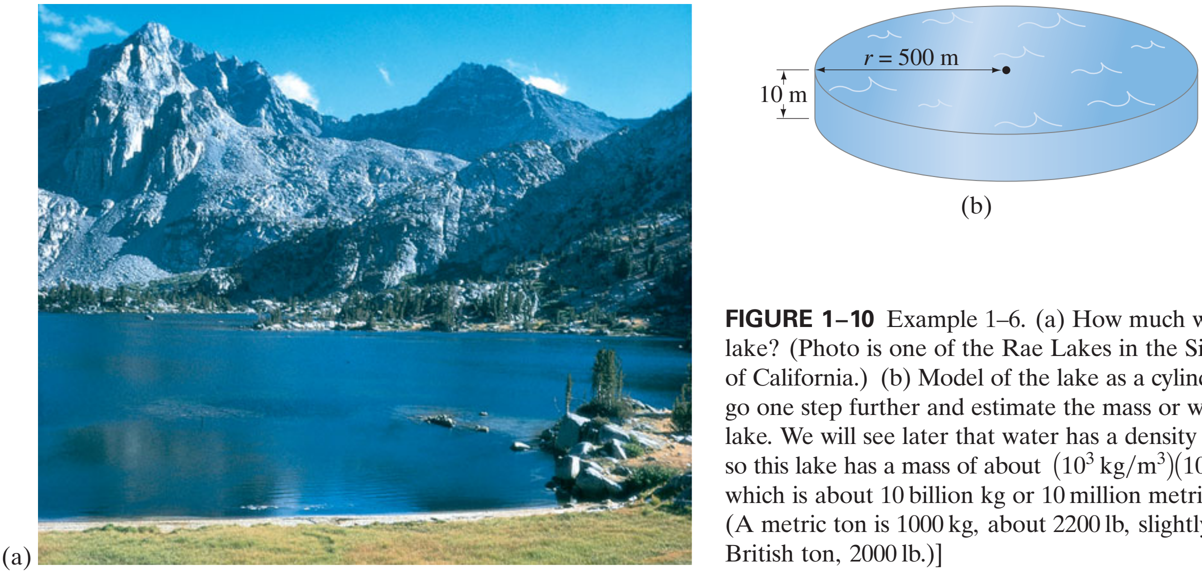


FIGURE 1–10 Example 1–6. (a) How much water is in this lake? (Photo is one of the Rae Lakes in the Sierra Nevada of California.) (b) Model of the lake as a cylinder. [We could go one step further and estimate the mass or weight of this lake. We will see later that water has a density of $1000\,\mathrm{kg/m^3}$, so this lake has a mass of about $\left(10^3\,\mathrm{kg/m^3}\right)\left(10^7\,\mathrm{m^3}\right) \approx 10^{10}\,\mathrm{kg}$, which is about 10 billion kg or 10 million metric tons. (A metric ton is 1000 kg, about 2200 lb, slightly larger than a British ton, 2000 lb.)]

EXAMPLE 1–6 ESTIMATE **Volume of a lake.** Estimate how much water there is in a particular lake, Fig. 1–10a, which is roughly circular, about 1 km across, and you guess it has an average depth of about 10 m.

APPROACH No lake is a perfect circle, nor can lakes be expected to have a perfectly flat bottom. We are only estimating here. To estimate the volume, we can use a simple model of the lake as a cylinder: we multiply the average depth of the lake times its roughly circular surface area, as if the lake were a cylinder (Fig. 1–10b).

PHYSICS APPLIED
Estimating the volume (or mass) of a lake; see also Fig. 1–10

SOLUTION The volume V of a cylinder is the product of its height h times the area of its base: $V = h\pi r^2$, where r is the radius of the circular base.[†] The radius r is $\frac{1}{2}$ km $= 500$ m, so the volume is approximately

$$V = h\pi r^2 \approx (10\,\mathrm{m}) \times (3) \times \left(5 \times 10^2\,\mathrm{m}\right)^2 \approx 8 \times 10^6\,\mathrm{m^3} \approx 10^7\,\mathrm{m^3},$$

where π was rounded off to 3. So the volume is on the order of $10^7\,\mathrm{m^3}$, ten million cubic meters. Because of all the estimates that went into this calculation, the order-of-magnitude estimate $\left(10^7\,\mathrm{m^3}\right)$ is probably better to quote than the $8 \times 10^6\,\mathrm{m^3}$ figure.

NOTE To express our result in U.S. gallons, we see in the Table on the inside front cover that $1\text{ liter} = 10^{-3}\,\mathrm{m^3} \approx \frac{1}{4}$ gallon. Hence, the lake contains $\left(8 \times 10^6\,\mathrm{m^3}\right)\left(1\text{ gallon}/4 \times 10^{-3}\,\mathrm{m^3}\right) \approx 2 \times 10^9$ gallons of water.

[†] Formulas like this for volume, area, etc., are found inside the back cover of this book.

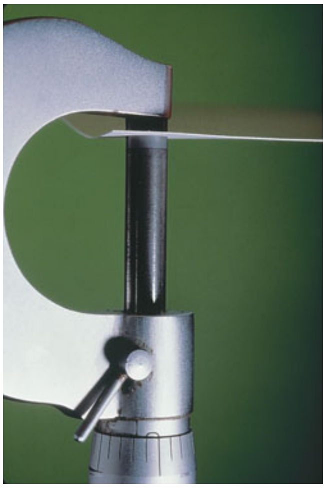


FIGURE 1–11 Example 1–7. Micrometer used for measuring small thicknesses.

EXAMPLE 1–7 ESTIMATE Thickness of a sheet of paper. Estimate the thickness of a page of this book.

APPROACH At first you might think that a special measuring device, a micrometer (Fig. 1–11), is needed to measure the thickness of one page since an ordinary ruler can not be read so finely. But we can use a trick or, to put it in physics terms, make use of a *symmetry*: we can make the reasonable assumption that all the pages of this book are equal in thickness.

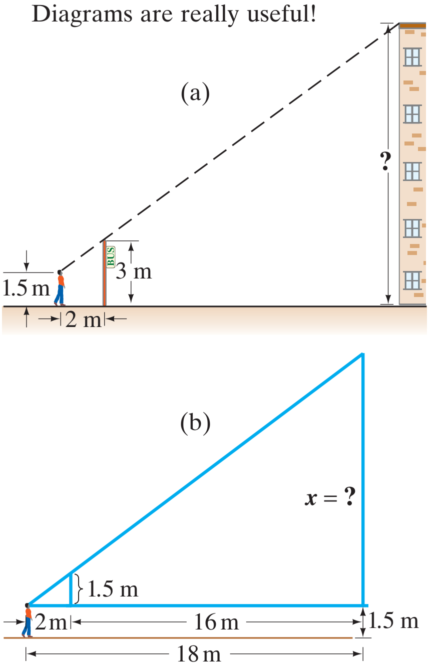
SOLUTION We can use a ruler to measure hundreds of pages at once. If you measure the thickness of the first 500 pages of this book (page 1 to page 500), you might get something like 1.5 cm. Note that 500 numbered pages, counted front and back, is 250 separate pieces of paper. So one sheet must have a thickness of about

$$\frac{1.5\text{ cm}}{250\text{ sheets}} \approx 6 \times 10^{-3}\text{ cm} = 6 \times 10^{-2}\text{ mm},$$

or less than a tenth of a millimeter (0.1 mm).

It cannot be emphasized enough how important it is to draw a diagram when solving a physics Problem, as the next Example shows.

FIGURE 1–12 Example 1–8. Diagrams are really useful!



EXAMPLE 1–8 ESTIMATE Height by triangulation. Estimate the height of the building shown in Fig. 1–12, by "triangulation," with the help of a bus-stop pole and a friend.

APPROACH By standing your friend next to the pole, you estimate the height of the pole to be 3 m. You next step away from the pole until the top of the pole is in line with the top of the building, Fig. 1–12a. You are 5 ft 6 in. tall, so your eyes are about 1.5 m above the ground. Your friend is taller, and when she stretches out her arms, one hand touches you, and the other touches the pole, so you estimate that distance as 2 m (Fig. 1–12a). You then pace off the distance from the pole to the base of the building with big, 1-m-long steps, and you get a total of 16 steps or 16 m.

SOLUTION Now you draw, to scale, the diagram shown in Fig. 1–12b using these measurements. You can measure, right on the diagram, the last side of the triangle to be about $x = 13$ m. Alternatively, you can use similar triangles to obtain the height x:

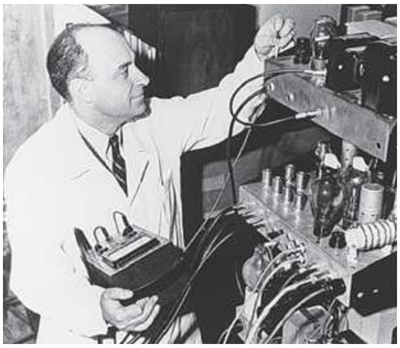
$$\frac{1.5\text{ m}}{2\text{ m}} = \frac{x}{18\text{ m}},$$

so

$$x \approx 13\tfrac{1}{2}\text{ m}.$$

Finally you add in your eye height of 1.5 m above the ground to get your final result: the building is about 15 m tall.

FIGURE 1–13 Enrico Fermi. Fermi contributed significantly to both theoretical and experimental physics, a feat almost unique in modern times.



Another approach, this one made famous by Enrico Fermi (1901–1954, Fig. 1–13), was to show his students how to estimate the number of piano tuners in a city, say, Chicago or San Francisco. To get a rough order-of-magnitude estimate of the number of piano tuners today in San Francisco, a city of about 800,000 inhabitants, we can proceed by estimating the number of functioning pianos, how often each piano is tuned, and how many pianos each tuner can tune. To estimate the number of pianos in San Francisco, we note that certainly not everyone has a piano. A guess of 1 family in 3 having a piano would correspond to 1 piano per 12 persons, assuming an average family of 4 persons.

As an order of magnitude, let's say 1 piano per 10 people. This is certainly more reasonable than 1 per 100 people, or 1 per every person, so let's proceed with the estimate that 1 person in 10 has a piano, or about 80,000 pianos in San Francisco. Now a piano tuner needs an hour or two to tune a piano. So let's estimate that a tuner can tune 4 or 5 pianos a day. A piano ought to be tuned every 6 months or a year—let's say once each year. A piano tuner tuning 4 pianos a day, 5 days a week, 50 weeks a year can tune about 1000 pianos a year. So San Francisco, with its (very) roughly 80,000 pianos, needs about 80 piano tuners. This is, of course, only a rough estimate.[†] It tells us that there must be many more than 10 piano tuners, and surely not as many as 1000.

PROBLEM SOLVING

Estimating how many piano tuners there are in a city

A Harder Example—But Powerful

EXAMPLE 1–9 ESTIMATE **Estimating the radius of Earth.** Believe it or not, you can estimate the radius of the Earth without having to go into space (see the photograph on page 1). If you have ever been on the shore of a large lake, you may have noticed that you cannot see the beaches, piers, or rocks at water level across the lake on the opposite shore. The lake seems to bulge out between you and the opposite shore—a good clue that the Earth is round. Suppose you climb a stepladder and discover that when your eyes are 10 ft (3.0 m) above the water, you can just see the rocks at water level on the opposite shore. From a map, you estimate the distance to the opposite shore as $d \approx 6.1$ km. Use Fig. 1–14 with $h = 3.0$ m to estimate the radius R of the Earth.

APPROACH We use simple geometry, including the theorem of Pythagoras,

$$c^2 = a^2 + b^2,$$

where c is the length of the hypotenuse of any right triangle, and a and b are the lengths of the other two sides.

SOLUTION For the right triangle of Fig. 1–14, the two sides are the radius of the Earth R and the distance $d = 6.1\text{ km} = 6100\text{ m}$. The hypotenuse is approximately the length $R + h$, where $h = 3.0$ m. By the Pythagorean theorem,

$$\begin{aligned} R^2 + d^2 &\approx (R + h)^2 \\ &\approx R^2 + 2hR + h^2. \end{aligned}$$

We solve algebraically for R, after cancelling R^2 on both sides:

$$\begin{aligned} R \approx \frac{d^2 - h^2}{2h} &= \frac{(6100\text{ m})^2 - (3.0\text{ m})^2}{6.0\text{ m}} \\ &= 6.2 \times 10^6\text{ m} \\ &= 6200\text{ km}. \end{aligned}$$

NOTE Precise measurements give 6380 km. But look at your achievement! With a few simple rough measurements and simple geometry, you made a good estimate of the Earth's radius. You did not need to go out in space, nor did you need a very long measuring tape.

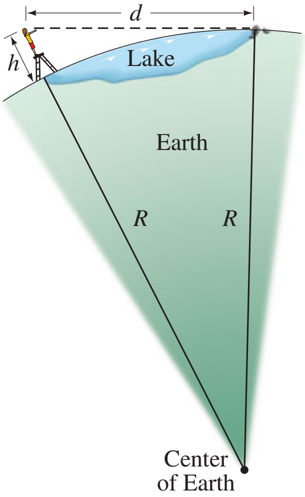


FIGURE 1–14 Example 1–9, but not to scale. You can just barely see rocks at water level on the opposite shore of a lake 6.1 km wide if you stand on a stepladder.

EXERCISE F Return to the second Chapter-Opening Question, page 1, and answer it again now. Try to explain why you may have answered differently the first time.

[†] A check of the San Francisco Yellow Pages (done after this calculation) reveals about 60 listings. Each of these listings may employ more than one tuner, but on the other hand, each may also do repairs as well as tuning. In any case, our estimate is reasonable.

*1–8 Dimensions and Dimensional Analysis

When we speak of the **dimensions** of a quantity, we are referring to the type of base units or base quantities that make it up. The dimensions of area, for example, are always length squared, abbreviated $[L^2]$, using square brackets; the units can be square meters, square feet, cm^2, and so on. Velocity, on the other hand, can be measured in units of km/h, m/s, or mi/h, but the dimensions are always a length $[L]$ divided by a time $[T]$: that is, $[L/T]$.

The formula for a quantity may be different in different cases, but the dimensions remain the same. For example, the area of a triangle of base b and height h is $A = \frac{1}{2}bh$, whereas the area of a circle of radius r is $A = \pi r^2$. The formulas are different in the two cases, but the dimensions of area are always $[L^2]$.

Dimensions can be used as a help in working out relationships, a procedure referred to as **dimensional analysis**. One useful technique is the use of dimensions to check if a relationship is *incorrect*. Note that we add or subtract quantities only if they have the same dimensions (we don't add centimeters and hours); and the quantities on each side of an equals sign must have the same dimensions. (In numerical calculations, the units must also be the same on both sides of an equation.)

For example, suppose you derived the equation $v = v_0 + \frac{1}{2}at^2$, where v is the speed of an object after a time t, v_0 is the object's initial speed, and the object undergoes an acceleration a. Let's do a dimensional check to see if this equation could be correct or is surely incorrect. Note that numerical factors, like the $\frac{1}{2}$ here, do not affect dimensional checks. We write a dimensional equation as follows, remembering that the dimensions of speed are $[L/T]$ and (as we shall see in Chapter 2) the dimensions of acceleration are $[L/T^2]$:

$$\begin{aligned}\left[\frac{L}{T}\right] &\stackrel{?}{=} \left[\frac{L}{T}\right] + \left[\frac{L}{T^2}\right][T^2] \\ &\stackrel{?}{=} \left[\frac{L}{T}\right] + [L].\end{aligned}$$

The dimensions are incorrect: on the right side, we have the sum of quantities whose dimensions are not the same. Thus we conclude that an error was made in the derivation of the original equation.

A dimensional check can only tell you when a relationship is wrong. It can't tell you if it is completely right. For example, a dimensionless numerical factor (such as $\frac{1}{2}$ or 2π) could be missing.

Dimensional analysis can also be used as a quick check on an equation you are not sure about. For example, consider a simple pendulum of length ℓ. Suppose that you can't remember whether the equation for the period T (the time to make one back-and-forth swing) is $T = 2\pi\sqrt{\ell/g}$ or $T = 2\pi\sqrt{g/\ell}$, where g is the acceleration due to gravity and, like all accelerations, has dimensions $[L/T^2]$. (Do not worry about these formulas—the correct one will be derived in Chapter 11; what we are concerned about here is a person's recalling whether it contains ℓ/g or g/ℓ.) A dimensional check shows that the former (ℓ/g) is correct:

$$[T] = \sqrt{\frac{[L]}{[L/T^2]}} = \sqrt{[T^2]} = [T],$$

whereas the latter (g/ℓ) is not:

$$[T] \neq \sqrt{\frac{[L/T^2]}{[L]}} = \sqrt{\frac{1}{[T^2]}} = \frac{1}{[T]}.$$

The constant 2π has no dimensions and so can't be checked using dimensions.

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*Some Sections of this book, such as this one, may be considered *optional* at the discretion of the instructor, and they are marked with an asterisk (*). See the Preface for more details.

Summary

[*The Summary that appears at the end of each Chapter in this book gives a brief overview of the main ideas of the Chapter. The Summary* cannot *serve to give an understanding of the material, which can be accomplished only by a detailed reading of the Chapter.*]

Physics, like other sciences, is a creative endeavor. It is not simply a collection of facts. Important **theories** are created with the idea of explaining **observations**. To be accepted, theories are "tested" by comparing their predictions with the results of actual experiments. Note that, in general, a theory cannot be "proved" in an absolute sense.

Scientists often devise models of physical phenomena. A **model** is a kind of picture or analogy that helps to describe the phenomena in terms of something we already know. A **theory**, often developed from a model, is usually deeper and more complex than a simple model.

A scientific **law** is a concise statement, often expressed in the form of an equation, which quantitatively describes a wide range of phenomena.

Measurements play a crucial role in physics, but can never be perfectly precise. It is important to specify the **uncertainty** of a measurement either by stating it directly using the ± notation, and/or by keeping only the correct number of **significant figures**.

Physical quantities are always specified relative to a particular standard or **unit**, and the unit used should always be stated. The commonly accepted set of units today is the **Système International** (SI), in which the standard units of length, mass, and time are the **meter**, **kilogram**, and **second**.

When converting units, check all **conversion factors** for correct cancellation of units.

Making rough, **order-of-magnitude estimates** is a very useful technique in science as well as in everyday life.

[*The **dimensions** of a quantity refer to the combination of base quantities that comprise it. Velocity, for example, has dimensions of [length/time] or $[L/T]$. Working with only the dimensions of the various quantities in a given relationship (this technique is called **dimensional analysis**) makes it possible to check a relationship for correct form.]

Questions

1. What are the merits and drawbacks of using a person's foot as a standard? Consider both (*a*) a particular person's foot, and (*b*) any person's foot. Keep in mind that it is advantageous that fundamental standards be accessible (easy to compare to), invariable (do not change), indestructible, and reproducible.
2. What is wrong with this road sign:

   Memphis 7 mi (11.263 km)?
3. Why is it incorrect to think that the more digits you include in your answer, the more accurate it is?
4. For an answer to be complete, the units need to be specified. Why?
5. You measure the radius of a wheel to be 4.16 cm. If you multiply by 2 to get the diameter, should you write the result as 8 cm or as 8.32 cm? Justify your answer.
6. Express the sine of 30.0° with the correct number of significant figures.
7. List assumptions useful to estimate the number of car mechanics in (*a*) San Francisco, (*b*) your hometown, and then make the estimates.

MisConceptual Questions

[List all answers that are valid.]

1. A student's weight displayed on a digital scale is 117.2 lb. This would suggest her weight is
(*a*) within 1% of 117.2 lb.
(*b*) exactly 117.2 lb.
(*c*) somewhere between 117.18 and 117.22 lb.
(*d*) somewhere between 117.0 and 117.4 lb.

2. Four students use different instruments to measure the length of the same pen. Which measurement implies the greatest precision?
(*a*) 160.0 mm. (*b*) 16.0 cm. (*c*) 0.160 m. (*d*) 0.00016 km.
(*e*) Need more information.

3. The number 0.0078 has how many significant figures?
(*a*) 1. (*b*) 2. (*c*) 3. (*d*) 4.

4. How many significant figures does 1.362 + 25.2 have?
(*a*) 2. (*b*) 3. (*c*) 4. (*d*) 5.

5. Accuracy represents
(*a*) repeatability of a measurement, using a given instrument.
(*b*) how close a measurement is to the true value.
(*c*) an ideal number of measurements to make.
(*d*) how poorly an instrument is operating.

6. To convert from ft^2 to yd^2, you should
(*a*) multiply by 3.
(*b*) multiply by 1/3.
(*c*) multiply by 9.
(*d*) multiply by 1/9.
(*e*) multiply by 6.
(*f*) multiply by 1/6.

7. Which is *not* true about an order-of-magnitude estimation?
(*a*) It gives you a rough idea of the answer.
(*b*) It can be done by keeping only one significant figure.
(*c*) It can be used to check if an exact calculation is reasonable.
(*d*) It may require making some reasonable assumptions in order to calculate the answer.
(*e*) It will always be accurate to at least two significant figures.

***8.** $[L^2]$ represents the dimensions for which of the following?
(*a*) cm^2.
(*b*) square feet.
(*c*) m^2.
(*d*) All of the above.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

[The Problems at the end of each Chapter are ranked I, II, *or* III *according to estimated difficulty, with* (I) *Problems being easiest. Level* III *are meant as challenges for the best students. The Problems are arranged by Section, meaning that the reader should have read up to and including that Section, but not only that Section—Problems often depend on earlier material. Next is a set of "General Problems" not arranged by Section and not ranked. Finally, there are "Search and Learn" Problems that require rereading parts of the Chapter.]*

1–4 Measurement, Uncertainty, Significant Figures

*(*Note: *In Problems, assume a number like* 6.4 *is accurate to* ± 0.1; *and* 950 *is* ± 10 *unless* 950 *is said to be "precisely" or "very nearly"* 950, *in which case assume* 950 ± 1.*)*

1. (I) How many significant figures do each of the following numbers have: (*a*) 214, (*b*) 81.60, (*c*) 7.03, (*d*) 0.03, (*e*) 0.0086, (*f*) 3236, and (*g*) 8700?

2. (I) Write the following numbers in powers of 10 notation: (*a*) 1.156, (*b*) 21.8, (*c*) 0.0068, (*d*) 328.65, (*e*) 0.219, and (*f*) 444.

3. (I) Write out the following numbers in full with the correct number of zeros: (*a*) 8.69×10^4, (*b*) 9.1×10^3, (*c*) 8.8×10^{-1}, (*d*) 4.76×10^2, and (*e*) 3.62×10^{-5}.

4. (II) The age of the universe is thought to be about 14 billion years. Assuming two significant figures, write this in powers of 10 in (*a*) years, (*b*) seconds.

5. (II) What is the percent uncertainty in the measurement $5.48 \pm 0.25\,\text{m}$?

6. (II) Time intervals measured with a stopwatch typically have an uncertainty of about 0.2 s, due to human reaction time at the start and stop moments. What is the percent uncertainty of a hand-timed measurement of (*a*) 5.5 s, (*b*) 55 s, (*c*) 5.5 min?

7. (II) Add $(9.2 \times 10^3\,\text{s}) + (8.3 \times 10^4\,\text{s}) + (0.008 \times 10^6\,\text{s})$.

8. (II) Multiply $3.079 \times 10^2\,\text{m}$ by $0.068 \times 10^{-1}\,\text{m}$, taking into account significant figures.

9. (II) What, approximately, is the percent uncertainty for a measurement given as $1.57\,\text{m}^2$?

10. (III) What, roughly, is the percent uncertainty in the volume of a spherical beach ball of radius $r = 0.84 \pm 0.04\,\text{m}$?

11. (III) What is the area, and its approximate uncertainty, of a circle of radius $3.1 \times 10^4\,\text{cm}$?

1–5 and 1–6 Units, Standards, SI, Converting Units

12. (I) Write the following as full (decimal) numbers without prefixes on the units: (*a*) 286.6 mm, (*b*) 85 μV, (*c*) 760 mg, (*d*) 62.1 ps, (*e*) 22.5 nm, (*f*) 2.50 gigavolts.

13. (I) Express the following using the prefixes of Table 1–4: (*a*) 1×10^6 volts, (*b*) 2×10^{-6} meters, (*c*) 6×10^3 days, (*d*) 18×10^2 bucks, and (*e*) 7×10^{-7} seconds.

14. (I) One hectare is defined as $1.000 \times 10^4\,\text{m}^2$. One acre is $4.356 \times 10^4\,\text{ft}^2$. How many acres are in one hectare?

15. (II) The Sun, on average, is 93 million miles from Earth. How many meters is this? Express (*a*) using powers of 10, and (*b*) using a metric prefix (km).

16. (II) Express the following sum with the correct number of significant figures: $1.80\,\text{m} + 142.5\,\text{cm} + 5.34 \times 10^5\,\mu\text{m}$.

17. (II) A typical atom has a diameter of about $1.0 \times 10^{-10}\,\text{m}$. (*a*) What is this in inches? (*b*) Approximately how many atoms are along a 1.0-cm line, assuming they just touch?

18. (II) Determine the conversion factor between (*a*) km/h and mi/h, (*b*) m/s and ft/s, and (*c*) km/h and m/s.

19. (II) A **light-year** is the distance light travels in one year (at speed $= 2.998 \times 10^8\,\text{m/s}$). (*a*) How many meters are there in 1.00 light-year? (*b*) An astronomical unit (AU) is the average distance from the Sun to Earth, $1.50 \times 10^8\,\text{km}$. How many AU are there in 1.00 light-year?

20. (II) How much longer (percentage) is a one-mile race than a 1500-m race ("the metric mile")?

21. (II) American football uses a field that is 100.0 yd long, whereas a soccer field is 100.0 m long. Which field is longer, and by how much (give yards, meters, and percent)?

22. (II) (*a*) How many seconds are there in 1.00 year? (*b*) How many nanoseconds are there in 1.00 year? (*c*) How many years are there in 1.00 second?

23. (II) Use Table 1–3 to estimate the total number of protons or neutrons in (*a*) a bacterium, (*b*) a DNA molecule, (*c*) the human body, (*d*) our Galaxy.

24. (III) A standard baseball has a circumference of approximately 23 cm. If a baseball had the same mass per unit volume (see Tables in Section 1–5) as a neutron or a proton, about what would its mass be?

1–7 Order-of-Magnitude Estimating

*(*Note: *Remember that for rough estimates, only round numbers are needed both as input to calculations and as final results.)*

25. (I) Estimate the order of magnitude (power of 10) of: (*a*) 2800, (*b*) 86.30×10^3, (*c*) 0.0076, and (*d*) 15.0×10^8.

26. (II) Estimate how many books can be shelved in a college library with $3500\,\text{m}^2$ of floor space. Assume 8 shelves high, having books on both sides, with corridors 1.5 m wide. Assume books are about the size of this one, on average.

27. (II) Estimate how many hours it would take to run (at 10 km/h) across the U.S. from New York to California.

28. (II) Estimate the number of liters of water a human drinks in a lifetime.

29. (II) Estimate how long it would take one person to mow a football field using an ordinary home lawn mower (Fig. 1–15). (State your assumption, such as the mower moves with a 1-km/h speed, and has a 0.5-m width.)

FIGURE 1–15 Problem 29.

30. (II) Estimate the number of gallons of gasoline consumed by the total of all automobile drivers in the U.S., per year.

31. (II) Estimate the number of dentists (*a*) in San Francisco and (*b*) in your town or city.

32. (III) You are in a hot air balloon, 200 m above the flat Texas plains. You look out toward the horizon. How far out can you see—that is, how far is your horizon? The Earth's radius is about 6400 km.

33. (III) I agree to hire you for 30 days. You can decide between two methods of payment: either (1) \$1000 a day, or (2) one penny on the first day, two pennies on the second day and continue to double your daily pay each day up to day 30. Use quick estimation to make your decision, and justify it.

34. (III) Many sailboats are docked at a marina 4.4 km away on the opposite side of a lake. You stare at one of the sailboats because, when you are lying flat at the water's edge, you can just see its deck but none of the side of the sailboat. You then go to that sailboat on the other side of the lake and measure that the deck is 1.5 m above the level of the water. Using Fig. 1–16, where $h = 1.5\,\text{m}$, estimate the radius R of the Earth.

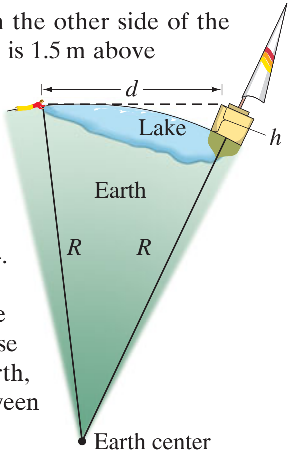

FIGURE 1–16 Problem 34. You see a sailboat across a lake (not to scale). R is the radius of the Earth. Because of the curvature of the Earth, the water "bulges out" between you and the boat.

35. (III) You are lying on a beach, your eyes 20 cm above the sand. Just as the Sun sets, fully disappearing over the horizon, you immediately jump up, your eyes now 150 cm above the sand, and you can again just see the top of the Sun. If you count the number of seconds ($= t$) until the Sun fully disappears again, you can estimate the Earth's radius. But for this Problem, use the known radius of the Earth to calculate the time t.

*1–8 Dimensions

***36.** (I) What are the dimensions of density, which is mass per volume?

***37.** (II) The speed v of an object is given by the equation $v = At^3 - Bt$, where t refers to time. (*a*) What are the dimensions of A and B? (*b*) What are the SI units for the constants A and B?

***38.** (II) Three students derive the following equations in which x refers to distance traveled, v the speed, a the acceleration $\left(\text{m/s}^2\right)$, t the time, and the subscript zero $\left({}_0\right)$ means a quantity at time $t = 0$. Here are their equations: (*a*) $x = vt^2 + 2at$, (*b*) $x = v_0 t + \frac{1}{2}at^2$, and (*c*) $x = v_0 t + 2at^2$. Which of these could possibly be correct according to a dimensional check, and why?

***39.** (III) The smallest meaningful measure of length is called the **Planck length**, and is defined in terms of three fundamental constants in nature: the speed of light $c = 3.00 \times 10^8\,\text{m/s}$, the gravitational constant $G = 6.67 \times 10^{-11}\,\text{m}^3/\text{kg}\cdot\text{s}^2$, and Planck's constant $h = 6.63 \times 10^{-34}\,\text{kg}\cdot\text{m}^2/\text{s}$. The Planck length ℓ_P is given by the following combination of these three constants:

$$\ell_\text{P} = \sqrt{\frac{Gh}{c^3}}.$$

Show that the dimensions of ℓ_P are length $[L]$, and find the order of magnitude of ℓ_P. [Recent theories (Chapters 32 and 33) suggest that the smallest particles (quarks, leptons) are "strings" with lengths on the order of the Planck length, $10^{-35}\,\text{m}$. These theories also suggest that the "Big Bang," with which the universe is believed to have begun, started from an initial size on the order of the Planck length.]

General Problems

40. **Global positioning satellites (GPS)** can be used to determine your position with great accuracy. If one of the satellites is 20,000 km from you, and you want to know your position to ± 2 m, what percent uncertainty in the distance is required? How many significant figures are needed in the distance?

41. **Computer chips** (Fig. 1–17) are etched on circular silicon wafers of thickness 0.300 mm that are sliced from a solid cylindrical silicon crystal of length 25 cm. If each wafer can hold 400 chips, what is the maximum number of chips that can be produced from one entire cylinder?

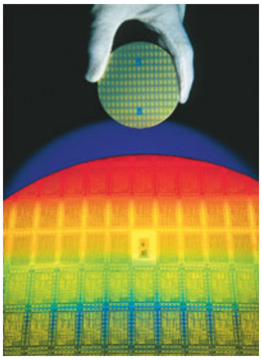

FIGURE 1–17 Problem 41. The wafer held by the hand is shown below, enlarged and illuminated by colored light. Visible are rows of integrated circuits (chips).

42. A typical adult human lung contains about 300 million tiny cavities called alveoli. Estimate the average diameter of a single alveolus.

43. If you used only a keyboard to enter data, how many years would it take to fill up the hard drive in a computer that can store 1.0 terabytes $\left(1.0 \times 10^{12}\ \text{bytes}\right)$ of data? Assume 40-hour work weeks, and that you can type 180 characters per minute, and that one byte is one keyboard character.

44. An average family of four uses roughly 1200 L (about 300 gallons) of water per day $\left(1\,\text{L} = 1000\,\text{cm}^3\right)$. How much depth would a lake lose per year if it covered an area of $50\,\text{km}^2$ with uniform depth and supplied a local town with a population of 40,000 people? Consider only population uses, and neglect evaporation, rain, creeks and rivers.

45. Estimate the number of jelly beans in the jar of Fig. 1–18.

FIGURE 1–18 Problem 45. Estimate the number of jelly beans in the jar.

46. How big is a ton? That is, what is the volume of something that weighs a ton? To be specific, estimate the diameter of a 1-ton rock, but first make a wild guess: will it be 1 ft across, 3 ft, or the size of a car? [*Hint*: Rock has mass per volume about 3 times that of water, which is 1 kg per liter $(10^3\,\text{cm}^3)$ or 62 lb per cubic foot.]

47. A certain compact disc (CD) contains 783.216 megabytes of digital information. Each byte consists of exactly 8 bits. When played, a CD player reads the CD's information at a constant rate of 1.4 megabits per second. How many minutes does it take the player to read the entire CD?

48. Hold a pencil in front of your eye at a position where its blunt end just blocks out the Moon (Fig. 1–19). Make appropriate measurements to estimate the diameter of the Moon, given that the Earth–Moon distance is 3.8×10^5 km.

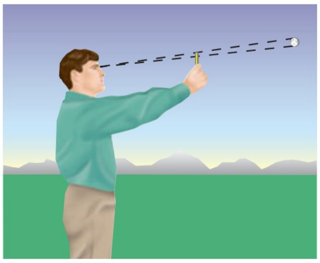

FIGURE 1–19
Problem 48. How big is the Moon?

49. A storm dumps 1.0 cm of rain on a city 6 km wide and 8 km long in a 2-h period. How many metric tons $(1 \text{ metric ton} = 10^3\,\text{kg})$ of water fell on the city? ($1\,\text{cm}^3$ of water has a mass of $1\,\text{g} = 10^{-3}\,\text{kg}$.) How many gallons of water was this?

50. Estimate how many days it would take to walk around the Earth, assuming 12 h walking per day at 4 km/h.

51. One liter $(1000\,\text{cm}^3)$ of oil is spilled onto a smooth lake. If the oil spreads out uniformly until it makes an oil slick just one molecule thick, with adjacent molecules just touching, estimate the diameter of the oil slick. Assume the oil molecules have a diameter of 2×10^{-10} m.

52. A watch manufacturer claims that its watches gain or lose no more than 8 seconds in a year. How accurate are these watches, expressed as a percentage?

53. An angstrom (symbol Å) is a unit of length, defined as 10^{-10} m, which is on the order of the diameter of an atom. (*a*) How many nanometers are in 1.0 angstrom? (*b*) How many femtometers or fermis (the common unit of length in nuclear physics) are in 1.0 angstrom? (*c*) How many angstroms are in 1.0 m? (*d*) How many angstroms are in 1.0 light-year (see Problem 19)?

54. Jim stands beside a wide river and wonders how wide it is. He spots a large rock on the bank directly across from him. He then walks upstream 65 strides and judges that the angle between him and the rock, which he can still see, is now at an angle of 30° downstream (Fig. 1–20). Jim measures his stride to be about 0.8 m long. Estimate the width of the river.

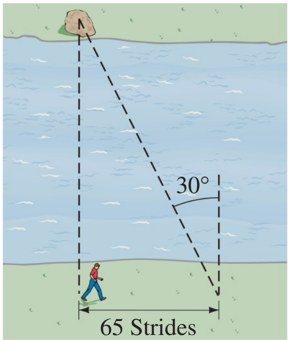

FIGURE 1–20
Problem 54.

55. Determine the percent uncertainty in θ, and in $\sin\theta$, when (*a*) $\theta = 15.0° \pm 0.5°$, (*b*) $\theta = 75.0° \pm 0.5°$.

56. If you walked north along one of Earth's lines of longitude until you had changed latitude by 1 minute of arc (there are 60 minutes per degree), how far would you have walked (in miles)? This distance is a **nautical mile**.

57. Make a rough estimate of the volume of your body (in m^3).

58. The following formula estimates an average person's lung capacity V (in liters, where $1\,\text{L} = 10^3\,\text{cm}^3$):

$$V = 4.1H - 0.018A - 2.7,$$

where H and A are the person's height (in meters) and age (in years), respectively. In this formula, what are the units of the numbers 4.1, 0.018, and 2.7?

59. One mole of atoms consists of 6.02×10^{23} individual atoms. If a mole of atoms were spread uniformly over the Earth's surface, how many atoms would there be per square meter?

60. The density of an object is defined as its mass divided by its volume. Suppose a rock's mass and volume are measured to be 6 g and $2.8325\,\text{cm}^3$. To the correct number of significant figures, determine the rock's density (mass/volume).

61. Recent findings in astrophysics suggest that the observable universe can be modeled as a sphere of radius $R = 13.7 \times 10^9$ light-years $= 13.0 \times 10^{25}$ m with an average total mass density of about $1 \times 10^{-26}\,\text{kg/m}^3$. Only about 4% of total mass is due to "ordinary" matter (such as protons, neutrons, and electrons). Estimate how much ordinary matter (in kg) there is in the observable universe. (For the light-year, see Problem 19.)

Search and Learn

1. Galileo is to Aristotle as Copernicus is to Ptolemy. See Section 1–1 and explain this analogy.

2. How many wavelengths of orange krypton-86 light (Section 1–5) would fit into the thickness of one page of this book?

3. Using the French Academy of Sciences' original definition of the meter, determine Earth's circumference and radius in those meters.

4. Estimate the ratio (order of magnitude) of the mass of a human to the mass of a DNA molecule.

5. To the correct number of significant figures, use the information inside the front cover of this book to determine the ratio of (*a*) the surface area of Earth compared to the surface area of the Moon; (*b*) the volume of Earth compared to the volume of the Moon.

ANSWERS TO EXERCISES

A: (*d*).

B: All three have three significant figures; the number of decimal places is (*a*) 2, (*b*) 3, (*c*) 4.

C: (*a*) 2.58×10^{-2}, 3; (*b*) 4.23×10^4, 3 (probably); (*c*) 3.4450×10^2, 5.

D: (*f*).

E: No: 15 m/s ≈ 34 mi/h.

F: (*c*).