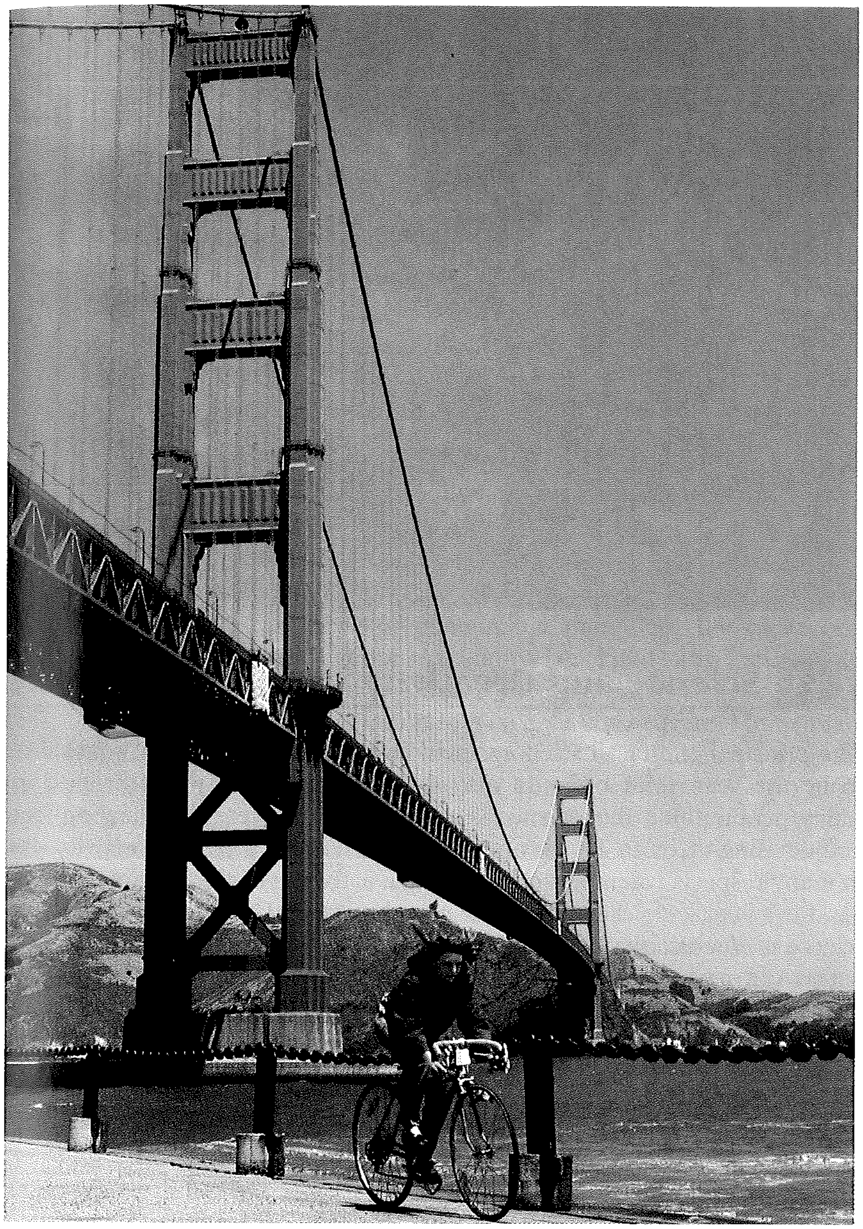


How many aspects of Physics do you see in this photograph? (Partial answer given upside down at bottom of photograph.)

Motion, speed, momentum, work, energy, structures and forces within them (why do they stay up?), rotational motion, torque, angular momentum, fluids, drag forces, friction, wave motion, . . .

C H A P T E R

INTRODUCTION 1

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 the areas of motion, fluids, heat, sound, light, electricity and magnetism, and the modern topics of relativity, atomic structure, condensed-matter physics, nuclear physics, elementary particles, and astrophysics. We will cover all these topics in this book, beginning with motion (or mechanics, as it is often called). But before we begin on the physics itself, let us take a brief look at how this overall activity called "science," including physics, is actually practiced.

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, Sophocles, and Diogenes.

1–1 Science and Creativity

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. This is not the case. Science is a creative activity that in many respects resembles other creative activities of the human mind.

Observation

Let's take some examples to see why this is true. One important aspect of science is *observation* of events. But observation requires imagination, for scientists can never include everything in a description of what they observe. Hence, scientists must make judgments about what is relevant in their observations. As an example, let us consider how two great minds, Aristotle (384–322 B.C.; Fig. 1–1) and Galileo (1564–1642; Fig. 2–15), 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 believed that the natural state of an object is to be at rest. Galileo, in his reexamination of horizontal motion in the early 1600s, 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 approach, Galileo founded our modern view of motion (more details in Chapters 2, 3, and 4), and he did so with a leap of the imagination. Galileo made this leap conceptually, without actually eliminating friction.

Theories are creations

Observation and careful experimentation and measurement are 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. They 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 certainly not arrived at because someone observed atoms. 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.

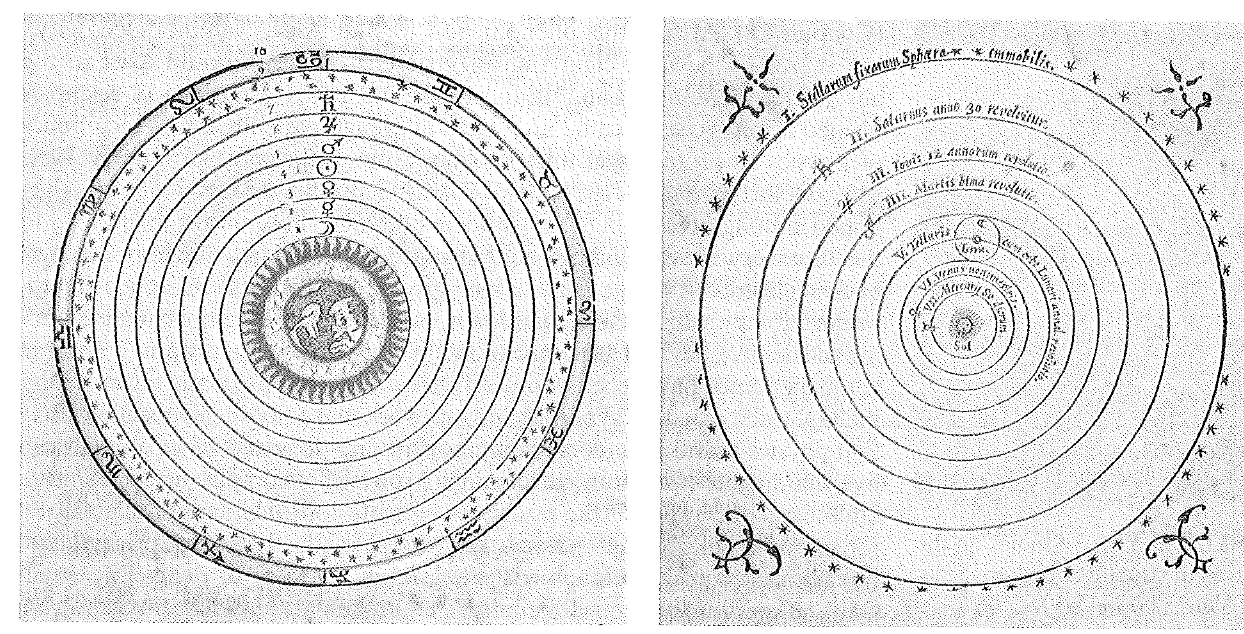
Testing a theory

Although the testing of theories can be considered to distinguish science from other creative fields, it should not be assumed that a theory is "proved" by testing. First of all, no measuring instrument is perfect, so exact confirmation cannot be possible. Furthermore, it is not possible to test a theory for every possible set of circumstances. Hence a theory can never be absolutely "proved." In fact, theories themselves are generally not perfect—a theory rarely agrees with experiment exactly, within experimental error, in every single case in which it is tested. Indeed, the history of science tells us that long-held theories are sometimes replaced by new ones. The process of one theory replacing another is an important subject in the philosophy of science; we can discuss it here only briefly.

Theory acceptance

A new theory is accepted by scientists in some cases because its predictions are quantitatively in much 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 (or no more complex) and richer theory, one which unifies and explains a greater variety of phenomena, is more useful and beautiful to a scientist. And this aspect,

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)

as well as quantitative agreement, plays a major role in the acceptance of a theory.

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. In this respect, the theory of relativity might be considered as mere "fine-tuning" of the older theory. 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 $E = mc^2$). Indeed, our view of the world underwent a major change when relativity theory came to be accepted.

1–2 Physics and Its Relation to Other Fields

For a long time science was more or less a united whole known as natural philosophy. Not until the last century or two 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 but 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. Later, in the 1930s and 1940s, a number of scientists trained as physicists became interested in applying the ideas and techniques of physics to problems in microbiology. Among the most prominent were Max Delbrück (1906–1981) and Erwin Schrödinger (1887–1961). They hoped, among other things, that studying biological organisms might lead to the discovery of new unsuspected laws of physics. Alas, this hope has not been realized; but their efforts helped give rise to the field we now call molecular biology, which has resulted in a dramatic increase in our understanding of the genetics and structure of living beings.

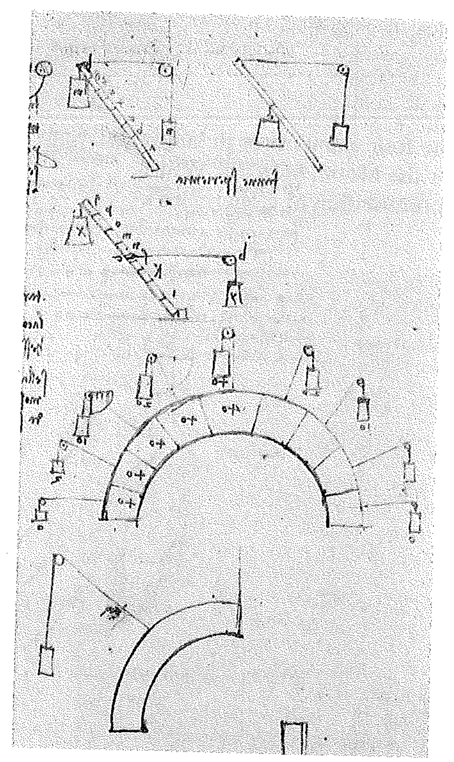


FIGURE 1–3 Studies on the forces in structures by Leonardo da Vinci (1452–1519).

You do not have to be a research scientist in, say, medicine or molecular biology to be able to use physics in your work. 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 do a more effective job 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 them-

(a) (b)

FIGURE 1–4 (a) This Greek temple in Paestum, Italy, was built 2500 years ago, and still stands. (b) Collapse of the Hartford Civic Center in 1978, just two years after it was built.

selves may never have to calculate, for example, 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). But architects must know the principles behind these analyses in order to make realistic designs and to communicate effectively with engineering consultants and other specialists. From the aesthetic or psychological point of view, too, architects must be aware of the forces involved in a structure—for instability, even if only illusory, can be discomforting to those who must live or work in the structure. Indeed, many of the features we admire in the architecture of the past three millennia were introduced not for their decorative effect but rather for practical purposes. The development of the arch as a means to span a space and at the same time support a heavy load will be discussed in Chapter 9, where we will see that the pointed, or Gothic, arch was not originally a decorative device but a technological development of considerable importance.

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

Models

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 we are 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 if it were 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 onto—when we cannot see what actually is happening. Models often give us a deeper understanding: the analogy to a known system (for instance, water waves in the above example) can suggest new experiments to perform and can provide ideas about what other related phenomena might occur.

Theories (vs. models)

You may wonder what the difference is between a theory and a model. Sometimes the words are used interchangeably. Usually, however, a model is relatively simple and provides a structural similarity to the phenomena being studied, whereas a **theory** is broader, more detailed, and can give quantitatively testable predictions, often with great precision. Sometimes, as a model is developed and modified and corresponds more closely to experiment over a wide range of phenomena, it may come to be referred to as a theory. The atomic theory is an example, as is the wave theory of light.

Models can be very helpful, and they often lead to important theories. But it is important not to confuse a model, or a theory, with the real system or the phenomena themselves.

Laws and principles

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

To be called a law, a statement must be found experimentally valid over a wide range of observed phenomena. In a sense, the law brings a unity to many observations. For less general statements, the term **principle** is often used (such as Archimedes' principle). Where to draw the line between laws and principles is, of course, arbitrary, and there is not always complete consistency.

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. Even then, as new information comes in, certain laws may have to be modified or discarded.

Scientists normally do their work 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

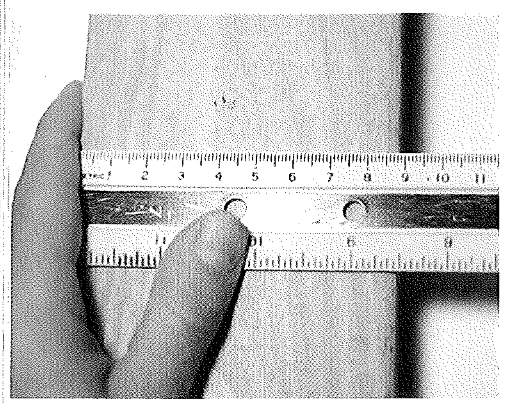


FIGURE 1–5 Measuring the width of a board with a centimeter ruler. Accuracy is about ±1 mm.

In the quest to understand the world around us, scientists seek to find relationships among the various physical quantities they observe and measure.

We may ask, for example, in what way does the magnitude of a force on an object affect the object's speed or acceleration? Or by how much does the pressure of gas in a closed container (such as a tire) change if the temperature is raised or lowered? Scientists normally try to express such relationships quantitatively, in terms of equations whose symbols represent the quantities involved. To determine (or confirm) the form of a relationship, careful experimental measurements are required, although creative thinking also plays a role.

Every measurement has an uncertainty

Accurate measurements are an important part of physics. But no measurement is absolutely precise. There is an uncertainty associated with every measurement. Uncertainty arises from different sources. Among the most important, 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 accurate to about 0.1 cm, the smallest division on the ruler. The reason is that it is difficult for the observer to interpolate between the smallest divisions, and the ruler itself may not have been manufactured or calibrated to an accuracy very much better than this.

Stating the uncertainty

When giving the result of a measurement, it is also important to state the precision, or **estimated uncertainty**, in the measurement. For example, the width of a board might be written as 5.2 ± 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 5.1 and 5.3 cm. The **percent uncertainty** is simply the ratio of the uncertainty to the measured value, multiplied by 100. For example, if the measurement is 5.2 and the uncertainty about 0.1 cm, the percent uncertainty is

$$\frac{0.1}{5.2} \times 100 = 2\%.$$

Assumed uncertainty

Often the uncertainty in a measured value is not specified explicitly. In such cases, the uncertainty is generally assumed to be one or two units (or even three) in the last digit specified. For example, if a length is given as 5.2 cm, the uncertainty is assumed to be about 0.1 cm (or perhaps 0.2 cm). It is important in this case that you do not write 5.20 cm, for this implies an uncertainty on the order of 0.01 cm; it assumes that the length is probably between 5.19 cm and 5.21 cm, when actually you believe it is between 5.1 and 5.3 cm.

Which digits are significant?

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 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? If we say it is *about* 80 km between two cities, there is only one significant figure (the 8) since the zero is merely a place holder. If it is 80 km within an accuracy of 1 or 2 km, then the 80 has two significant figures. If it is precisely 80 km measured to within ± 0.1 km, then we write 80.0 km.

When making measurements, or when doing calculations, you should avoid the temptation to keep more digits in the final answer than is justified. For example, to calculate the area of a rectangle 11.3 cm by 6.8 cm, the result of multiplication would be 76.84 cm^2. But this answer is clearly not accurate to 0.01 cm^2, since (using the outer limits of the assumed uncertainty for each measurement) the result could be between $11.2 \times 6.7 = 75.04$ cm^2 and $11.4 \times 6.9 = 78.66$ cm^2. At best, we can quote the answer as 77 cm^2, which implies an uncertainty of about 1 or 2 cm^2. The other two digits (in the number 76.84 cm^2) must be dropped since they are not significant. As a general rule, *the final result of a multiplication or division should have only as many digits as the number with the least number of significant figures used in the calculation*. In our example, 6.8 cm has the least number of significant figures, namely two. Thus the result 76.84 cm^2 needs to be rounded off to 77 cm^2.

PROBLEM SOLVING

Report only the proper number of significant figures in the final result. An extra digit or two can be kept during the calculation.

Similarly, when adding or subtracting numbers, the final result is no more accurate than the least accurate number used. For example, the result of subtracting 0.57 from 3.6 is 3.0 (and not 3.03). 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 0.66666666. Digits should not be quoted (or written down) in a result, unless they are truly significant figures. However, to obtain the most accurate result, it is good

Careful: Electronic calculators err with significant figures practice to keep an extra significant figure or two throughout a calculation, and round off only in the final result. 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 good to two significant figures, so the proper answer is 8.0.

Powers of ten (scientific notation)

It is common in science to write numbers in "powers of ten," or "exponential" notation—for instance 36,900 as 3.69×10^4, or 0.0021 as 2.1×10^{-3}. (For more details, see Appendices A–2 and A–3.) One advantage of exponential notation 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 exponential notation the ambiguity can be avoided: if the number is known to an accuracy of three significant figures, we write 3.69×10^4, but if it is known to four, we write 3.690×10^4.

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 grams. The next day you weigh the returned diamond again, getting 8.09 grams. Is this your diamond?

RESPONSE The scale readings are measurements and do not give the actual 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 there is no reason to doubt that the returned diamond is yours, at least based on the scale readings. (But check the color!)

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 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 meaningless. The unit *must* be given; for clearly, 18.6 meters is very different from 18.6 inches or 18.6 millimeters.

Standard of length (meter)

The first real international standard was the **meter** (abbreviated m) established as the standard of **length** by the French Academy of Sciences in the 1790s. In a spirit of rationality, 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. (This turns out to be, very roughly, the distance from the tip of your nose to the tip of your longest 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 greater precision and reproducibility, the meter was redefined as 1,650,763.73 wavelengths of a particular orange light emitted by

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

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 precisely 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 characteristic lengths, from very small to very large.

Standard of time (second)

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. The standard second is now defined more precisely in terms of the frequency of radiation emit-

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

Length (or distance)	Meters (approximate)
Neutron or proton (radius)	10^{-15} m
Atom	10^{-10} m
Virus [see Fig. 1–6]	10^{-7} m
Sheet of paper (thickness)	10^{-4} m
Finger width	10^{-2} m
Football field length	10^{2} m
Mt. Everest height [see Fig. 1–6]	10^{4} m
Earth diameter	10^{7} m
Earth to Sun	10^{11} m
Nearest star, distance	10^{16} m
Nearest galaxy	10^{22} m
Farthest galaxy visible	10^{26} m

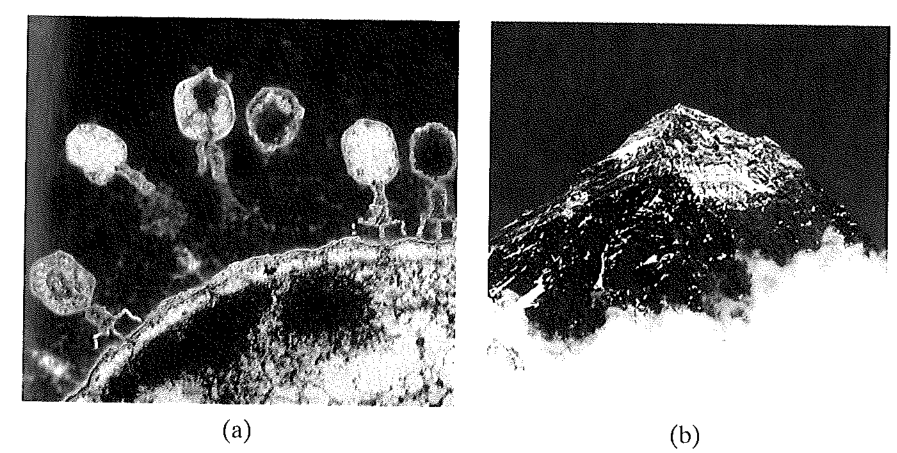


FIGURE 1–6 (a) Some viruses (about 10^{-7} m long) attacking a cell. (b) Mt. Everest's height is on the order of 10^4 m (8848 m to be precise).

†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 1–2 Some typical Time Intervals

Time interval	Seconds (approximate)
Lifetime of very unstable 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^{14} s
Life on Earth	10^{17} s
Age of Universe	10^{18} s

TABLE 1–3 Some Masses

Object	Kilograms (approx.)
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
Person	10^{2} kg
Ship	10^{8} kg
Earth	6×10^{24} kg
Sun	2×10^{30} kg
Galaxy	10^{41} kg

ted by cesium atoms when they pass between two particular states. Specifically, one second is defined as the time required for 9,192,631,770 periods of this radiation. There are, of course, precisely 60 s in one minute (min) and 60 minutes in one hour (h). Note that these two factors of 60 (as well as the 2.54 cm per inch) are definitions and hence have an indefinite number of significant figures. Table 1–2 presents a range of measured time intervals.

Standard of mass (kilogram)

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.]

When dealing with atoms and molecules, the **unified atomic mass unit** (u) is usually used. 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.

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 metric unit. For example, a centiliter (cL) is $\frac{1}{100}$ liter (L) and a kilogram (kg) is 1000 grams (g).

PROBLEM SOLVING
Always use a consistent set of units

SI 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** takes as its standards the foot for length, the pound for force, and the second for time.

SI units are the principal ones used today in scientific work. We will therefore use SI units almost exclusively in this book, although we will give the cgs and British units for various quantities when introduced.

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 table is 21.5 inches wide, and we want to express this in centimeters. We must use a **conversion factor** which in this case is

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

or, written another way,

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

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

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

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

EXAMPLE 1–2 The 100-m dash. What is the length of the 100-m dash expressed in yards?

SOLUTION Let us assume the distance is accurately known to four significant figures, 100.0 m. One yard (yd) is precisely 3 feet (36 inches), so we can write

$$1\ \text{yd} = 3\ \text{ft} = 36\ \text{in.} = (36\ \text{in.})\left(2.540\ \frac{\text{cm}}{\text{in.}}\right) = 91.44\ \text{cm}$$

or,

$$1\ \text{yd} = 0.9144\ \text{m},$$

since 1 m = 100 cm. We can rewrite this result as

$$1\ \text{m} = \frac{1\ \text{yd}}{0.9144} = 1.094\ \text{yd}.$$

Then

$$100\ \text{m} = (100\ \text{m})\left(1.094\ \frac{\text{yd}}{\text{m}}\right) = 109.4\ \text{yd},$$

so a 100-m dash is 9.4 yards longer than a 100-yard dash.

TABLE 1–4 Metric (SI) Prefixes

Prefix	Abbreviation	Value
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}

† μ is the Greek letter "mu."

EXAMPLE 1–3 **Area of a cell membrane.** A round membrane has an area of 1.25 square inches. Express this in square centimeters.

SOLUTION Because 1 in. = 2.54 cm, then

$$1\ \text{in.}^2 = (2.54\ \text{cm})^2 = 6.45\ \text{cm}^2.$$

So

$$1.25\ \text{in.}^2 = (1.25\ \text{in.}^2)\left(2.54\,\frac{\text{cm}}{\text{in.}}\right)^2 = (1.25\ \text{in.}^2)\left(6.45\,\frac{\text{cm}^2}{\text{in.}^2}\right) = 8.06\ \text{cm.}^2$$

EXAMPLE 1–4 **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)?

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

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

Conversion factors = 1

Note that each conversion factor is equal to one. We also know that 1 hour equals (60 min/h) × (60 s/min) = 3600 s/h, so

$$55\,\frac{\text{mi}}{\text{h}} = \left(55\,\frac{\text{mi}}{\text{h}}\right)\left(1609\,\frac{\text{m}}{\text{mi}}\right)\left(\frac{1\ \text{h}}{3600\ \text{s}}\right) = 25\ \text{m/s}.$$

(*b*) Now we use 1 mi = 1609 m = 1.609 km; then

$$55\,\frac{\text{mi}}{\text{h}} = \left(55\,\frac{\text{mi}}{\text{h}}\right)\left(1.609\,\frac{\text{km}}{\text{mi}}\right) = 88\,\frac{\text{km}}{\text{h}}.$$

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 1–4(*a*), if we had incorrectly used the factor $(\frac{100\ \text{cm}}{1\ \text{m}})$ instead of $(\frac{1\ \text{m}}{100\ \text{cm}})$, the meter units would not have cancelled out; we would not have ended up with meters.

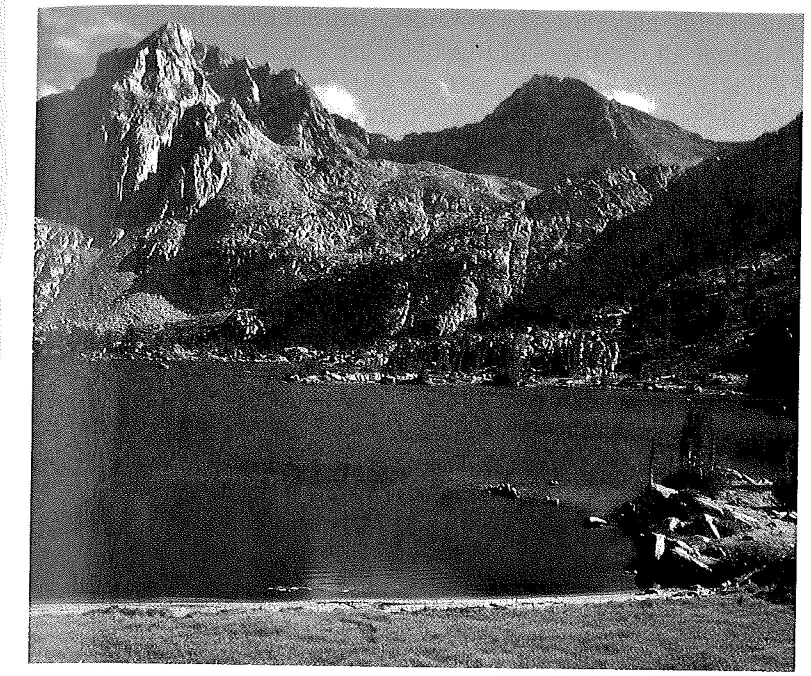
1–7 Order of Magnitude: Rapid Estimating

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 an accurate calculation made on a calculator, to make sure that no blunders were made when entering the numbers.

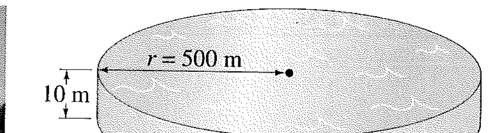
PROBLEM SOLVING
How to make a rough estimate

A rough estimate is made by rounding off all numbers to one significant figure and its power of 10, and after the calculation is made, again only one significant figure is kept. 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.

To give you some idea of how useful and powerful rough estimates can be, let us do a few "worked-out Examples."



(a)



(b)

FIGURE 1–7 Example 1–5. (a) How much water is in this lake? (Photo is of 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 kg/m³, so this lake has a mass of about $(10^3\ \text{kg/m}^3)(10^7\ \text{m}^3) \approx 10^{10}$ kg, which is about 10 billion kg or 10 million metric tons. (A metric ton is 1000 kg, about 2200 lbs, slightly larger than a British ton, 2000 lbs.)]

EXAMPLE 1–5 **ESTIMATE** **Volume of a lake.** Estimate how much water there is in a particular lake, Fig. 1–7, which is roughly circular, about 1 km across, and you guess it to have an average depth of about 10 m.

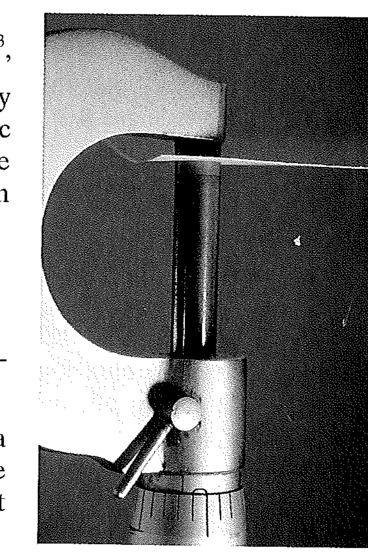
SOLUTION No lake is a perfect circle, nor can lakes be expected to have a perfectly flat bottom. We are only estimating here. To estimate the volume, we use a simple model of the lake as a cylinder: we multiply the average depth of the lake times its roughly circular surface area, as if the lake were a cylinder (Fig. 1–7b). 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

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

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

Here's another Example:

FIGURE 1–8 A micrometer, which is used for measuring small thicknesses.



EXAMPLE 1–6 **ESTIMATE** **Thickness of a page.** Estimate the thickness of a page of this book.

SOLUTION At first you might think that a special measuring device, a micrometer (Fig. 1–8), is needed to measure the thickness of one page since an ordinary ruler clearly won't do. But we can use a trick or, to put

PROBLEM SOLVING

Use symmetry when possible

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. Thus, we can use a ruler to measure hundreds of pages at once. This book is about 1000 pages long, when you count both sides of the page (front and back), so it contains about 500 separate pieces of paper. It is about 4 cm thick (don't include the cover, of course). So if 500 pages are 4 cm thick, one page must be about

$$\frac{4\text{ cm}}{500\text{ pages}} \approx 8 \times 10^{-3}\text{ cm} = 8 \times 10^{-2}\text{ mm}$$

or, rounding off even more, about a tenth of a millimeter (0.1 mm), or 10^{-4} m.

PROBLEM SOLVING

Diagrams are a necessity in physics!

Now let's take a simple Example of how a diagram can be useful for making an estimate. It cannot be emphasized enough how important it is to draw a diagram when trying to solve a physics problem.

EXAMPLE 1–7 ESTIMATE Height by triangulation. Estimate the height of the building shown in Fig. 1–9a, by "triangulation," with the help of a bus-stop pole and a friend.

SOLUTION 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. 1–9a. 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. 1–9a). 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. Now you draw, to scale, the diagram shown in Fig. 1–9b 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:

$$\frac{1.5\text{ m}}{2\text{ m}} = \frac{x}{18\text{ m}}, \qquad \text{so} \quad x \approx 13\tfrac{1}{2}\text{ m}.$$

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.

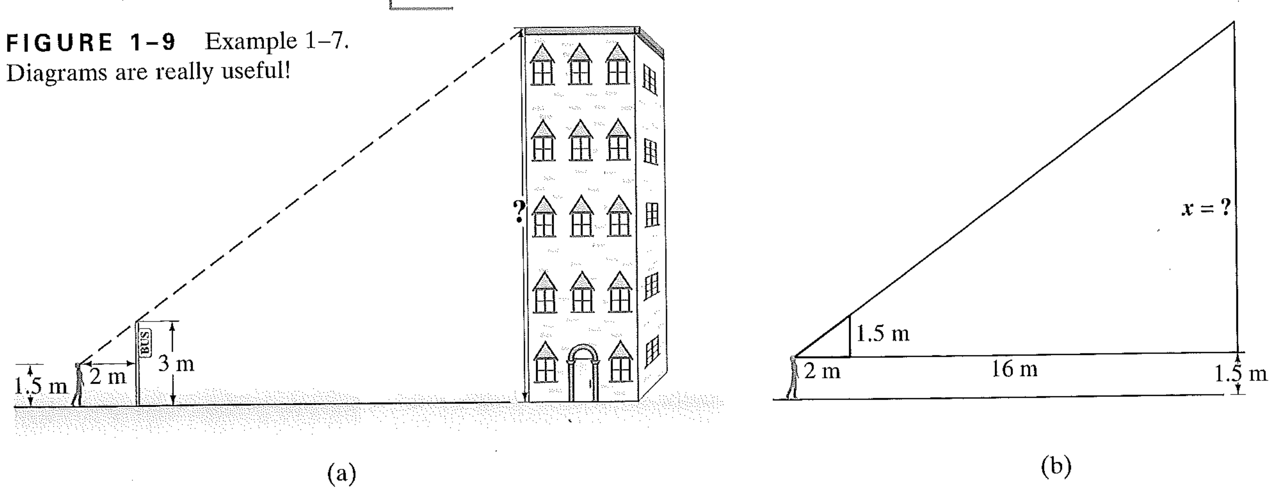


FIGURE 1–9 Example 1–7. Diagrams are really useful!

PROBLEM SOLVING

Estimating how many piano tuners there are in a city

Another example, this one made famous by the physicist Enrico Fermi, is 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 700,000 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 5 or 6 having a piano would correspond to 1 piano per 20 persons, assuming an average family of 3 or 4 persons. As an order of magnitude, 1 piano per 20 people 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 20 has a piano, or about 35,000 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 about 3 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 3 pianos a day, 5 days a week, 50 weeks a year can tune about 700 pianos a year. So San Francisco, with its (very) roughly 35,000 pianos needs about 50 piano tuners. This is, of course, only a rough estimate. It tells us that there must be many more than 5 piano tuners, and surely not as many as 500. A check of the San Francisco Yellow Pages (done after this calculation) reveals about 50 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 Mathematics in Physics

Check the mathematical Appendices (end of book)

Physics is sometimes thought of as being a difficult subject. However, sometimes it is the mathematics used that is the source of difficulties rather than the physics itself. The appendices at the end of this book contain a brief summary of simple mathematical techniques, including algebra, geometry, and trigonometry, that will be used in this book. You may find it useful to examine those appendices now to review old topics or learn any new ones. You may also want to reread them later when you need those concepts. Some mathematical techniques, such as vectors and trigonometric functions, are treated in the text itself, when we first need them.

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 seems to explain the phenomena. 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 particular range of phenomena over a wide range of cases.

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.

QUESTIONS

1. It is advantageous that fundamental standards, such as those for length and time, be accessible (easy to compare to), invariable (do not change), indestructible, and reproducible. Discuss why these are advantages and whether any of these criteria can be incompatible with others.

2. What are the merits and drawbacks of using a person's foot as a standard? Discuss in terms of the criteria mentioned in Question 1. Consider both (*a*) a particular person's foot, and (*b*) any person's foot.

3. When traveling a highway in the mountains, you may see elevation signs that read "914 m (3000 ft)." Critics of the metric system claim that such numbers show the metric system is more complicated. How would you alter such signs to be more consistent with a switch to the metric system?

4. Suggest a way to measure the distance from Earth to the Sun.

5. What is wrong with this road sign:

Boston 7 mi (11.263 km)?

6. List assumptions useful to estimate the number of car mechanics in (*a*) San Francisco, (*b*) your hometown, and then make the estimates.

7. Discuss how you would estimate the number of hours you have spent in school thus far in your life. Then make the estimate.

8. Discuss how the notion of symmetry could be used to estimate the number of marbles in a one-liter jar.

9. 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.

PROBLEMS

[The problems at the end of each chapter are ranked I, II, or III according to estimated difficulty, with I problems being easiest. The problems are arranged by Sections, meaning that the reader should have read up to and including that Section, but not only that Section—problems often depend on earlier material. Each chapter also has a group of General Problems that are not arranged by Section and not ranked.]

SECTION 1–4

1. (I) The age of the universe is thought to be somewhere around 10 billion years. Assuming one significant figure, write this in powers of ten in (*a*) years, (*b*) seconds.

2. (I) Write out the following numbers in full with a decimal point and correct number of zeros: (*a*) 8.69×10^4, (*b*) 7.1×10^3, (*c*) 6.6×10^{-1}, (*d*) 8.76×10^2, and (*e*) 8.62×10^{-5}.

3. (I) Write the following numbers in powers of ten notation: (*a*) 1,156,000, (*b*) 218, (*c*) 0.0068, (*d*) 27.635, (*e*) 0.21, and (*f*) 22.

4. (I) How many significant figures do each of the following numbers have: (*a*) 142, (*b*) 81.60, (*c*) 7.63, (*d*) 0.03, (*e*) 0.0086, (*f*) 3236, and (*g*) 8700?

5. (I) What is the percent uncertainty in the measurement 2.26 ± 0.25 m?

6. (I) What, approximately, is the percent uncertainty for the measurement 1.67?

7. (I) Time intervals measured with a stopwatch typically have an uncertainty of about a half second, due to human reaction time at the start and stop moments. What is the percent uncertainty of a hand-timed measurement of (*a*) 5 s, (*b*) 50 s, (*c*) 5 min?

8. (II) Multiply 2.079×10^2 m by 0.072×10^{-1}, taking into account significant figures.

9. (II) Add 7.2×10^3 s + 8.3×10^4 s + 0.09×10^6 s.

10. (II) What is the area, and its approximate uncertainty, of a circle of radius 2.8×10^4 cm?

11. (II) What is the percent uncertainty in the volume of a spherical beach ball whose radius is $r = 3.86 \pm 0.08$ m?

SECTIONS 1–5 AND 1–6

12. (I) Express the following using the prefixes of Table 1–4: (*a*) 10^6 volts, (*b*) 10^{-6} meters, (*c*) 5×10^3 days, (*d*) 8×10^2 bucks, and (*e*) 8×10^{-9} pieces.

13. (I) Write the following as full (decimal) numbers with standard units: (*a*) 86.6 mm, (*b*) 35 μV, (*c*) 860 mg, (*d*) 600 picoseconds, (*e*) 12.5 femtometers, (*f*) 250 gigavolts.

14. (I) How many kisses is 50 hectokisses? What would you be if you earned a megabuck a year?

15. (I) Determine your height in meters.

16. (I) The Sun, on average, is 93 million miles from the Earth. How many meters is this? Express (*a*) using powers of ten, and (*b*) using a metric prefix.

17. (II) A typical atom has a diameter of about 1.0×10^{-10} m. (*a*) What is this in inches? (*b*) How many atoms are there along a 1.0-cm line?

18. (II) Express the following sum with the correct number of significant figures:

$$1.00 \text{ m} + 142.5 \text{ cm} + 1.24 \times 10^5\ \mu\text{m}.$$

19. (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.

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

21. (II) A *light-year* is the distance light (speed = 2.998×10^8 m/s) travels in 1.00 year. (*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, 1.50×10^8 km. How many AU are there in 1.00 light-year? (*c*) What is the speed of light in AU/h?

22. (III) The diameter of the moon is 3480 km. What is the surface area, and how does it compare to the land surface area of the Earth?

SECTION 1–7

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

23. (I) Estimate the order of magnitude (power of ten) of: (*a*) 7800, (*b*) 9.630×10^2, (*c*) 0.00076, and (*d*) 150×10^8.

24. (II) Estimate how long it would take a good runner to run across the United States from New York to California.

25. (II) Make a rough estimate of the percentage of a house's outside wall area that consists of window area.

26. (II) Estimate the number of times a human heart beats in a lifetime.

27. (II) Make a rough estimate of the volume of your body (in cm^3).

28. (II) Estimate the time to drive from Beijing (Peking) to Paris (*a*) today, and (*b*) in 1906 when a great car race was run between those two cities.

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

30. (II) Estimate how long it would take one person to mow a football field using an ordinary home lawn mower.

31. (III) The rubber worn from tires mostly enters the atmosphere as particulate pollution. Estimate how much rubber (in kg) is put into the air in the United States every year. To get you started, a good estimate for a tire tread's depth is 1 cm when new, and the density of rubber is about 1200 kg/m^3.

GENERAL PROBLEMS

32. An angstrom (symbol Å) is an older unit of length, defined as 10^{-10} m. (*a*) How many nanometers are in 1.0 angstrom? (*b*) How many femtometers (the common unit of length in nuclear physics) are in 1.0 angstrom? (*c*) How many angstroms are in 1.0 meter? (*d*) How many angstroms are in 1.0 light-year (see Problem 21)?

33. (*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?

34. Estimate the number of bus drivers (*a*) in Washington, D.C., and (*b*) in your town.

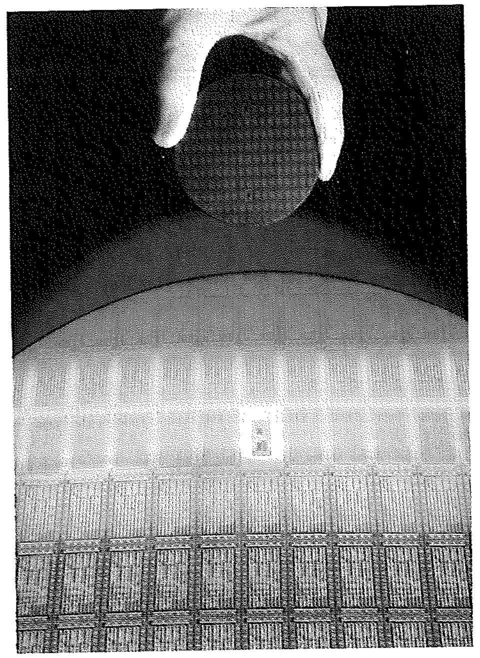


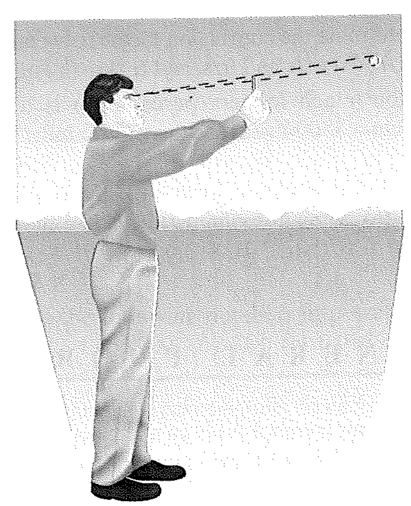
FIGURE 1–10 Problem 35. The wafer held by hand (above) is shown below, enlarged and illuminated by colored light. Visible are rows of integrated circuits (chips).

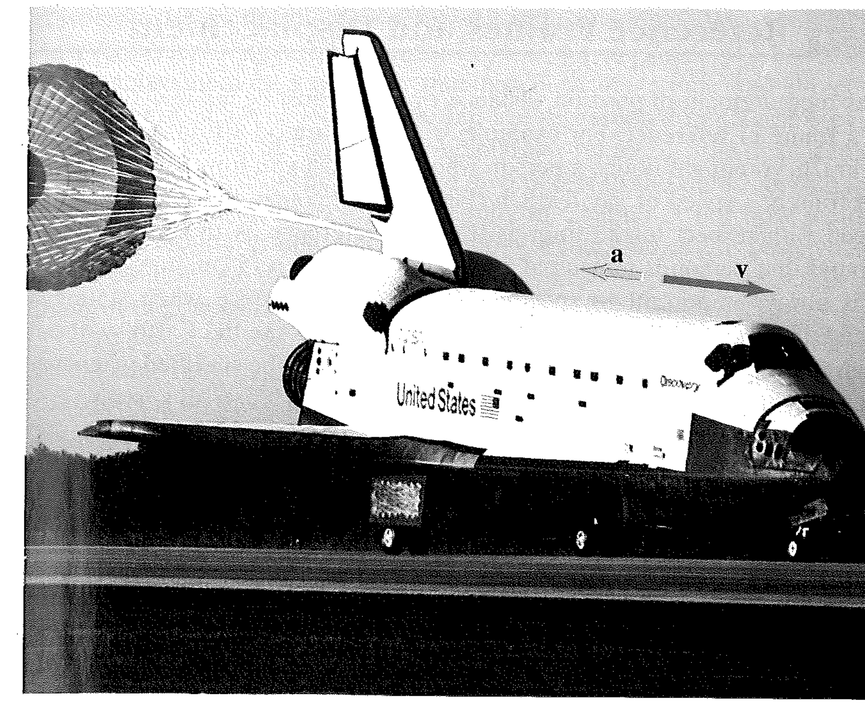
35. Computer chips (Fig. 1–10) are etched on circular silicon wafers of thickness 0.60 mm that are sliced from a solid cylindrical silicon crystal of length 30 cm. If each wafer can hold 100 chips, what is the maximum number of chips that can be produced from one entire cylinder?
36. Estimate the number of gallons of gasoline consumed by automobile drivers in the United States, per year.
37. Estimate the number of gumballs in the machine shown in Fig. 1–11.

FIGURE 1–11 Problem 37. Estimate the number of gumballs in the machine.

38. An average family of four uses roughly 1200 liters (about 300 gallons) of water per day. (One liter = $1000\ \text{cm}^3$.) How much depth would a lake lose per year if it uniformly covered an area of 50 square kilometers and supplied a local town with a population of 40,000 people? Consider only population uses, and neglect evaporation and so on.
39. 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 lbs per cubic foot.]
40. A violent rainstorm dumps 1.0 cm of rain on a city 5 km wide and 8 km long in a 2-h period. How many metric tons (1 ton = 10^3 kg) of water fell on the city? [1 cm^3 of water has a mass of 1 gram = 10^{-3} kg.]
41. Hold a pencil in front of your eye at a position where its end just blocks out the Moon (Fig. 1–12). Make appropriate measurements to estimate the diameter of the Moon, given that the Earth–Moon distance is 3.8×10^5 km.
42. The volume of an object is $1000\ \text{m}^3$. Express this volume in (*a*) cm^3, (*b*) ft^3, (*c*) in^3.
43. Estimate how long it would take to walk around the world.
44. Noah's ark was ordered to be 300 cubits long, 50 cubits wide, and 30 cubits high. The cubit was a unit of measure equal to the length of a human forearm, elbow to the tip of the longest finger. Express the dimensions of Noah's ark in meters.

FIGURE 1–12 Problem 41. How big is the Moon?





Space shuttle Discovery landing on Earth. The parachute helps it to reduce its speed quickly. The directions of Discovery's velocity and acceleration are shown by the green (**v**) and gold (**a**) arrows. Note that they (**v** and **a**) point in opposite directions.

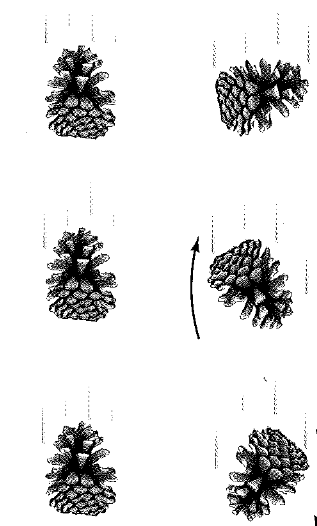
CHAPTER 2

DESCRIBING MOTION: KINEMATICS IN ONE DIMENSION

The motion of objects—baseballs, automobiles, joggers, and even the Sun and Moon—is an obvious part of everyday life. Although the ancients acquired significant insight into motion, it was not until comparatively recently, in the sixteenth and seventeenth centuries, that our modern understanding of motion was established. Many contributed to this understanding, but, as we shall soon see, two individuals stand out above the rest: Galileo Galilei (1564–1642) and Isaac Newton (1642–1727).

The study of the motion of objects, and the related concepts of force and energy, form the field called **mechanics**. Mechanics is customarily divided into two parts: **kinematics**, which is the description of how objects move, and **dynamics**, which deals with force and why objects move as they do. This chapter and the next deal with kinematics.

We start by discussing objects that move without rotating (Fig. 2–1a). Such motion is called **translational motion**. In the present chapter we will be concerned with describing an object that moves along a straight-line path, which is one-dimensional motion. In Chapter 3 we will study how to describe translational motion in two (or three) dimensions.



(a) (b)

FIGURE 2–1 The pinecone in (a) undergoes pure translation as it falls, whereas in (b) it is rotating as well as translating.