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Technical College Physics

Second Edition

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Preface

The second edition of *Technical College Physics*, like the first, presents the basic principles of introductory physics along with many technical applications. Not only does the student gain a foundation in physical principles, but also insight into how they are used and applied—the basics plus applications.

There have been various revisions, reorganization, and the addition of new features in this edition based on the input of users and reviewers of the text. The number of Exercises and Problems at the end of each chapter has been expanded and graded, with more difficult problems being indicated. Also, the problems have been listed by section for ease of selection. The topic coverage is still of sufficient scope to allow the instructor some choice of course content in a three-quarter or two-semester course. In addition, there are special interest topics. For example, in the electricity and magnetism section, you will find such topics as household circuits, wire gauges, electrical safety, induction heating (in industry and in new kitchen stove tops), and magnetic levitation (the MagLev train); in the optics section, nonreflecting lenses, fiber optics, color, and LCDs; in the modern physics section, xerography and electrostatic copiers, nuclear waste and proliferation, and solar energy technology. Scan the Table of Contents for yourself.

Some special pedagogical features of the text are

- A section on problem solving
- Solved example problems in each section
- Many illustrations and photographs of principles and technical applications
- Use of both SI and British systems of units, but with comprehensive coverage and explanation of the SI system in the first chapter
- Summaries of important terms and formulas at the end of each chapter
- Expanded end-of-the-chapter Questions and Exercises, and Problems with graded markings
- Special Features and Chapter Supplements, including

The Meter
Automobile Efficiency
Galloping Gertie: The Tacoma Narrows Bridge Collapse
Radar and the Doppler Effect
Heat Pump Cooling and Heating
Superconductivity
MagLev: The Train of the Future
Personal Safety and Electrical Effects

Lasers in the Supermarket
Cooling from Heat: The Absorption Refrigerator

Nor is the historical background of physics neglected. There are Special Features on

Isaac Newton
Galileo Galilei
Marie and Pierre Curie

Did Galileo really drop things from the Tower of Pisa? See

Galileo and the Leaning Tower of Pisa

Finally, the text is accompanied by several ancillaries: Instructor's Resource Manual, Student Study Guide (packaged with the text), and Overhead Transparencies.

The preparation of a text requires a great deal of assistance. I greatly appreciate the photographs of technical applications and products supplied by many commercial companies. Special thanks go to Ruth H. Hodges for typing and to Jocelyn Sanders for photographic work. The text was improved by the helpful comments and suggestions of Professor William K. Bates of Milwaukee Area Technical College, Professor Eddie Pederson of Texas State Technical Institute, and Professor John Thornton of Stark Technical College. Thanks are also extended to the editorial and production staff at Saunders College Publishing.

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Lander College

Contents

> *When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of meager and unsatisfactory kind.*
>
> Lord Kelvin

Measurement and Systems of Units

Chapter 1

1.1 What We Measure

How tall are you? How much do you weigh? What time is it? The answers to these and many other such questions require that measurements be made. Rarely does a day go by that we do not make or use measurements. Many times we are not aware that we are doing this. For example, when you tell someone what time it is, you are stating a measurement. Your clock is the measurement instrument.

Let's think of some things we commonly measure. With a little thought, you might say length. (I am 5 feet 8 inches tall or I live three miles from school.) Some of us frequently weigh ourselves. (I weigh 160 pounds.) And then there is time. (Class periods are 50 minutes long.)

When buying gas for your car, you may buy 10 gallons of gasoline. So we should add volume or capacity to our list of commonly measured items. Summarizing, we have

Commonly Measured Items
Length
Weight (mass)*
Time
Volume or capacity

There are other things we measure, but let's keep the list simple for our discussion. It should be noted that volume really involves length measurements. Recall that volume (V) of a box is its length (l) times its width (w) times its height (h), or in an equation, $V = l \times w \times h$. However, width and height are lengths too. So volume is a combination of lengths.

In science and technology, things are described as simply as possible. This is done in terms of basic fundamental properties, which include length, mass, and time. These properties describe the concepts of space, matter, and time.

Length describes an object's size and specifies its position in space.

Mass is the quantity of matter an object contains.

*The distinction between mass and weight will be made shortly.

Time is an involved concept and is sometimes defined as the continuous, forward flow of events. Time "flows" forward, never backward. Two events define an interval of time.

(There is one other fundamental property associated with electricity, the electric charge. More will be said about this property in a later chapter.)

The vast majority of what we observe in nature can be measured or described in terms of these four fundamental properties and their various combinations.

Mass and Weight

Before discussing how we make measurements, let's first distinguish between mass and weight, since there is an important difference.

Mass is the quantity of matter an object contains.

Weight is the force of gravitational attraction on an object by some celestial body, most commonly Earth.

Of course, mass and weight are related—the greater the mass of an object, the greater its weight. The relationship between weight (w) and mass (m) is expressed by the equation

$$w = mg \qquad \textbf{(Eq. 1.1)}$$

where g is called the acceleration due to gravity and is taken to be constant near the surface of the Earth. (More about this later.)

Mass is the fundamental property, since in general the mass of an object does not change. However, an object's weight can change due to variations in the value of g. For example, an object will have the same mass or quantity of matter on Earth and on the moon; but the object will weigh only about $\frac{1}{6}$ as much on the moon as on Earth (Fig. 1.1). This is because the value of g on the moon (g_m) is $\frac{1}{6}$ the value of g on Earth ($g_m = \frac{1}{6}g$).

Notice from Figure 1.1 that when we "mass" an object with a balance, we are comparing it with an object of known mass. In a balanced condition, the weights of the objects are also equal, i.e., $w_1 = m_1g = m_2g = w_2$. As can be seen, the g's cancel and $m_1 = m_2$, whether on Earth or on the moon. However, the weights as determined by spring scales are different for the different cases. If you

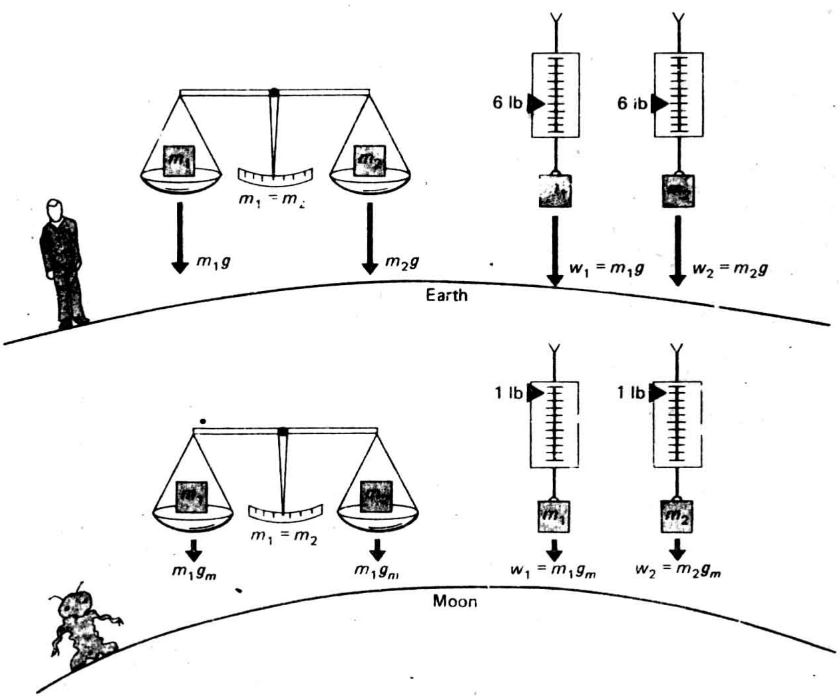


Figure 1.1 Mass is a fundamental property and weight is not. Two objects with the same mass have the same quantity of matter either on Earth or on the moon. However, the weights are less on the moon because the gravitational attraction there is less, about ⅙ that on Earth.

weigh 180 lb on Earth, you would weigh only 30 lb on the moon, since $g_m' = \frac{1}{6}g$, but your mass would be the same.

Density

The mass or quantity of matter an object contains depends not only on its size, but also on how compact the matter is in the object. For example, a block of iron has more mass than a block of ice of equal size or volume. To have an equal mass of ice would require a block of ice several times the size of the iron block.

The compactness of matter in a substance is expressed in terms of its **mass density** (ρ), which is the mass (m) per volume (V)

$$\rho = m/V \qquad \text{(Eq. 1.2)}$$

Density is not a fundamental property, but a combination of these properties (mass and length).

The density of iron is about $8\frac{3}{4}$ times that of ice, or iron is $8\frac{3}{4}$ times more dense than ice. This means that for a given volume, iron has $8\frac{3}{4}$ times more matter than ice. (How much larger would a block of ice have to be if it had a mass equal to that of a block of iron?)

A weight density is often used in engineering applications. The **weight density** (D) of an object is its weight per volume

$$D = w/V \qquad \text{(Eq. 1.3)}$$

Since $w = mg$, we have $D = w/V = mg/V = (m/V)g = \rho g$, or the weight density is just the mass density ρ times g.

We often say that density is the mass (or weight) per *unit* volume. We'll come back to this once we have defined some units.

1.2 Units and Systems of Units

Now that we know what we measure, how do we do it? It's really a matter of choice. For example, a table has a certain length no matter how we choose to describe it. One person might measure the table in feet, another in yards, and still another in meters. Certainly the length of the table doesn't change, only the choice of units used to describe it.

The measurement *unit* is the key word. If a particular unit becomes popular and/or officially accepted, it becomes a standard unit. **A standard unit has a fixed and reproducible value for the purpose**

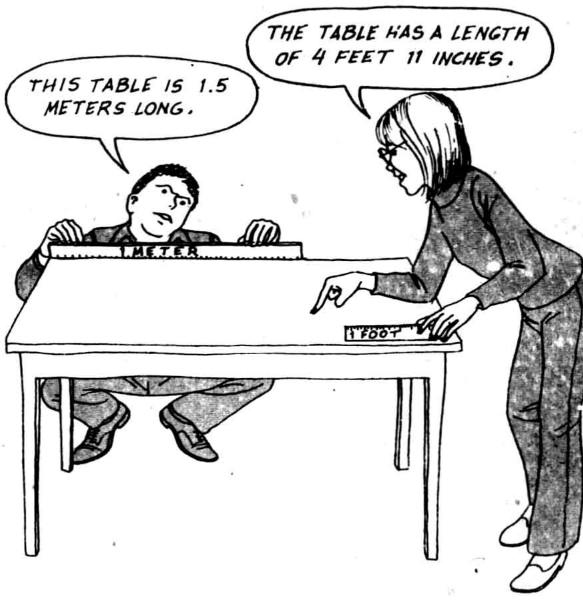


Figure 1.2 A measurement is a quantitative description of a fundamental property compared to a standard. The standard units of measurement may be different, but the length of the table is the same in any case.

of taking accurate measurements. For example, the foot and the meter are standard units. To measure something in feet, we compare it to a standard foot ruler or yardstick. To measure something in meters, we compare it to a meterstick standard (Fig. 1.2).

But who establishes or chooses a standard unit? Traditionally, it has been the head of state or government. Early standards were referenced to parts of the human body. (What could be more convenient?) Some units of the British or English system, which is the customary system of units in the United States, originated from anatomical references. For example, the inch was referenced to the thumb (Fig. 1.3), which of course varied from person to person. In the 1300's King Edward II of England decreed the official inch to be equal to three barleycorns taken from the middle of the ear and laid end to end. (Not a great improvement.) He also decreed the foot to be equal to 12 three-barleycorn inches. Perhaps this was the length of his royal foot. Another English monarch, King Henry I, established the yard as the distance from the tip of his nose to the end of the middle finger of his outstretched arm.

Later, material standards were made. King Henry VII had an iron bar made that was to be used as the yard standard (the first yardstick?). Today, most gov-

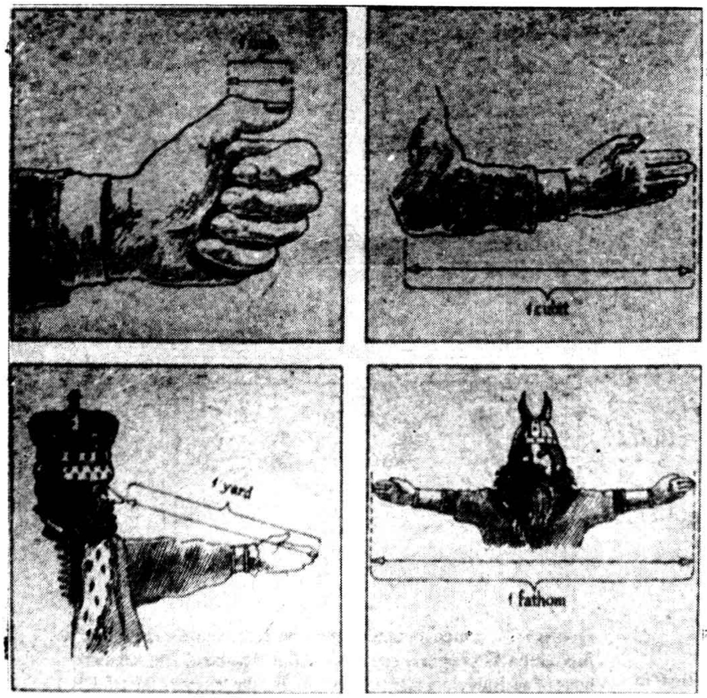


Figure 1.3 Anatomical units. Many units were originally defined in reference to parts of the human body. Variations from person to person gave rise to the need for standard units. (Courtesy Hagley Museum, Wilmington, Delaware.)

ernments have agencies that maintain and establish material standards for common and scientific measurements. In the United States, this is the responsibility of the National Bureau of Standards of the Department of Commerce.

Systems of Units

There are two major systems of units in the world today—the British and metric systems. As you are no doubt aware, the United States is in a unit transition period. There is a great deal of discussion on the pros and cons of conversion from the British system to the metric system. Regardless of the controversy, metric units are coming into increasingly common use. Hence, it is important for a person in a technical field to be familiar with metric units.

The metric system will be emphasized in the text so you can become more familiar with its units. However, the British system will not be completely ignored, since you will still commonly use these units in many everyday measurements. By learning the metric system, you will be "ahead of the game" when the official conversion takes place. Many think that this will be relatively soon, even though it will involve an enormous cost for retooling for a change in standards. But, as may be seen from Figure 1.4, we are an island in a metric world, and international trade and commerce exert a great pressure for conversion.

Once you have learned the metric units, it will be shown how easy it is to convert from one system to the other in the next section.

The Metric System

The need for a more uniform and convenient system of units led to the development of the metric system, which is now used in most countries around the world. Let's take a look at the length, mass, volume, and time units in the metric system, along with their British counterparts.

Length

The metric standard of length is the meter (see Special Feature 1.1). The meter, abbreviated m, is a little longer than a yard, 3.37 inches longer (Fig. 1.5).

With a length standard selected, the next job is to define submultiple and multiple units. (For example, in the British system, 1 foot = 12 inches and 3 feet = 1 yard.) The metric system is a decimal or "base-10" system. That is, larger and smaller units

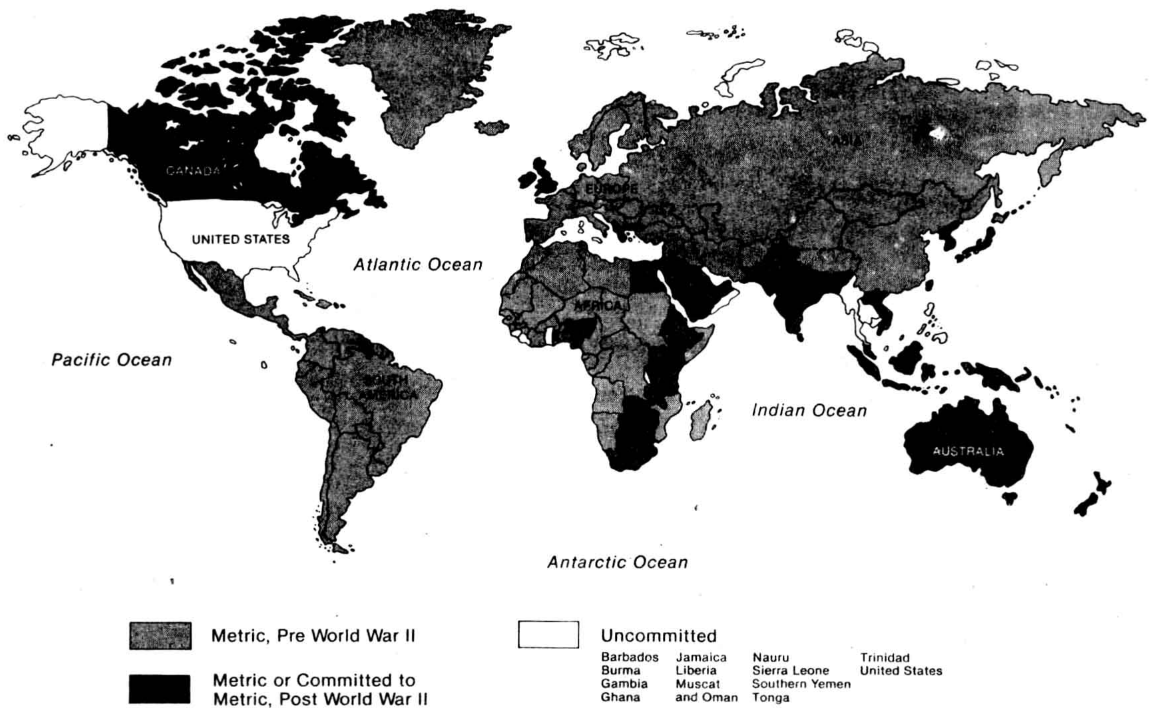
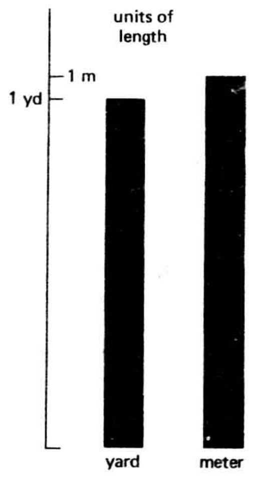


Figure 1.4 Islands in a metric world. The map shows the few countries that are uncommitted, or have not officially adopted, the metric system. (Courtesy U.S. Dept. of Commerce.)



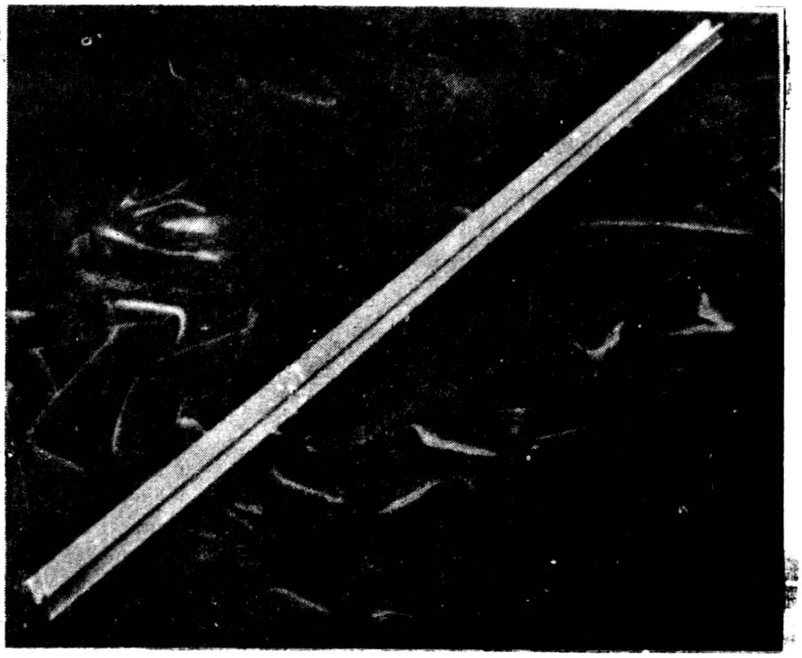


Figure 1.5 The meter and the yard. (a) The meter is slightly longer than a yard (3.37 inches longer). (b) The prototype meter bar that is the United States' copy of the Standard Meter (Prototype Meter No. 27). The bar was sent from France in 1890. (Courtesy U.S. Dept. of Commerce.)

Special Feature 1.1

The Meter

In 1790, in the midst of the French Revolution, the National Assembly of France requested the French Academy of Sciences to "deduce an invariable standard for all the measures and all the weights." The commission appointed by the Academy created a system that was simple and scientific. The name *metre*, which we spell meter, was assigned to the unit of length. This name was derived from the Greek word *metron*, meaning "to measure." The length of the meter was defined as one ten-millionth of the distance along a meridian from the North Pole to the Equator (Fig. 1.6). A portion of a meridian running near Dunkirk in France and Barcelona in Spain was surveyed and the length of a meter determined. Based on these results, a 1-meter bar of platinum was constructed. This bar became the "Meter of the Archives," from which copies were made.

The use of metric weights and measures was legalized in the United States in 1866, and since 1893 the yard has been defined in terms of the meter. Metal bar meter lengths are used for common measurement reference standards, but these lengths are affected by temperature variations. In 1960, the meter was defined in terms of the wavelength of light. In 1983, a new definition was adopted that references the meter to a distance light travels in a vacuum (see Table 1.2).

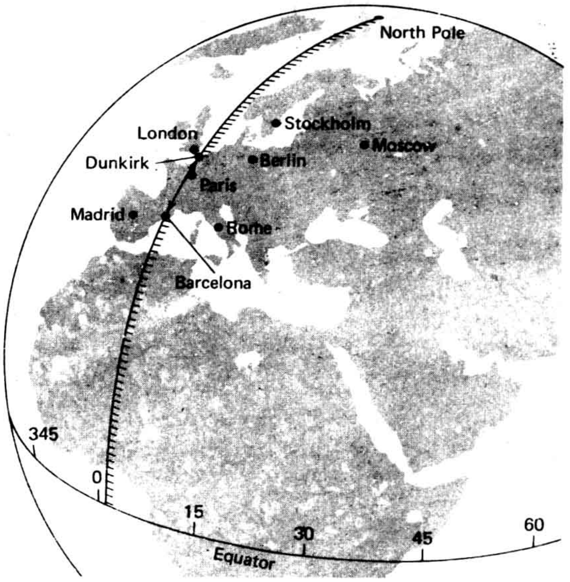


Figure 1.6 Definition of the meter. The meter was originally defined as one ten-millionth of the distance from the North Pole to the Equator along a meridian that ran through France.

are obtained by multiplying or dividing standard units by factors of ten.

A list of the metric prefixes used to indicate these factors is given in Table 1.1. However, only three prefixes are usually needed to describe everyday measurements of length (see Fig. 1.7):

milli — 0.001 (1/1000)
 1 millimeter (mm) = 0.001 meter
 or 1 m = 1000 mm
centi — 0.01 (1/100)
 1 centimeter = 0.01 meter
 or 1 m = 100 cm
kilo — 1000 (pronounced kil-oh-meter)
 1 kilometer (km) = 1000 m
 or 1 m = 0.001 km

Let's take a closer look at the decimal base of the metric system, which is one of its greatest advantages. You are already familiar with a similar decimal system—our money system. The dollar is divided into cents, with 100 cents (pennies) making one dollar. If a dollar is compared to a meter, then a cent or penny is comparable to a centimeter. In fact, we could call a penny a "centidollar." For example,

150 cm = 1.50 m and 150 cents = $1.50

We can carry this analogy a step further. You may have heard how property taxes (or school-bond levies) are assessed in mils. A mil is $\frac{1}{10}$ of a cent, and there are 1000 mils in a dollar. Hence a mil or "mildollar" is analogous to a millimeter.

Notice how much easier it is to convert from one unit to another in the metric decimal system than in the British system. The British system is a duodecimal or "base-12" system with 12 inches in one standard foot. For example, 118 cm can be directly determined to be 1.18 m. Can you tell as quickly how many feet there are in 118 inches?

Mass and Volume

In the metric system, the mass standard was originally related to length. The quantity of water in a particular metric volume was originally used to de-

Table 1.1 Metric Prefixes

Prefix (abbreviation)	Pronounciation*	Value	Meaning
exa (E)	ex'a (*a* as in *about*)	10^{18}	One quintrillion times
peta (P)	as in *petal*	10^{15}	One quadrillion times
tera (T)	as in *terrace*	10^{12}	One trillion times
giga (G)	jig'a (*a* as in *about*)	10^{9}	One billion times
mega (M)	as in *megaphone*	10^{6}	One million times
kilo (k)	as in *kilowatt*	10^{3}	One thousand times
hecto (h)	heck toe	10^{2}	One hundred times
deka (da)	deck'a (*a* as in *about*)	10	Ten times
deci (d)	as in *decimal*	10^{-1}	One tenth of
centi (c)	as in *sentiment*	10^{-2}	One hundredth of
milli (m)	as in *military*	10^{-3}	One thousandth of
micro (μ)	as in *microphone*	10^{-6}	One millionth of
nano (n)	nan'oh (*an* as in *ant*)	10^{-9}	One billionth of
pico (p)	peek'oh	10^{-12}	One trillionth of
femto (f)	fem'toe (*fem* as in *feminine*)	10^{-15}	One quadrillionth of
atto (a)	as in *anatomy*	10^{-18}	One quintrillionth of

*Source: Metric Guide for Educational Materials, American National Metric Council.

fine the standard metric mass unit. A container 10 cm on a side has a volume of 10 cm × 10 cm × 10 cm = 1000 cm^3 (cubic centimeter, sometimes abbreviated cc). See Figure 1.8. Filling the container with water, the mass of this quantity of water (1000 cm^3) was defined to be 1 kilogram (kg).*

Since the metric prefix "kilo-" means 1000, it follows that 1 kg = 1000 grams (g), and one cubic centimeter of water has a mass of 1 gram. The gram unit is often divided into milligrams (1 g = 1000 mg or 1 mg = 0.001 g), which is a convenient unit for small quantities. For larger quantities, a metric ton (sometimes written *tonne*) is defined to be 1000 kg.

Density is the mass per *unit* volume. In the metric system standard units, this would be kg/m^3. That is, for a substance with a uniform density, each cubic meter (m^3) would contain a certain number of kilograms (kg). For example, the density of iron is $\rho_{iron} = 7900\ kg/m^3$, or each cubic meter (unit volume) contains 7900 kg of iron. On a smaller scale, $\rho_{iron} = 7.9\ g/cm^3$, or each cubic centimeter contains 7.9 grams of iron. Notice that by definition the density of water is $\rho_{water} = 1.0\ g/cm^3$ in these units. Why?

The unit of mass in the British system is operationally defined in terms of weight or force. As a result, the British system is said to be a gravitational system. The standard unit of force or weight is the pound (lb). The standard unit of mass, the slug, is then defined by the pound through Equation 1.1, $w = mg$, using a standard value of g.† A mass of one slug on Earth has a weight of

$$w = mg = (1\ slug)(32\ ft/s^2) = 32\ lb$$

*At standard atmospheric pressure and at the temperature of the maximum density of water (4°C). See Chapter 17.

†It is unfortunate that the official abbreviation for the gram (g) is the same as the commonly used symbol for the acceleration due to gravity (g). When working with both quantities, gram is sometimes abbreviated gm for distinction.

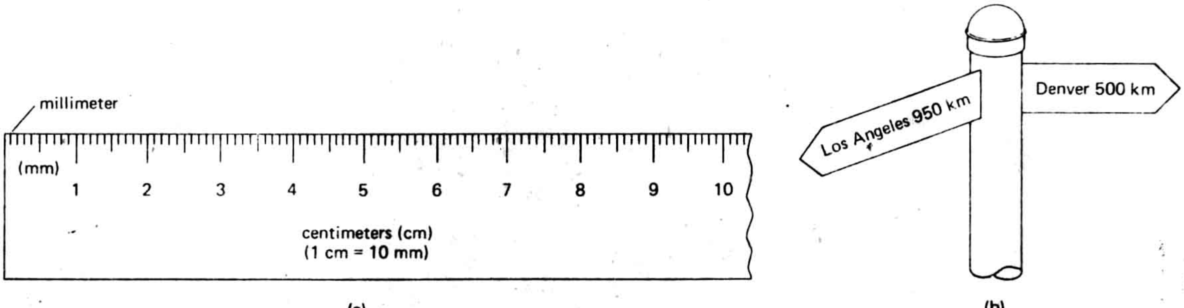


Figure 1.7 Metric prefixes. Only three metric prefixes are needed to describe most everyday measurements: (a) millimeter (mm) and centimeter (cm), and (b) kilometer (km).

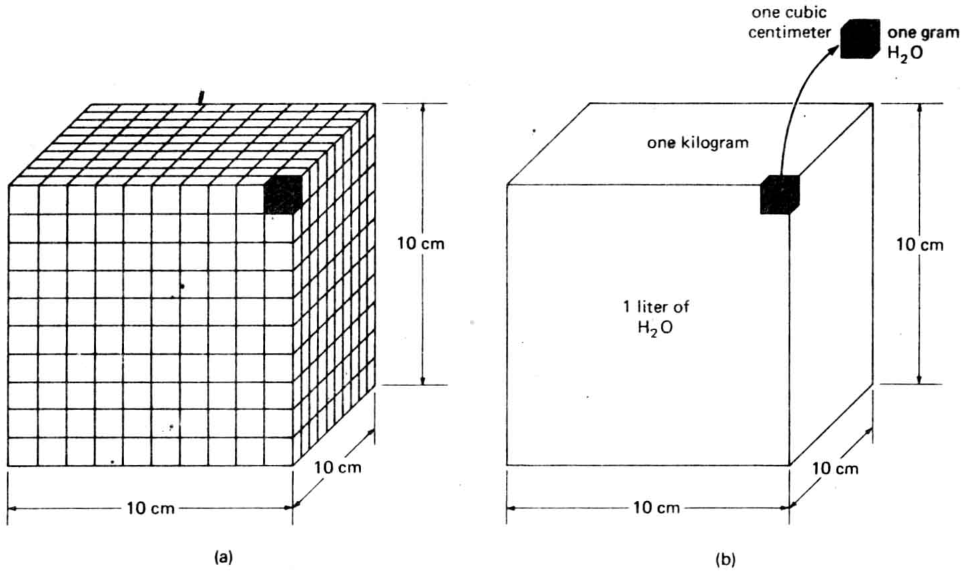


Figure 1.8 Mass units were related to length in the metric system. (a) A cube 10 cm on a side has a volume of 1000 cm^3. (b) The amount of water that fills this volume has a mass of 1 kilogram, and 1 cm^3 of water has a mass of 1 gram. (The volume 1000 cm^3 is defined to be a liter.)

where the value of g in the British system is 32 ft/s^2. It is possible that you may never have heard of the standard British unit of mass. Notice how the value of g is a combination of standard units. Such combinations are referred to as derived units.

The relationship between the kilogram and pound units is that 1 kg mass has an equivalent weight of 2.2 pounds (lb) on the surface of the Earth. This relationship is illustrated in Figure 1.9, along with the metal prototype kilogram standard. The unit of force in the metric system is the newton (N). One kilogram has a *weight* force of 9.8 N since $w = mg = (1 \text{ kg})(9.8 \text{ m/s}^2) = 9.8$ N, where $g = 9.8$ m/s^2 in the metric system. More about this later.

The metric unit of volume or capacity is the volume used in defining the kilogram. **A volume of**

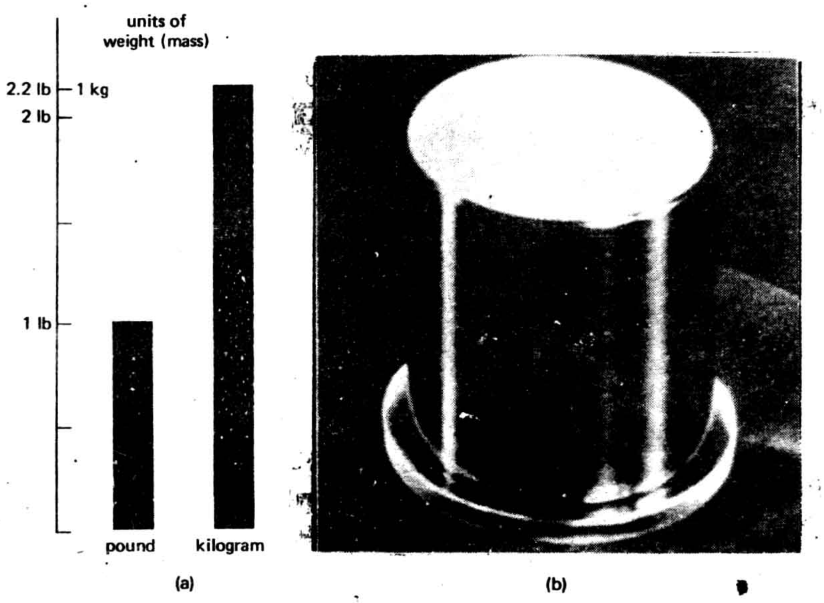


Figure 1.9 The kilogram and the pound. (a) The metric kilogram unit of mass has an equivalent weight of 2.2 lb. (b) The prototype kilogram standard cylinder (Prototype Kilogram No. 20) is the national standard mass for the United States. (Courtesy U.S. Dept. of Commerce.)