B
Units and Numbers

Science Through the Day | The Hardware Store

Walk into any hardware store in the United States and immediately you will notice that the things for sale are measured in many different ways. You buy paint by the gallon, grass seed by the pound, and insulation in terms of how many BTUs will leak through it. In some cases, the units are strange indeed—nails, for example, are ranked by "penny" (abbreviated "d"). A 16d nail is a fairly substantial object, perfect for holding the framework of a house together, whereas a 6d nail might find use tacking up a wall shelf.

But no matter what the material, there is a unit to measure how much is being sold. In the same way, all areas of science have systems of units to measure how much of a given quantity there is. We've encountered some of these units in the text—the newton as a measure of force, for example, and the degree as a measure of temperature. Every quantity used in the sciences has an appropriate unit associated with it.

Systems of Units and Standards •

We customarily use certain kinds of units together, in what is called a system of units. In a given system, units are assigned to fundamental quantities such as mass, length, time, and temperature. Someone measuring with that system will use only those units and ignore the units associated with other systems. Once units of mass, length, and time have been specified, a whole series of derived units (for force, for example, or energy) follow from them.

Two systems of units are in common use in the United States. The one encountered most often in everyday life is the English system. This traditional system of units has roots that go back into the Middle Ages. The basic unit of length is the foot (which was defined in terms of the average length of the shoes of men outside a certain church on a certain day), and the basic unit of weight is the pound.

Throughout this book, and throughout most of the world outside the United States, the preferred system of units is the metric system, or, more correctly, the International System (or Systéme Internationale, SI). In this system, the unit of length is the meter (originally defined as a certain fraction of the distance around Earth at the longitude of Paris), and the unit of mass is the kilogram. In both the SI and English systems, the basic unit of time is the second.

Systems of units are one case where governments become intimately involved with science, because the maintenance of standards has traditionally been the task of governments. In the Magna Carta, a document signed in England in 1215 and generally considered to be one of the founding instruments of modern democracy, King John agreed that "There shall be a standard measure of wine, corn, and ale throughout the kingdom," and to establish measures of length (for cloth merchants) and weights. Since that time, governments have maintained standards for use in industry and commerce. When you buy a pound of meat in a supermarket, for example, you know that you are getting full weight for your money because the scale is certified by a state agency, which ultimately relies on international standards of weight maintained by a treaty between all nations.

Originally, the standards were kept in sealed vaults at the International Bureau of Weights and Measures near Paris, with secondary copies at places such as the National Institute of Standards and Technology (formerly National Bureau of Standards) in the United States. The meter, for example, was defined as the distance between two marks on a particular bar of metal; the kilogram as the mass of a particular block of iridium-platinum alloy; the second as a certain fraction of the length of the day.

Today, however, only the kilogram is still defined in this way. Since 1967, the second has been defined as the time it takes for 9,192,631,770 crests of the light emitted by a certain quantum jump in a cesium atom to pass by a given point. In 1960, the meter was defined as the length of 1,650,763.73 wavelengths of the radiation from a particular quantum jump in the krypton atom. In 1983, the meter was redefined to be the distance light travels in 1/299,792,458 of a second. In all these cases, the old standards have been replaced by numbers relating to atoms—standards that any reasonably equipped laboratory can maintain for itself. Atomic standards have the additional advantage of being truly universal—every cesium or krypton atom in the universe is equivalent to any other. Only mass is still defined in the old way, in relation to a specific block of material kept in a vault, and scientists are working hard to replace that standard by one based on the mass of individual atoms.

The International System of Units •

Within the SI system, units are based on multiples of 10. Thus the centimeter is one-hundredth the length of a meter, the millimeter one-thousandth, and so on. In the same way, a kilometer is 1000 meters, a kilogram is 1000 grams, and so on. This organization differs from that of the English system, in which a foot equals 12 inches, and 3 feet make a yard. A list of metric prefixes follows.

Metric Prefixes

If the prefix is:	Multiply the basic unit by:
giga-	billion (thousand million)
mega-	million
kilo-	thousand
hecto-	hundred
deka-	ten
If the prefix is:	**Divide the basic unit by:**
deci-	ten
centi-	hundred
milli-	thousand
micro-	million
nano-	billion

Units of Length, Mass, and Temperature •

Next we give the conversion factors between SI and English units of length and mass.

Length and Mass Conversion from SI to English Units

To get:	Multiply:	By:
inches	meters	39.4
feet	meters	3.281
miles	kilometers	1.609
pounds	newtons	0.2248*

*Recall that the weight of a 1-kilogram mass is 9.806 newtons.

Thus, for example, a distance of 5 miles can be converted to kilometers by multiplying by the factor 1.609:

$$5 \text{ miles} \times 1.609 = 8.05 \text{ kilometers}$$

Length and Mass Conversion from English to SI Units

To get:	Multiply:	By:
meters	inches	0.0254
meters	feet	0.3048
kilometers	miles	0.6214
newtons	pounds	4.448

To convert from Celsius to Fahrenheit degrees, use the following formula:

$$T(\text{in } °F) = 1.8 \times T(\text{in } °C) + 32$$

To find temperatures in the Kelvin scale, simply add 273.15 to the temperature on the Celsius scale.

Units of Force, Energy, and Power •

Once the basic units of mass, length, time, and temperature have been defined, the units of other quantities such as force and energy follow. Recall the energy units that we have defined in the text:

joule: a force of 1 newton acting through 1 meter

foot-pound: a force of 1 pound acting through 1 foot

calorie: energy required to raise the temperature of 1 kilogram of water by 1 degree Celsius

British Thermal Unit, or BTU: energy required to raise the temperature of 1 pound of water by 1 degree Fahrenheit

kilowatt-hour: 1000 joules per second for 1 hour

Power units are:

watt: 1 joule per second

horsepower: 550 foot-pounds per second

Conversion factors between SI and English units for energy and power follow.

Energy and Power Conversion from SI to English Units

To get:	Multiply:	By:
BTUs	joules	0.00095
calories	joules	0.2390
kilowatt-hours	joules	2.78×10^{-7}
foot-pounds	joules	0.7375
horsepower	watts	0.00134

Energy and Power Conversion from English to SI Units

To get:	Multiply:	By:
joules	BTUs	1055
joules	calories	4.184
joules	kilowatt-hours	3.6 million
joules	foot-pounds	1.356
watts	horsepower	745.7

Powers of 10 •

Powers of ten notation allows us to write very large or very small numbers conveniently, in a compact way. Any number can be written by the following three rules:

1. Every number is written as a number between 1 and 10 followed by 10 raised to a power, or an exponent.
2. If the power of 10 is positive, it means "move the decimal point this many places to the right."
3. If the power of 10 is negative, it means "move the decimal point this many places to the left."

Thus, using this notation, five trillion is written 5×10^{12}, instead of 5,000,000,000,000. Similarly, five-trillionths is written 5×10^{-12}, instead of 0.000000000005.

Multiplying or dividing numbers with powers of 10 requires special care. If you are multiplying two numbers, such as 2.5×10^3 and 4.3×10^5, you multiply 2.5 and 4.3, but you add the two exponents:

$$\begin{aligned}(2.5 \times 10^3) \times (4.3 \times 10^5) &= (2.5 \times 4.3) \times 10^{3+5}\\ &= 10.75 \times 10^8\\ &= 1.075 \times 10^9\end{aligned}$$

When dividing two numbers, such as 4.3×10^5 divided by 2.5×10^3, you divide 4.3 by 2.5, but you subtract the denominator exponent from the numerator exponent:

$$\begin{aligned}\frac{4.3 \times 10^5}{2.5 \times 10^3} &= \frac{4.3}{2.5} \times 10^{5-3}\\ &= 1.72 \times 10^2\\ &= 172\end{aligned}$$

Conversion to Metric Units •

The reasons that the United States still uses English units long after most of the rest of the world has converted to SI have to do with nonscientific factors such as the geographical isolation of the country, the size of our economy (the world's largest), and, perhaps most importantly, the expense of making the conversion. Think, for example, of what it would cost to change all of the road signs on the Interstate Highway System so that the distances read in kilometers instead of miles.

To understand the debate over conversion, you have to realize one important point about units. There is no such thing as a "right" or "scientific" system of units. Units can only be convenient or inconvenient. Thus U.S. manufacturers who sell significant quantities of goods in foreign markets long ago converted to metric standards to make those sales easier. Builders, on the other hand, whose market is largely restricted to the United States, have not.

By the same token, very few scientists use SI units exclusively in their work. United States engineers use English units almost exclusively—indeed, when the federal government was considering a tax on energy use in 1993, it was referred to as a "BTU tax," not as a "joule tax." Hospital and medical professionals routinely use the so-called "cgs" system, in which the unit of length is the centimeter and the unit of mass is the gram. Next time you have blood drawn, take a look at the needle. It will be calibrated in "cc"—cubic centimeters. Even scientists doing basic research sometimes choose non-SI units for convenience. Astronomers, for example, talk about light-years, or parsecs instead of meters. Nuclear physicists measure distances in "fermis"—roughly the distance across a proton.

Stop and Think! Given this wide range of units actually in use, how much emphasis should the U.S. government give to metric conversion? How much money should the government be willing to spend on the conversion process: how many new signs as opposed to how many repaired potholes on the road?