Almost any human endeavor from subsistence farming to modern science requires an agreed-upon set of standards for measuring things as diverse as the amount of grain harvested or the wavelength of a particular color of light. Over the centuries many different measurement standards have been used. These standards were often arbitrary and imprecise. The English inch, for example, was defined in 1324 by King Edward II of England to be "three grains of barley, dry and round, placed end to end, lengthwise." The metric system was proposed in 1790 with the goal to be "for all times, for all people" because the measurement units would be related to natural physical quantities. Thus the unit of distance, the meter, was defined to be one ten-millionth of the distance from the Earth's north pole to the equator, measured along a great circle. Such a definition was adequate for a century or so, but is too imprecise for modern needs.

Modern science uses the International System of Units, or SI units, from the French *Système International d'Unités*. These units for the commonly needed measures of distance, time, electrical charge, etc. are now all defined in terms of fundamental physical constants such as the speed of light and the charge of the electron.

The Fundamental Physical Constants

In 2018, after many years of careful measurement and discussion, representatives of 60 nations unanimously agreed on values for seven fundamental physical constants, from which seven SI base units can be defined. Table center1 shows these seven fundamental physical constants. Note that the numerical values shown in the table are by definition exact.

Most of the quantities in Table center1 should be familiar from introductory physics and chemistry, but a couple warrant comment. The hypefine transition frequency of the cesium-133 atom refers to the frequency of microwave radiation that corresponds to an electron jump between two closely spaced energy levels of a neutral cesium-133 atom (in "field-free space," that is, in the absence of gravitational, electrical, or magnetic fields, which can change the atom's internal energy levels). The value of $\Delta\nu_{\mathrm{Cs}}$ gives a fundamental standard for specifying frequency, measured in Hertz, which is cycles (or periods) per second. The strangest of these constants is the luminous efficacy K_{cd}, which is a measure of how well a light source using a given power (in Watts) produces visible light (as seen by a normal human eye), measured in lumens. K_{cd} is defined to be the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hertz, which is green light. Exact definitions of these quantities and further discussion can be found in the National Institute of Standards and Technology Special Publication 330.

The SI Base Units

The seven fundamental physical constants seen in Table center1 can be used to define seven SI *base units*, which are more convenient for practical applications. Thus one second is defined via the fundamental $\Delta\nu_{\mathrm{Cs}}$ as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the

Physical Constant & Symbol & Exact Numerical Value & Unit

speed of light in vacuo & c & 299 792 458 & $\mathrm{m\,s^{-1}}$
Planck constant & h & $6.626\,070\,15 \times 10^{-34}$ & $\mathrm{J\,Hz^{-1}}$
elementary electrical charge & e & $1.602\,176\,634 \times 10^{-19}$ & C
Boltzman constant & k & $1.380\,649 \times 10^{-23}$ & $\mathrm{J\,K^{-1}}$
Avagadro constant & N_{A} & $6.022\,140\,76 \times 10^{23}$ & $\mathrm{mol^{-1}}$
hyperfine transition frequency of ^{133}Cs & $\Delta\nu_{\mathrm{Cs}}$ & 9 192 631 770 & Hz
luminous efficacy & K_{cd} & 683 & $\mathrm{lm\,W^{-1}}$

Table 1: The seven fundamental physical constants used to define the SI base units. The numerical values in the third column are by definition exact.

cesium-133 atom, or

$$1 \text{ second} \equiv \frac{9\,192\,631\,770}{\Delta\nu_{\mathrm{Cs}}}\,.$$

Similarly, the meter is defined using the speed of light and the fundamental frequency by

$$1 \text{ meter} \equiv \frac{9\,192\,631\,770}{299\,792\,458}\frac{c}{\Delta\nu_{\mathrm{Cs}}}\,.$$

The Planck constant h has units of J s or kg $\mathrm{m^{-2}}$ s. Thus the kilogram can be defined using h and the definitions of the meter and second:

$$1 \text{ kg} \equiv \frac{(299\,792\,458)^2}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)}\frac{h\Delta\nu_{\mathrm{Cs}}}{c^2}\,.$$

The definitions of the remaining base units are defined in similar ways as given in NIST Special Publication 330, cited above. Suppose, for the sake of argument, that the speed of light changes with time as the universe ages. Since the second is fixed by the value of the fundamental constant $\Delta\nu_{\mathrm{Cs}}$, a change in c would result in a change in the length of the meter, so that the speed of light will remain 299 792 458 $\mathrm{m\,s^{-1}}$, now and forever.

Table center2 shows the seven SI base units, plus two supplementary units that are convenient for measurement of plane and solid angle. All other quantities are derivable from these units. With the exception of the candela, which is needed only for the discussion of photometry, we presume that the reader is familiar with these SI units from basic physics and chemistry.

The nomenclature and symbols most widely used today in optical oceanography follow the recommendations of the Committee on Radiant Energy in the Sea of the International Association of Physical Sciences of the Ocean (IAPSO; see Morel and Smith (1982)). However, neither the SI units nor the recommended IAPSO notation are entirely satisfactory. In particular, they are sometimes inconvenient for measurements and mathematical manipulations; consequently we occasionally shall make minor deviations from the IAPSO recommendations. Several derived units that we shall need are shown in Table center3.

There are other non-SI units that are commonly used and acceptable. These include minutes, hours, and days, which are multiples of the second; the liter, which is one-thousandth of a cubic meter; degrees, minutes, and seconds of angles, which are fractions of a radian; and so on. Again, it is assumed that the reader is familiar with these units.

Physical quantity & Base Unit & Symbol

length & meter & m
mass & kilogram & kg
time & second & s
electric current & ampere & A
temperature & kelvin & K
amount of substance & mole & mol
luminous intensity & candela & cd
& &

& **Supplementary units** &

plane angle & radian & rad
solid angle & steradian & sr

Table 2: SI base units.

Physical quantity & Derived Unit & Symbol & Definition

wavelength of light & nanometer & nm & 10^{-9} m
energy & joule & J & 1 kg m^2 s^{-2}
power & watt& W & 1 kg m^2 s^{-3}
number of photons & einstein & einst & 1 mol of photons

Table 3: Derived units useful in radiative transfer studies.

The Fundamental Photon Properties

As was noted on the Brief History of Light page, most physicists view photons as elementary particles whose energy q, linear momentum p, and angular momentum ℓ are given by

$$q = \&\frac{hc}{\lambda} \qquad \left[\frac{\mathrm{kg\ m^2}}{\mathrm{s^2}}\right] \tag{1}$$

$$p = \&\frac{h}{\lambda} \qquad \left[\frac{\mathrm{kg\ m}}{\mathrm{s}}\right] \tag{2}$$

$$\ell = \&\frac{h}{2\pi} \qquad \left[\frac{\mathrm{kg\ m^2}}{\mathrm{s}}\right]\,, \tag{3}$$

where h is Planck's constant, c is the speed of light, and λ is the wavelength. As will be seen on the Light from the Sun page, the only one of these properties that matters in oceanography is the energy.

Historical Note

The United States is one of only three countries that do not use the SI system (the other two are Myanmar and Liberia). If you live in the USA, you have to learn, for example, that there are 5280 feet in a mile. Where does such a number come from? In England, a (statute) mile was originally defined as 8 furlongs. A furlong (a furrow long) was defined as the distance a team of oxen could plow without resting. A furlong was divided into 40 rods, and a rod was 16.5 feet, where a foot was defined as the average length of the left feet of 16 men chosen at random as they left church on Sunday. Seriously, you can't make this stuff up! So a mile is 8 x 40 x 16.5 = 5280 feet. No wonder the rest of the world makes fun of Americans for not converting to metric units. Fortunately, American scientists have enough sense to use SI units, even if the average American does not.