2. The International System of Units (SI), Physical Quantities, and Their Dimensions

Werner Martienssen†

In this chapter, we introduce the International System of Units (SI) on the basis of the SI brochure *Le Système International d'unités* (SI) [2.1], supplemented by [2.2]. We give a short review of how the SI was worked out and who is responsible for the further development of the system. Following the above-mentioned publications, we explain the concepts of base physical quantities and derived physical quantities on which the SI is founded, and present a detailed description of the SI base units and of a large selection of SI derived units. The base units comprise the meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela. For derived units, we describe how they are defined by equations in terms of the base physical quantities as products or ratios of the units for the base quantities. We also discuss a number of non-SI units which still are in use, especially in some specialized fields. A table (Table 2.17) presenting the values of various energy equivalents closes the chapter.

2.1 The International System of Units (SI)

All data in this handbook are given in the International System of Units (Système International d'Unités), abbreviated internationally to SI, which is the modern metric system of measurement and is acknowledged worldwide. The system of SI units was introduced by the General Conference of Weights and Measures (Conférence Générale des Poids et Measures), abbreviated internationally to CGPM, in 1960. The system not only is used in science, but also is dominant in technology, industrial production, and international commerce and trade.

Who takes care of this system of SI units?

The Bureau International des Poids et Mesures (BIPM), which has its headquarters in Sèvres near Paris, has taken on a commitment to ensure worldwide unification of physical measurements. Its function is thus to:

- Establish fundamental standards and scales for the measurement of the principal physical quantities and maintain the international prototypes
- Carry out comparison of national and international standards
- Ensure the coordination of the corresponding measuring techniques
- Carry out and coordinate measurements of the fundamental physical constants relevant to those activities.

The BIPM operates under the exclusive supervision of the Comité International des Poids et Mesures (CIPM), which itself comes under the authority of the Conférence Générale des Poids et Mesures and reports to it on the work accomplished by the BIPM. The BIPM itself was set up by the convention du Mètre signed in

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Paris in 1875 by 17 states during the final session of the Conference on the Meter. The convention was amended in 1921.

Delegates from all member states of the Convention du Mètre attend the Conférence Générale, which, at present, meets every four years. The function of these meetings is to:

- Discuss and initiate the arrangements required to ensure the propagation and improvement of the International System of Units.
- Confirm the results of new fundamental metrological determinations and confirm various scientific resolutions with international scope.
- Take all major decisions concerning the finance, organization, and development of the BIPM.

The CIPM has 18 members, each from a different state; at present, it meets every year. The officers of this committee present an annual report on the administrative and financial position of the BIPM to the governments of the member states of the Convention du Mètre. The principal task of the CIPM is to ensure worldwide uniformity in units of measurement. It does this by direct action or by submitting proposals to the CGPM.

The BIPM publishes monographs on special metrological subjects and the brochure *Le Système international d'unités (SI)* [2.1, 2], which is periodically updated and in which all decisions and recommendations concerning units are collected together.

The scientific work of the BIPM is published in the open scientific literature, and an annual list of publications appears in the *Procès-Verbaux* of the CIPM.

Since 1965, *Metrologica*, an international journal published under the auspices of the CIPM, has printed articles dealing with scientific metrology, improvements in methods of measurements, and work on standards and units, as well as reports concerning the activities, decisions, and recommendations of the various bodies created under the Convention du Mètre.

2.2 Physical Quantities

Physical quantities are tools which allow us to specify and quantify the properties of physical objects and to model the events, phenomena, and patterns of behavior of objects in nature and in technology. The system of physical quantities used with the SI units is dealt by Technical Committee 12 of the International organization for standardization (ISO/TC 12). Since 1955, ISO/TC 12 has published a series of international standards on quantities and their units, in which the use of SI units is strongly recommended.

2.2.1 How Are Physical Quantities Defined?

It turns out that it is possible to divide the system of all known physical quantities into two groups:

- A small number of *base quantities*
- A much larger number of other quantities, which are called *derived quantities*.x

The derived quantities are introduced into physics unambiguously by a defining equation in terms of the base quantities; the relationships between the derived quantities and the base quantities are expressed in a series of equations, which contain a good deal of our knowledge of physics but are used in this system as the defining equations for new physical quantities. One might say that, in this system, physics is described in the rather low-dimensional space of a small number of base quantities.

Base quantities, on the other hand, cannot be introduced by a defining equation; they cannot be traced back to other quantities; this is what we mean by calling them *base*. How can base quantities then be introduced unambiguously into physics at all?

Base physical quantities are introduced into physics in three steps:

- We borrow the qualitative meaning of the word for a base quantity from the meaning of the corresponding word in everyday language.
- We specify this meaning by indicating an appropriate method for measuring the quantity. For example, length is measured by a measuring rule, and time is measured by a clock.
- We fix a unit for this quantity, which allows us to communicate the result of a measurement. Length, for example, is measured in meters; time is measured in seconds.

On the basis of these three steps, it is expected that everyone will understand what is meant when the name of a base quantity is mentioned.

In fact, the number of base quantities chosen and the selection of the quantities which are considered as base quantities are a matter of expediency; in different fields and applications of physics, it might well be expedient to use different numbers of base quantities and different selections of base quantities. It should be kept in mind, however, that the number and selection of base quantities are only a matter of different representations of physics; physics itself is not affected by the choice that is made.

Today, many scientists therefore prefer to use the *conventional system* recommended by ISO. This system uses seven base quantities, which are selected according to the seven base units of the SI system. Table 2.1 shows the recommended names, symbols, and measuring devices for the conventional seven base quantities.

All other physical quantities can then be defined as derived quantities; this means they can be defined by equations in terms of the seven base quantities. Within this *conventional system*, the set of all defining equations for the derived physical quantities also defines the units for the derived quantities in terms of the units of the base quantities. This is the great advantage of the *conventional system*.

The quantity velocity v, for example, is defined by the equation

$$v = \frac{\mathrm{d}l}{\mathrm{d}t} .$$

Table 2.1 The ISO recommended base quantities

Name of quantity	Symbol	Measured by
Length	l	A measuring rule
Time	t	A clock
Mass	m	A balance
Electrical current	I	A balance
Temperature	T	A thermometer
Particle number	N	Counting
Luminous intensity	I_v	A photometer

In this way, velocity is traced back to the two base quantities length l and time t. On the right-hand side of this equation, we have a differential of length $\mathrm{d}l$ divided by a differential of time $\mathrm{d}t$. The algebraic combination of the base quantities in the defining equation for a derived quantity are called the *dimensions* of the derived quantity. So velocity has the dimensions length/time, acceleration has the dimensions length/time squared, and so on.

Data for a physical quantity are always given as a product of a number (the *numerical value* of the physical quantity) and a unit in which the quantity has been measured.

2.3 The SI Base Units

Formal definitions of the seven SI base units have to be approved by the CGPM. The first such definition was approved in 1889. These definitions have been modified, however, from time to time as techniques of measurement have evolved and allowed more accurate realizations of the base units. Table 2.2 summarizes the present status of the SI base units and their symbols.

In the following, the current definitions of the base units adopted by the CGPM are shown in detail, together with some explanatory notes. Related decisions which clarify these definitions but are not formally part of them are also shown indented, but in a font of normal weight.

Table 2.2 The seven SI base units and their symbols

Base quantity	Symbol for quantity	Unit	Symbol for unit
Length	l	Metre	m
Time	t	Second	s
Mass	m	Kilogram	kg
Electrical current	I	Ampere	A
Temperature	T	Kelvin	K
Particle number	N	Mole	mol
Luminous intensity	I_v	Candela	cd

2.3.1 Unit of Length: The Meter

The unit of length, the meter, was defined in the first CGPM approval in 1889 by an international prototype: the length of a bar made of a platinum-iridium alloy defined a length of 1 m. In 1960 this definition was replaced by a definition based upon a wavelength of krypton-86 radiation. Since 1983 (17th CGPM), the meter has been defined as:

> The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

As a result of this definition, the fundamental constant *speed of light in vacuum* c is fixed at exactly 299 792 458 m/s.

2.3.2 Unit of Mass: The Kilogram

Since the first CGPM in 1889, the unit of mass, the kilogram, has been defined by an international prototype, a metal block made of a platinum-iridium alloy, kept at the BIPM at Sèvres. The relevant declaration was modified slightly at the third CGPM in 1901 to confirm that:

> The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

2.3.3 Unit of Time: The Second

The unit of time, the second, was originally considered to be the fraction 1/86 400 of the mean solar day. Measurements, however, showed that irregularities in the rotation of the Earth could not be taken into account by theory, and these irregularities have the effect that this definition does not allow the required accuracy to be achieved. The same turned out to be true for other definitions based on astronomical data. Experimental work, however, had already shown that an atomic standard of time interval, based on a transition between two energy levels of an atom or a molecule, could be realized and reproduced much more precisely. Therefore, the 13th CGPM (1967–1968) replaced the definition of the second by:

> The second is 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 caesium 133 atom.
>
> At its 1997 meeting, the CIPM affirmed that:
>
> This definition refers to a caesium atom at rest at a temperature of 0 K.

This note was intended to make it clear that the definition of the SI second is based on a Cs atom unperturbed by black-body radiation, that is, in an environment whose temperature is 0 K.

2.3.4 Unit of Electric Current: The Ampere

International electrical units for current and resistance were introduced by the International electrical congress in Chicago as early as in 1893 and were confirmed by an international conference in London in 1908. They were replaced by an *absolute* definition of the ampere as the unit for electric current at the 9th CGPM in 1948, which stated:

> The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

As a result of this definition, the fundamental constant *magnetic field constant* μ_0 (also known as the permeability of free space) is fixed at exactly $4\pi \times 10^{-7}\,\mathrm{N/A^2}$.

2.3.5 Unit of (Thermodynamic) Temperature: The Kelvin

The definition of the unit of (thermodynamic) temperature was given in substance by the 10th CGPM in 1954, which selected the triple point of water as the fundamental fixed point and assigned to it the temperature 273.16 K, so defining the unit. After smaller amendments, made at the 13th CGPM in 1967–1968, the definition of the unit of (thermodynamic) temperature reads

> The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

Because of the way temperature scales used to be defined, it remains common practice to express a thermodynamic temperature, symbol T, in terms of its difference from the reference temperature $T_0 = 273.15\,\mathrm{K}$, the ice point. This temperature difference is called the Celsius temperature, symbol t, and is defined by the equation $t = T - T_0$. The unit of Celsius temperature is the degree Celsius, symbol °C, which is, by definition, equal in magnitude to the kelvin. A difference or interval of temperature may therefore be expressed either in kelvin or in degrees Celsius.

The numerical value of a Celsius temperature t expressed in degrees Celsius is given by $t\,(^\circ\mathrm{C}) = T\,(\mathrm{K}) - 273.15$.

2.3.6 Unit of Amount of Substance: The Mole

The *amount of substance* of a sample is understood as a measure of the number of elementary entities (for example atoms or molecules) that the sample consists of. Owing to the fact that on macroscopic scales this number cannot be counted directly in most cases, one has to relate this quantity *amount of substance* to a more easily measurable quantity, the mass of a sample of that substance.

On the basis of an agreement between the International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) in 1959/1960, physicists and chemists have ever since agreed to assign, by definition, the value 12, exactly, to the relative atomic mass (formerly called *atomic weight*) of the isotope of carbon with mass number 12 (carbon-12, ^{12}C). The scale of the masses of all other atoms and isotopes based on this agreement has been called, since then, the scale of relative atomic masses.

It remains to define the unit of the *amount of substance* in terms of the mass of the corresponding amount of the substance. This is done by fixing the mass of a particular amount of carbon-12; by international agreement, this mass has been fixed at 0.012 kg. The corresponding unit of the quantity *amount of substance* has been given the name *mole* (symbol mol).

On the basis of proposals by IUPAC, IUPAP, and ISO, the CIPM formulated a definition of the mole in 1967 and confirmed it in 1969. This definition was adopted by the 14th CGPM in 1971 in two statements:

> 1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12; its symbol is *mol*.
> 2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

In 1980, the CIPM approved the report of the Comité Consultatif des Unités (Comité Consultatif des Unités), which specified that:

> In this definition, it is understood that unbound atoms of carbon-12, at rest and in their ground state, are referred to.

2.3.7 Unit of Luminous Intensity: The Candela

The base unit candela allows one to establish a quantitative relation between radiometric and photometric measurements of light intensities. In physics and chemistry, the intensities of radiation fields of various natures are normally determined by radiometry; in visual optics, in lighting engineering, and in the physiology of the visual system, however, it is necessary to assess the intensity of the radiation field by photometric means.

There are, in fact, three different ways to quantify the intensity of a radiation beam. One way is to measure the *radiant intensity* I_e, defined as the radiant flux $\Delta\Phi_e$ per unit solid angle $\Delta\Omega$ of the beam. The subscript e stands for *energetic*. Here, the radiant flux Φ_e is defined as the energy of the radiation per unit time, and is accordingly measured in units of watts (W). The radiant intensity I_e, therefore, has the dimensions of energy per time per solid angle, and is measured in the derived unit *watt per steradian* (W/sr).

Another way to quantify the intensity of a beam of radiation is to measure the *particle intensity* I_p, which is defined as the particle flux Φ_p divided by the solid angle $\Delta\Omega$ of the beam. The subscript p stands for *particle*. The particle flux Φ_p itself is measured by counting the number of particles per unit time in the beam; in the case of a light beam, for example, the particles are photons. The corresponding SI unit for the particle flux is seconds^{-1} (1/s). The quantity particle intensity I_p therefore has the dimensions of number per time per solid angle; the corresponding derived SI unit for the particle intensity I_p is *seconds*$^{-1}$ *times steradian*$^{-1}$ (1/(s sr)).

In addition to these two radiometric assessments of the beam intensity, for beams of visible light there is a third possibility, which is to quantify the intensity of the beam by the intensity of visual perception by the human eye. Physical quantities connected with this physiological type of assessment are called photometric quantities, in contrast to the two radiometric quantities described above. In photometry, the intensity of the beam is called the *luminous intensity* I_v. The subscript v stands for *visual*. The luminous intensity I_v is an ISO recommended base quantity; the corresponding SI base unit is the candela (cd). The luminous flux Φ_v is determined as the product of the luminous intensity and the solid angle. Its dimensions therefore are luminous intensity times solid angle, so that the SI unit of the luminous flux Φ_v turns out to be *candela times steradian* (cd sr). A derived unit, the lumen (lm), such that 1 lm = 1 cd sr, has been introduced for this product.

Table 2.3 summarizes the names, definitions, and SI units for the most frequently used radiometric and photometric quantities in radiation physics.

The history of the base unit candela is as follows. Before 1948, the units for photometric measurements were be based on flame or incandescent-filament standards. They were replaced initially by the *new candle* based on the luminance of a Planckian radiator (a blackbody radiator) at the temperature of freezing platinum. This modification was ratified in 1948 by the 9th CGPM, which also adopted the new international name for the base unit of luminous intensity, the candela, and its symbol cd. The 13th CGPM gave an amended version of the 1948 definition in 1967.

Table 2.3 Radiometric and photometric quantities in radiation physics

Quantity	Symbol and definition	Dimensions	SI unit	Symbol for unit
Radiant flux	$\Phi_e = \Delta E/\Delta t$[a]	Power = energy/time	Watt	$W = J/s$
Particle flux, activity	$\Phi_p = \Delta N_p/\Delta t$	1/time	Second^{-1}	1/s
Luminous flux	$\Phi_v = I_v \Omega$[b]	Luminous intensity times solid angle	Lumen	lm = cd sr
Radiant intensity	$I_e = \Delta\Phi_e/\Delta\Omega$	Power/solid angle	Watt/steradian	W/sr
Particle intensity	$I_p = \Delta\Phi_p/\Delta\Omega$	(Time times solid angle)$^{-1}$	(Second times steradian)$^{-1}$	1/(s sr)
Luminous intensity	I_v, base quantity	Luminous intensity	Candela	cd
Radiance[c]	$L_e = \Delta I_e(\varphi)/[\Delta A_1 g(\varphi)]$[d]	Power per source area and solid angle	Watt/(meter^2 times steradian)	$W/(m^2\,sr) = kg/(s^3\,sr)$
Particle radiance[c]	$L_p = \Delta I_p(\varphi)/[\Delta A_1 g(\varphi)]$[d]	(Time times area times solid angle)$^{-1}$	1/(second times meter^2 times steradian)	$1/(s\,m^2\,sr)$
Luminance[c]	$L_v = \Delta I_v(\varphi)/[\Delta A_1 g(\varphi)]$[d]	Luminous intensity/source area	Candela/meter^2	cd/m^2
Irradiance	$E_e = \Delta\Phi_e/\Delta A_2$[e]	Power/area	Watt/meter^2	W/m^2
Particle irradiance	$E_p = \Delta\Phi_p/\Delta A_2$[e]	Number of particles per (time times area)	1/(second times meter^2)	$1/(s\,m^2)$
Illuminance	$E_v = \Delta\Phi_v/\Delta A_2$[e]	Luminous flux per area	Lux = lumen/meter^2	$lx = lm/m^2 = cd\,sr/m^2$

[a] The symbol E stands for the radiant energy (Table 2.5).
[b] I_v stands for the luminous intensity, and Ω stands for the solid angle (Table 2.5).
[c] The radiance L_e, particle radiance L_p, and luminance L_v are important characteristic properties of sources, not radiation fields. For a blackbody source, the radiance L_e, for example, is dependent only on the frequency of the radiation and the temperature of the black body. The dependence is given by Planck's radiation law. In optical imaging, the radiance L_e of an object turns out to show an invariant property. In correct imaging, the image always radiates with the same radiance L_e as the object, independent of the magnification.
[d] φ is the angle between the direction of the beam axis and the direction perpendicular to the source area; A_1 indicates the area of the source; and $g(\varphi)$ is the directional characteristic of the source.
[e] A_2 indicates the irradiated area or the area of the detector.

Because of experimental difficulties in realizing a Planckian radiator at high temperatures and because of new possibilities in the measurement of optical radiation power, the 16th CGPM in 1979 adopted a new definition of the candela as follows:

> The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hertz and that has a radiant intensity in that direction of 1/683 Watt per steradian.

2.4 The SI Derived Units

The SI derived units are the SI units for derived physical quantities. In accordance with the defining equations for derived physical quantities in terms of the base physical quantities, the units for derived quantities can be expressed as products or ratios of the units for the base quantities. Table 2.4 shows some examples of SI derived units in terms of SI base units.

For convenience, certain derived units, which are listed in Table 2.5, have been given special names and symbols. Among these, the last four entries in Table 2.5 are of particular note, since they were accepted by the 15th (1975), 16th (1979), and 21st (1999) CGPMs specifically with a view to safeguarding human health.

In Tables 2.5 and 2.6, the final column shows how the SI units concerned may be expressed in terms of SI base units. In this column, factors such as m^0 and kg^0, etc. which are equal to 1, are not shown explicitly.

The special names and symbols for derived units listed in Table 2.5 may themselves be used to express other derived units. Table 2.6 shows some examples. The special names and symbols provide a compact form for the expression of units which are frequently used.

A derived unit can often be expressed in several different ways by combining the names of base units with special names for derived units. This, however, is an algebraic freedom whose use should be limited by common-sense physical considerations. The joule,

Table 2.4 Examples of SI derived units (for derived physical quantities) in terms of base units

Derived quantity	Defining equation	Name of SI derived unit	Symbol for unit
Area	$A = l_1 l_2$	Square meter	m^2
Volume	$V = l_1 l_2 l_3$	Cubic meter	m^3
Velocity	$v = \mathrm{d}l/\mathrm{d}t$	Meter per second	$\mathrm{m/s}$
Acceleration	$a = \mathrm{d}^2 l/\mathrm{d}t^2$	Meter per second squared	$\mathrm{m/s^2}$
Angular momentum	$L = \Theta\omega$	Meter squared kilogram/second	$\mathrm{m^2\,kg/s}$
Wavenumber	$k = 2\pi/\lambda$	Reciprocal meter	$1/\mathrm{m}$
Density	$\varrho = m/V$	Kilogram per cubic meter	$\mathrm{kg/m^3}$
Concentration (of amount of substance)	Concentration = amount/V	Mole per cubic meter	$\mathrm{mol/m^3}$
Current density	$j = I/A$	Ampere per square meter	$\mathrm{A/m^2}$
Magnetic exciting field	$H = I/l$	Ampere per meter	$\mathrm{A/m}$
Radiance (of a radiation source)	$L_\mathrm{e} = \Delta I_\mathrm{e}(\varphi)/[\Delta A_1 g(\varphi)]^\mathrm{a}$	Watt per (square meter × steradian)	$\mathrm{W/(m^2\,sr) = kg/(s^3\,sr)}$
Luminance (of a light source)	$L_\mathrm{v} = \Delta I_\mathrm{v}(\varphi)/[\Delta A_1 g(\varphi)]^\mathrm{b}$	Candela per square meter	$\mathrm{cd/m^2}$
Refractive index	$n = c_\mathrm{mat}/c$	(number one)	1

[a] φ is the angle between the direction of the beam axis and the direction perpendicular to the source area; $I_\mathrm{e}(\varphi)$ is the radiant intensity emitted in the direction φ; A_1 is the radiating area of the source; and $g(\varphi)$ is the directional characteristic of the source.

[b] φ is the angle between the direction of the beam axis and the direction perpendicular to the source area; $I_\mathrm{v}(\varphi)$ is the luminous intensity emitted in the direction φ; A_1 is the radiating area of the light source; and $g(\varphi)$ is the directional characteristic of the source.

Table 2.5 SI derived units with special names and symbols

Derived quantity		SI derived unit			
Name	**Symbol**	**Name**	**Symbol**	**Expressed in terms of other SI units**	**Expressed in terms of SI base units**
Plane angle	$\alpha, \Delta\alpha$	Radian[a]	rad		$\mathrm{m/m} = 1^\mathrm{b}$
Solid angle	$\Omega, \Delta\Omega$	Steradian[a]	sr[c]		$\mathrm{m^2/m^2} = 1^\mathrm{b}$
Frequency	ν	Hertz	Hz		$1/\mathrm{s}$
Force	F	Newton	N		$\mathrm{m\,kg/s^2}$
Pressure, stress	P	Pascal	Pa	$\mathrm{N/m^2}$	$\mathrm{(1/m)\,kg/s^2}$
Energy, work, quantity of heat	E, A, Q	Joule	J	N m	$\mathrm{m^2\,kg/s^2}$
Power, radiant flux	P, Φ_e	Watt	W	J/s	$\mathrm{m^2\,kg/s^3}$
Electric charge, quantity of electricity	q, e	Coulomb	C		A s
Electric potential difference, electromotive force	V	Volt	V	W/A	$\mathrm{(1/A)\,m^2\,kg/s^3}$
Capacitance	C	Farad	F	C/V	$\mathrm{A^2\,(1/(m^2\,kg))\,s^4}$
Electrical resistance	R	Ohm	Ω	V/A	$\mathrm{(1/A^2)\,m^2\,kg/s^3}$
Electrical conductance	$1/R$	Siemens	S	A/V	$\mathrm{A^2\,(1/(m^2\,kg))s^3}$
Magnetic flux	Φ	Weber	Wb	V s	$\mathrm{(1/A)\,m^2\,kg(1/s^2)}$
Magnetic field strength	B	Tesla	T	$\mathrm{Wb/m^2}$	$\mathrm{(1/A)\,kg/s^2}$
Inductance	L	Henry	H	Wb/A	$\mathrm{(1/A^2)\,m^2\,kg/s^2}$
Celsius temperature	t	Degree Celsius	°C		K; $T\,(\mathrm{K}) = t\,(^\circ\mathrm{C}) + 273.15$
Luminous flux	Φ_v	Lumen	lm	cd sr[c]	$\mathrm{(m^2/m^2)\,cd = cd}$
Illuminance	$E_\mathrm{v} = \Delta\Phi_\mathrm{v}/\Delta A$	Lux	lx	$\mathrm{lm/m^2}$	$\mathrm{(m^2/m^4)\,cd = cd/m^2}$
Activity (referred to a radionuclide)	A	Becquerel	Bq		$1/\mathrm{s}$
Absorbed dose	D	Gray	Gy	J/kg	$\mathrm{m^2/s^2}$
Dose equivalent	H	Sievert	Sv	J/kg	$\mathrm{m^2/s^2}$
Catalytic activity		Katal	kat		$\mathrm{(1/s)\,mol}$

[a] The units radian and steradian may be used with advantage in expressions for derived units to distinguish between quantities of different nature but the same dimensions. Some examples of their use in forming derived units are given in Tables 2.5 and 2.6.

[b] In practice, the symbols rad and sr are used where appropriate, but the derived unit is generally omitted in combination with a numerical value.

[c] In photometry, the name steradian and the symbol sr are frequently retained in expressions for units.

Table 2.6 Examples of SI derived units whose names and symbols include SI derived units with special names and symbols

Derived quantity		**SI derived unit**		
Name	**Symbol**	**Name**	**Symbol**	**Expressed in terms of SI base units**
Dynamic viscosity	η	Pascal second	Pa s	(1/m) kg/s
Moment of force	M	Newton meter	N m	$\mathrm{m^2\,kg/s^2}$
Surface tension	σ	Newton per meter	N/m	$\mathrm{kg/s^2}$
Angular velocity	ω	Radian per second	rad/s	$\mathrm{m/(m\,s)} = 1/\mathrm{s}$
Angular acceleration	$\mathrm{d}\omega/\mathrm{d}t$	Radian per second squared	$\mathrm{rad/s^2}$	$\mathrm{m/(m\,s^2)} = 1/\mathrm{s^2}$
Heat flux density	q_th	Watt per square meter	$\mathrm{W/m^2}$	$\mathrm{kg/s^3}$
Heat capacity, entropy	C, S	Joule per kelvin	J/K	$\mathrm{m^2\,kg/(s^2\,K)}$
Specific heat capacity, specific entropy	C_mass, S_mass	Joule per (kilogram kelvin)	J/(kg K)	$\mathrm{m^2/(s^2\,K)}$
Specific energy		Joule per kilogram	J/kg	$\mathrm{m^2/s^2}$
Energy density	w	Joule per cubic meter	$\mathrm{J/m^3}$	$\mathrm{(1/m)\,kg/s^2}$
Thermal conductivity	λ	Watt per (meter kelvin)	W/(m K)	$\mathrm{m\,kg/(s^3\,K)}$
Electric charge density	ρ	Coulomb per cubic meter	$\mathrm{C/m^3}$	$\mathrm{(1/m^3)\,s\,A}$
Electric field strength	E	Volt per meter	V/m	$\mathrm{m\,kg/(s^3\,A)}$
Exciting electric field[b]	D	Coulomb per square meter	$\mathrm{C/m^2}$	$\mathrm{(1/m^2)\,s\,A}$
Molar energy	E_mol	Joule per mole	J/mol	$\mathrm{m^2\,kg/(s^2\,mol)}$
Molar heat capacity, molar entropy	C_mol, S_mol	Joule per (mole kelvin)	J/(mol K)	$\mathrm{m^2\,kg/(s^2\,K\,mol)}$
Exposure (x- and γ-rays)		Coulomb per kilogram	C/kg	(1/kg) s A
Absorbed dose rate	$\mathrm{d}D/\mathrm{d}t$	Gray per second	Gy/s	$\mathrm{m^2/s^3}$
Radiant intensity	I_ε	Watt per steradian	W/sr	$\mathrm{(m^4/m^2)\,kg/s^3 = m^2\,kg/s^3}$
Radiance[a]	L_e	Watt per (square meter steradian)	$\mathrm{W/(m^2\,sr)}$	$\mathrm{(m^2/m^2)\,kg/s^3 = kg/s^3}$
Catalytic (activity) concentration		Katal per cubic meter	$\mathrm{kat/m^3}$	$\mathrm{(1/(m^3\,s))\,mol}$

[a] The radiance is a property of the source of the radiation, not of the radiation field (footnote c to Table 2.3).

[b] Also called *electric flux density*

for example, may formally be written *newton meter* or even *kilogram meter squared per second squared*, but in a given situation some forms may be more helpful than others.

In practice, with certain quantities, preference is given to the use of certain special unit names or combinations of unit names, in order to facilitate making a distinction between different quantities that have the same dimensions. For example, the SI unit of frequency is called the hertz rather than the reciprocal second, and the SI unit of angular velocity is called the radian per second rather than the reciprocal second (in this case, retaining the word *radian* emphasizes that the angular velocity is equal to 2π times the rotational frequency). Similarly, the SI unit of moment of force is called the newton meter rather than the joule.

In the field of ionizing radiation, the SI unit of activity is called the becquerel rather than the reciprocal second, and the SI units of absorbed dose and dose equivalent are called the gray and the sievert, respectively, rather than the joule per kilogram. In the field of catalysis, the SI unit of catalytic activity is called the katal rather than the mole per second. The special names becquerel, gray, sievert, and katal were specifically introduced because of the dangers to human health which might arise from mistakes involving the units reciprocal second, joule per kilogram, and mole per second.

2.5 Decimal Multiples and Submultiples of SI Units

The 11th CGPM adopted, in 1960, a series of prefixes and prefix symbols for forming the names and symbols of the decimal multiples and submultiples of SI units ranging from 10^{12} to 10^{-12}. Prefixes for 10^{-15} and 10^{-18} were added by the 12th CGPM in 1964, and for 10^{15} and 10^{18} by the 15th CGPM in 1975. The 19th CGPM extended the scale in 1991 from 10^{-24} to 10^{24}. Table 2.7 lists all approved prefixes and symbols.

Table 2.7 SI prefixes and their symbol

Factor	Name	Symbol
10^{24}	Yotta	Y
10^{21}	Zeta	Z
10^{18}	Exa	E
10^{15}	Peta	P
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	Kilo	k
10^{2}	Hecto	h
10^{1}	Deca	da
10^{-1}	Deci	d
10^{-2}	Centi	c
10^{-3}	Milli	m
10^{-6}	Micro	μ
10^{-9}	Nano	n
10^{-12}	Pico	p
10^{-15}	Femto	f
10^{-18}	Atto	a
10^{-21}	Zepto	z
10^{-24}	Yocto	y

2.6 Units Outside the SI

The SI base units and SI derived units, including those with special names, have the important advantage of forming a coherent set, with the effect that unit conversions are not required when one is inserting particular values for quantities into equations involving quantities.

Nonetheless, it is recognized that some non-SI units still appear widely in the scientific, technical, and commercial literature, and some will probably continue to be used for many years. Other non-SI units, such as the units of time, are so widely used in everyday life and are so deeply embedded in the history and culture of human beings that they will continue to be used for the foreseeable future. For these reasons, some of the more important non-SI units are listed.

2.6.1 Units Used with the SI

In 1996 the CIPM agreed upon a categorization of the units used with the SI into three groups: units accepted for use with the SI, units accepted for use with the SI whose values are obtained experimentally, and other units currently accepted for use with the SI to satisfy the needs of special interests. The three groups are listed in Tables 2.8–2.10.

Table 2.8 Non-SI units accepted for use with the International System

Name	Symbol	Value in SI units
Minute	min	1 min = 60 s
Hour	h	1 h = 60 min = 3600 s
Day	d	1 d = 24 h = 86 400 s
Degree[a]	∘	$1^\circ = (\pi/180)$ rad
Minute of arc	′	$1' = (1/60)^\circ = (\pi/10\,800)$ rad
Second of arc	″	$1'' = (1/60)' = (\pi/648\,000)$ rad
Liter[b]	l, L	$1\,\mathrm{l} = 1\,\mathrm{dm}^3 = 10^{-3}\,\mathrm{m}^3$
Tonne[c]	t	$1\,\mathrm{t} = 10^3$ kg

[a] ISO 31 recommends that the degree be subdivided decimally rather than using the minute and second

[b] Unfortunately, printers from all over the world seem not to be willing to admit that in some texts it would be very helpful to have distinguishable symbols for *the number 1* and *the letter l*. Giving up any further discussion, the 16th CGPM therefore decided in 1979 that the symbol L should also be adopted to indicate the unit litre in order to avoid the risk of confusion between *the number 1* and *the letter l*

[c] This unit is also called the *metric ton* in some countries.

Table 2.9 Non-SI units accepted for use with the International System, whose values in SI units are obtained experimentally

Unit	Definition	Symbol	Value in SI units
Electron volt[a]	[b]	eV	$1\,\mathrm{eV} = 1.60217653(14) \times 10^{-19}\,\mathrm{J}$
Unified atomic mass unit[a]	[c]	u	$1\,\mathrm{u} = 1.66053886(28) \times 10^{-27}\,\mathrm{kg}$
Astronomical unit[d]	[e]	ua	$1\,\mathrm{ua} = 1.49597870691(30) \times 10^{11}\,\mathrm{m}$

[a] For the electron volt and the unified atomic mass unit, the values are quoted from the CODATA recommended values 2014 (Chap. 1).

[b] The electron volt is the kinetic energy acquired by an electron in passing through a potential difference of 1 V in vacuum.

[c] The unified atomic mass unit is equal to 1/12 of the mass of an unbound atom of the nuclide ^{12}C, at rest and in its ground state. In biochemistry, the unified atomic mass unit is also called the dalton, symbol Da.

[d] The value given for the astronomical unit is quoted from the IERS Convention (2003).

[e] The astronomical unit is a unit of length approximately equal to the mean Earth–Sun distance. Its value is such that, when it is used to describe the motion of bodies in the solar system, the heliocentric gravitational constant is $(0.01720209895)^2\,\mathrm{ua}^3/\mathrm{d}^2$.

Table 2.10 Other non-SI units currently accepted for use with the International System

Unit	Symbol	Value in SI units
Nautical mile[a]		1 nautical mile = 1852 m
Knot		1 knot = 1 nautical mile per hour = (1852/3600) m/s
Are[b]	a	$1\,\mathrm{a} = 1\,\mathrm{dam}^2 = 10^2\,\mathrm{m}^2$
Hectare[b]	ha	$1\,\mathrm{ha} = 1\,\mathrm{hm}^2 = 10^4\,\mathrm{m}^2$
Bar[c]	bar	$1\,\mathrm{bar} = 0.1\,\mathrm{MPa} = 100\,\mathrm{kPa} = 1000\,\mathrm{hPa} = 10^5\,\mathrm{Pa}$
Angstrom	Å	$1\,\text{Å} = 0.1\,\mathrm{nm} = 10^{-10}\,\mathrm{m}$
Barn[d]	b	$1\,\mathrm{b} = 100\,\mathrm{fm}^2 = 10^{-28}\,\mathrm{m}^2$

[a] The nautical mile is a special unit employed for marine and aerial navigation to express distance. The conventional value given above was adopted by the First International Extraordinary Hydrographic Conference, Monaco, 1929, under the name *International nautical mile*. As yet there is no internationally agreed symbol. This unit was originally chosen because one nautical mile on the surface of the Earth subtends approximately one minute of arc at the center.

[b] The units are and hectare and their symbols were adopted by the CIPM in 1879 and are used to express areas of land.

[c] The bar and its symbol were included in Resolution 7 of the 9th CGPM (1948).

[d] The barn is a special unit employed in nuclear physics to express effective cross sections.

Table 2.9 lists three non-SI units accepted for use with the SI, whose values expressed in SI units must be obtained by experiment and are therefore not known exactly. Their values are given with their combined standard uncertainties, which apply to the last two digits, shown in parentheses. These units are in common use in certain specialized fields.

Table 2.10 lists some other non-SI units which are currently accepted for use with the SI to satisfy the needs of commercial, legal, and specialized scientific interests. These units should be defined in relation to SI units in every document in which they are used. Their use is not encouraged.

2.6.2 Other Non-SI Units

Certain other non-SI units are still occasionally used. Some are important for the interpretation of older scientific texts. These are listed in Tables 2.11–2.16, but their use is not encouraged.

Table 2.11 deals with the relationship between CGS units and SI units, and lists those CGS units that were assigned special names. In mechanics, the CGS system of units was built upon three quantities and their corresponding base units: the centimeter, the gram, and the second. In the field of electricity and magnetism, units were expressed in terms of these three base units. Because this can be done in different ways, this led to the establishment of several different systems, for example the CGS electrostatic system, the CGS electromagnetic system, and the CGS Gaussian system. In those three systems, the system of quantities used and the corresponding system of defining equations for the derived quantities differ from those used with SI units.

Table 2.12 deals with the *natural unit*, which are based directly on fundamental constants or combinations of fundamental constants. Like the CGS system, this system is based on mechanical quantities only. The numerical values in SI units are given here according to the 2014 values of the Committee on Data for Science and Technology (CODATA) [2.3].

Table 2.13 presents numerical values in SI units for some of the most frequently used *atomic units* (a.u.), again based on the 2014 CODATA adjustment.

Table 2.11 Derived CGS units with special names

Unit	Symbol	Value in SI units
Erg [a]	erg	$1\,\mathrm{erg} = 10^{-7}\,\mathrm{J}$
Dyne [a]	dyn	$1\,\mathrm{dyn} = 10^{-5}\,\mathrm{N}$
Poise [a]	P	$1\,\mathrm{P} = 1\,\mathrm{dyn\,s/cm^2} = 0.1\,\mathrm{Pa\,s}$
Stokes	St	$1\,\mathrm{St} = 1\,\mathrm{cm^2/s} = 10^{-4}\,\mathrm{m^2/s}$
Gauss [b]	G	$1\,\mathrm{G} \equiv 10^{-4}\,\mathrm{T}$
Oersted [b]	Oe	$1\,\mathrm{Oe} \equiv (1000/4\pi)\,\mathrm{A/m}$
Maxwell [b]	Mx	$1\,\mathrm{Mx} \equiv 10^{-8}\,\mathrm{Wb}$
Stilb [a]	sb	$1\,\mathrm{sb} = 1\,\mathrm{cd/cm^2} = 10^4\,\mathrm{cd/m^2}$
Phot	ph	$1\,\mathrm{ph} = 10^4\,\mathrm{lx}$
Gal [c]	Gal	$1\,\mathrm{Gal} = 1\,\mathrm{cm/s^2} = 10^{-2}\,\mathrm{m/s^2}$

[a] This unit and its symbol were included in Resolution 7 of the 9th CGPM (1948).

[b] This unit is part of the *electromagnetic* three-dimensional CGS system and cannot strictly be compared with the corresponding unit of the International System, which has four dimensions if only mechanical and electrical quantities are considered. For this reason, this unit is linked to the SI unit using the mathematical symbol for *equivalent to* ($\equiv$) here.

[c] The gal is a special unit employed in geodesy and geophysics to express the acceleration due to gravity.

Table 2.12 Natural units (n.u.)

Unit	Symbol and definition	Value in SI units
n.u. of speed: speed of light in vacuum	c	$299\,792\,458\,\mathrm{m/s}$ (exact)
n.u. of action: reduced Planck constant	$\hbar = h/2\pi$	$1.054571800(13) \times 10^{-34}\,\mathrm{J\,s}$ $6.582119514(40) \times 10^{-16}\,\mathrm{eV\,s}$
n.u. of mass: electron mass	m_e	$9.10938356(11)10^{-31}\,\mathrm{kg}$
n.u. of energy	$m_e c^2$	$8.18710565(10)10^{-14}\,\mathrm{J}$ $0.5109989461(31)\,\mathrm{MeV}$
n.u. of momentum	$m_e c$	$2.730924488(34)10^{-22}\,\mathrm{kg\,m/s}$ $0.5109989461(31)\,\mathrm{MeV}/c$
n.u. of length	$\bar{\lambda}_{\mathrm{C}} = \hbar/m_e c$	$386.15926764(18)10^{-15}\,\mathrm{m}$
n.u. of time	$\hbar/m_e c^2$	$1.28808867712(58)10^{-21}\,\mathrm{s}$

Table 2.13 Atomic units (a.u.)

Unit	Symbol and definition	Value in SI units
a.u. of charge: elementary charge	e	$1.6021766208(98) \times 10^{-19}\,\mathrm{C}$
a.u. of mass: electron mass	m_e	$9.10938356(11) \times 10^{-31}\,\mathrm{kg}$
a.u. of action: reduced Planck constant	$\hbar = h/2\pi$	$1.054571800(13) \times 10^{-34}\,\mathrm{J\,s}$
a.u. of length, 1 bohr: Bohr radius	$a_0 = \alpha/(4\pi R_\infty)$	$0.52917721067(12) \times 10^{-10}\,\mathrm{m}$
a.u. of energy, 1 hartree: Hartree energy [a]	E_{H}	$4.359744650(54) \times 10^{-18}\,\mathrm{J}$
a.u. of time	$\hbar/E_{\mathrm{H}}$	$2.418884326509(14) \times 10^{-17}\,\mathrm{s}$
a.u. of force	E_{H}/a_0	$8.23872336(10) \times 10^{-8}\,\mathrm{N}$
a.u. of velocity	$\alpha c = a_0 E_{\mathrm{H}}/\hbar$	$2.18769126277(50) \times 10^{6}\,\mathrm{m/s}$
a.u. of momentum	$\hbar/a_0$	$1.992851882(24) \times 10^{-24}\,\mathrm{kg\,m/s}$
a.u. of current	$eE_{\mathrm{H}}/\hbar$	$6.623618183(41) \times 10^{-3}\,\mathrm{A}$
a.u. of charge density	e/a_0^3	$1.0812023770(67) \times 10^{12}\,\mathrm{C/m^3}$
a.u. of electric potential	E_{H}/e	$27.21138602(17)\mathrm{V}$
a.u. of electric field	$E_{\mathrm{H}}/(ea_0)$	$5.142206707(32) \times 10^{11}\,\mathrm{V/m}$
a.u. of electric dipole moment	ea_0	$8.478353552(52) \times 10^{-30}\,\mathrm{C\,m}$
a.u. of electric polarizability	$e^2 a_0^2/E_{\mathrm{H}}$	$1.6487772731(11) \times 10^{-41}\,\mathrm{C^2\,m^2/J}$
a.u. of magnetic flux density	$\hbar/(ea_0^2)$	$2.350517550(14) \times 10^{5}\,\mathrm{T}$
a.u. of magnetic dipole moment ($2\mu_{\mathrm{B}}$)	$2\mu_{\mathrm{B}} = \hbar e/m_e$	$1.854801999(11) \times 10^{-23}\,\mathrm{J/T}$
a.u. of magnetizability	$e^2 a_0^2/m_e$	$7.8910365886(90) \times 10^{-29}\,\mathrm{J/T^2}$
a.u. of permittivity	$e^2/(a_0 E_{\mathrm{H}})$	Fixed by definition as: $10^7/c^2 = 1.112650056\ldots \times 10^{-10}\,\mathrm{F/m}$

[a] The Hartree energy is defined as $E_{\mathrm{H}} = e^2/(4\pi\varepsilon_0 a_0) = 2R_\infty hc = \alpha^2 m_e c^2$.

Table 2.14 presents numerical values in SI units (based on the 2014 CODATA adjustment) for some x-ray-related quantities used in crystallography.

Table 2.15 lists some other units which are common in older texts. For current texts, it should be noted that if these units are used, the advantages of the SI are lost. The relation of these units to SI units should be specified in every document in which they are used.

For some selected quantities, there exists an international agreement that the numerical values of these quantities measured in SI units are fixed at the values given in Table 2.16.

Table 2.14 Units of some special x-ray-related quantities

Unit	Definition	Symbol	Value in SI units
Cu X unit	$\lambda(\mathrm{CuK}\alpha_1)/1537.400$	$\mathrm{xu}(\mathrm{CuK}\alpha_1)$	$1.00207697(28) \times 10^{-13}$ m
Mo X unit	$\lambda(\mathrm{MoK}\alpha_1)/707.831$	$\mathrm{xu}(\mathrm{MoK}\alpha_1)$	$1.00209952(53) \times 10^{-13}$ m
Angstrom star	$\lambda(\mathrm{WK}\alpha_1)/0.2090100$	Å*	$1.00001495(90) \times 10^{-10}$ m
Lattice parameter[a] of Si (in vacuum, at 22.5 °C)		a	$543.1020504(89) \times 10^{-12}$ m
(220) lattice spacing of Si (in vacuum, at 22.5 °C)	$d_{220} = a/\sqrt{8}$	d_{220}	$192.0155714(32) \times 10^{-12}$ m
Molar volume of Si (in vacuum, at 22.5 °C)	$V_\mathrm{m}(\mathrm{Si}) = N_\mathrm{A} a^3/8$	$V_\mathrm{m}(\mathrm{Si})$	$12.05883214(61) \times 10^{-6}\,\mathrm{m^3/mol}$

[a] This is the lattice parameter (unit cell edge length) of an ideal single crystal of naturally occurring silicon free from impurities and imperfections, and is deduced from measurements on extremely pure, nearly perfect single crystals of Si by correcting for the effects of impurities.

Table 2.15 Examples of other non-SI units

Unit	Symbol	Value in SI units
Curie[a]	Ci	$1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{Bq}$
Röntgen[b]	R	$1\,\mathrm{R} = 2.58 \times 10^{-4}\,\mathrm{C/kg}$
Rad[c,d]	rad	$1\,\mathrm{rad} = 1\,\mathrm{cGy} = 10^{-2}\,\mathrm{Gy}$
Rem[d,e]	rem	$1\,\mathrm{rem} = 1\,\mathrm{cSv} = 10^{-2}\,\mathrm{Sv}$
X unit[f]		$1\,\mathrm{X\,unit} \cong 1.002 \times 10^{-4}\,\mathrm{nm}$
Gamma[d]	γ	$1\,\gamma = 1\,\mathrm{nT} = 10^{-9}\,\mathrm{T}$
Jansky	Jy	$1\,\mathrm{Jy} = 10^{-26}\,\mathrm{W/(m^2\,Hz)}$
Fermi[d]		$1\,\mathrm{fermi} = 1\,\mathrm{fm} = 10^{-15}\,\mathrm{m}$
Metric carat[g]		$1\,\mathrm{metric\ carat} = 200\,\mathrm{mg} = 2 \times 10^{-4}\,\mathrm{kg}$
Torr	Torr	$1\,\mathrm{Torr} = (101\,325/760)\,\mathrm{Pa}$
Standard atmosphere	atm[h]	$1\,\mathrm{atm} = 101\,325\,\mathrm{Pa}$
Calorie	cal	[i]
Micron[j]	µ	$1\,\mu = 1\,\mu\mathrm{m} = 10^{-6}\,\mathrm{m}$

[a] The curie is a special unit employed in nuclear physics to express the activity of radionuclides.

[b] The röntgen is a special unit employed to express exposure to x-ray or γ radiation.

[c] The rad is a special unit employed to express absorbed dose of ionizing radiation. When there is a risk of confusion with the symbol for the radian, rd may be used as the symbol for 10^{-2} Gy.

[e] The rem is a special unit used in radioprotection to express dose equivalent.

[f] The X unit was employed to express wavelengths of x-rays. Its relationship to SI units is an approximate one.

[d] Note that this non-SI unit is exactly equivalent to an SI unit with an appropriate submultiple prefix.

[g] The metric carat was adopted by the 4th CGPM in 1907 for commercial dealings in diamonds, pearls, and precious stones.

[h] Resolution 4 of the 10th CGPM, 1954. The designation *standard atmosphere* for a reference pressure of 101 325 Pa is still acceptable.

[i] Several *calories* have been in use:

- The 15 °C calorie: $1\,\mathrm{cal}_{15} = 4.1855\,\mathrm{J}$ (value adopted by the CIPM in 1950)
- The IT (International Table) calorie: $1\,\mathrm{cal}_\mathrm{IT} = 4.1868\,\mathrm{J}$ (5th International Conference on the Properties of Steam, London, 1956)
- The thermochemical calorie: $1\,\mathrm{cal}_\mathrm{th} = 4.184\,\mathrm{J}$.

[j] The micron and its symbol, adopted by the CIPM in 1879 and repeated in Resolution 7 of the 9th CGPM (1948), were abolished by the 13th CGPM (1967–1968).

Table 2.16 Internationally adopted numerical values for selected quantities

Quantity	Symbol	Numerical value	Unit
Relative atomic mass[a] of ^{12}C	$A_r(^{12}\mathrm{C})$	12	
Molar mass constant	M_u	1×10^{-3}	kg/mol
Molar mass of ^{12}C	$\mathrm{M}(^{12}\mathrm{C})$	12×10^{-3}	kg/mol
Conventional value of the Josephson constant[b]	$K_{\text{J-90}}$	483 597.9	GHz/V
Conventional value of the von Klitzing constant[c]	$R_{\text{K-90}}$	25 812.807	Ω
Standard atmosphere		101 325	Pa
Standard acceleration of free fall[d]	g_n	9.80665	m/s^2

[a] The relative atomic mass $A_r(X)$ of a particle X with mass $m(X)$ is defined by $A_r(X) = m(X)/m_u$, where $m_u = m(^{12}\mathrm{C})/12 = M_u/N_A = 1\,\mathrm{u}$ is the atomic mass constant, M_u is the molar mass constant, N_A is the Avogadro number, and u is the (unified) atomic mass unit. Thus the mass of a particle X is $m(X) = A_r(X)\,\mathrm{u}$ and the molar mass of X is $M(X) = A_r(X)M_u$.

[b] This is the value adopted internationally for realizing representations of the volt using the Josephson effect.

[c] This is the value adopted internationally for realizing representations of the ohm using the quantum Hall effect.

[d] The value given was adopted by the 3rd General Conference on Weights and Measures (CGPM), 1903, and was the conventional value used to calculate the now obsolete unit kilogram force.

2.7 Some Energy Equivalents

In science and technology, energy is measured in many different units. Different units are used depending on the field of application, but owing to the different possible forms of the energy concerned, it is possible also to express the energy in terms of other quantities. All forms of the energy, however, are quantitatively related to one another and are therefore considered as being equivalent. Some of the most important equivalence relations are

$$\begin{aligned} E &= eU = mc^2 \\ &= hc/\lambda = h\nu = kT\,. \end{aligned}$$

These equations tell us that a given energy E, which is usually measured either in units of joule (J) or units of the Hartree energy ($E_H = 1$ hartree), can also be specified by giving a voltage U, a mass m, a wavelength λ, a frequency ν, or a temperature T. These equations contain, in addition to those variables, only well-known fundamental constants.

Table 2.17 gives the values of the energy equivalents of the joule and the hartree and for the SI units corresponding to the five quantities U, m, λ, ν, and T. The equivalents have been calculated on the basis of the 2002 CODATA adjustment of the values of the constants.

Table 2.17 Energy equivalents, expressed in the units joule (J), hartree (E_H), volt (V), kilogram (kg), (unified) atomic mass unit (u), reciprocal meter (m^{-1}), hertz (Hz), and kelvin (K)

Energy	Unit	
	Joule	Hartree
1 J	$(1\,\mathrm{J}) = 1\,\mathrm{J}$	$(1\,\mathrm{J}) = 2.293712317(28)\times10^{17}\,E_H$
1 E_H	$(1\,E_H) = .359744650(54)\times4\times10^{-18}\,\mathrm{J}$	$(1\,E_H) = 1\,E_H$
1 eV	$(1\,\mathrm{eV}) = 1.6021766208(98)\times10^{-19}\,\mathrm{J}$	$(1\,\mathrm{eV}) = 3.674932248(23)\times10^{-2}\,E_H$
1 kg	$(1\,\mathrm{kg})\,c^2 = 8.987551787\ldots\times10^{16}\,\mathrm{J}$	$(1\,\mathrm{kg})\,c^2 = 2.061485823(25)\times10^{34}\,E_H$
1 u	$(1\,\mathrm{u})\,c^2 = 1.492418062(18)\times10^{-10}\,\mathrm{J}$	$(1\,\mathrm{u})\,c^2 = 3.4231776902(16)\times10^{7}\,E_H$
1 m^{-1}	$(1\,\mathrm{m}^{-1})\,hc = 1.986445824(24)\times10^{-25}\,\mathrm{J}$	$(1\,\mathrm{m}^{-1})\,hc = 4.556335252767(27)\times10^{-8}\,E_H$
1 Hz	$(1\,\mathrm{Hz})\,h = 6.626070040(81)\times10^{-34}\,\mathrm{J}$	$(1\,\mathrm{Hz})\,h = 1.5198298460088(90)\times10^{-16}\,E_H$
1 K	$(1\,\mathrm{K})\,k = 1.38064852(79)\times10^{-23}\,\mathrm{J}$	$(1\,\mathrm{K})\,k = 3.1668105(18)\times10^{-6}\,E_H$

Table 2.17 (continued)

Energy	**Unit**	
	Volt	**Kilogram**
1 J	$(1\,\mathrm{J}) = 6.241509126(38) \times 10^{18}\,\mathrm{eV}$	$(1\,\mathrm{J})/c^2 = 1.112650056\ldots \times 10^{-17}\,\mathrm{kg}$
1 E_H	$(1\,E_\mathrm{H}) = 27.21138602(17)\,\mathrm{eV}$	$(1\,E_\mathrm{H})/c^2 = 4.850870129(60) \times 10^{-35}\,\mathrm{kg}$
1 eV	$(1\,\mathrm{eV}) = 1\,\mathrm{eV}$	$(1\,\mathrm{eV})/c^2 = 1.782661907(11) \times 10^{-36}\,\mathrm{kg}$
1 kg	$(1\,\mathrm{kg})\,c^2 = 5.609588650(34) \times 10^{35}\,\mathrm{eV}$	$(1\,\mathrm{kg}) = 1\,\mathrm{kg}$
1 u	$(1\,\mathrm{u})\,c^2 = 931.4940954(57) \times 10^{6}\,\mathrm{eV}$	$(1\,\mathrm{u}) = 1.660539040(20) \times 10^{-27}\,\mathrm{kg}$
1 m^{-1}	$(1\,\mathrm{m}^{-1})\,hc = 1.2398419739(76) \times 10^{-6}\,\mathrm{eV}$	$(1\,\mathrm{m}^{-1})\,h/c = 2.210219057(27) \times 10^{-42}\,\mathrm{kg}$
1 Hz	$(1\,\mathrm{Hz})\,h = 4.135667662(25) \times 10^{-15}\,\mathrm{eV}$	$(1\,\mathrm{Hz})\,h/c^2 = 7.372497201(91) \times 10^{-51}\,\mathrm{kg}$
1 K	$(1\,\mathrm{K})\,k = 8.6173303(50) \times 10^{-5}\,\mathrm{eV}$	$(1\,\mathrm{K})\,k/c^2 = 1.53617865(88) \times 10^{-40}\,\mathrm{kg}$
Energy	**Unit**	
	Atomic mass unit	**Reciprocal meter**
1 J	$(1\,\mathrm{J})/c^2 = 6.700535363(82) \times 10^{9}\,\mathrm{u}$	$(1\,\mathrm{J})/hc = 5.034116651(62) \times 10^{24}\,\mathrm{m}^{-1}$
1 E_H	$(1\,E_\mathrm{H})/c^2 = 2.9212623197(13) \times 10^{-8}\,\mathrm{u}$	$(1\,E_\mathrm{H})/hc = 2.194746313702(13) \times 10^{7}\,\mathrm{m}^{-1}$
1 eV	$(1\,\mathrm{eV})/c^2 = 1.0735441105(66) \times 10^{-9}\,\mathrm{u}$	$(1\,\mathrm{eV})/hc = 8.065544005(50) \times 10^{5}\,\mathrm{m}^{-1}$
1 kg	$(1\,\mathrm{kg}) = 6.022140857(74) \times 10^{26}\,\mathrm{u}$	$(1\,\mathrm{kg})\,c/h = 4.524438411(56) \times 10^{41}\,\mathrm{m}^{-1}$
1 u	$(1\,\mathrm{u}) = 1\,\mathrm{u}$	$(1\,\mathrm{u})\,c/h = 7.5130066166(34) \times 10^{14}\,\mathrm{m}^{-1}$
1 m^{-1}	$(1\,\mathrm{m}^{-1})\,h/c = 1.33102504900(61) \times 10^{-15}\,\mathrm{u}$	$(1\,\mathrm{m}^{-1}) = 1\,\mathrm{m}^{-1}$
1 Hz	$(1\,\mathrm{Hz})\,h/c^2 = 4.4398216616(20) \times 10^{-24}\,\mathrm{u}$	$(1\,\mathrm{Hz})/c = 3.335640951\ldots \times 10^{-9}\,\mathrm{m}^{-1}$
1 K	$(1\,\mathrm{K})\,k/c^2 = 9.2510842(53) \times 10^{-14}\,\mathrm{u}$	$(1\,\mathrm{K})\,k/hc = 69.503457(40)\,\mathrm{m}^{-1}$
Energy	**Unit**	
	Hertz	**Kelvin**
1 J	$(1\,\mathrm{J})/h = 1.509190205(19) \times 10^{33}\,\mathrm{Hz}$	$(1\,\mathrm{J})/k = 7.2429731(42) \times 10^{22}\,\mathrm{K}$
1 E_H	$(1\,E_\mathrm{H})/h = 2.194746313702(13) \times 10^{15}\,\mathrm{Hz}$	$(1\,E_\mathrm{H})/k = 3.1577513(18) \times 10^{5}\,\mathrm{K}$
1 eV	$(1\,\mathrm{eV})/h = 2.417989262(15) \times 10^{14}\,\mathrm{Hz}$	$(1\,\mathrm{eV})/k = 1.16045221(67) \times 10^{4}\,\mathrm{K}$
1 kg	$(1\,\mathrm{kg})\,c^2/h = 1.356392512(17) \times 10^{50}\,\mathrm{Hz}$	$(1\,\mathrm{kg})\,c^2/k = 6.5096595(37) \times 10^{39}\,\mathrm{K}$
1 u	$(1\,\mathrm{u})\,c^2/h = 2.2523427206(10) \times 10^{23}\,\mathrm{Hz}$	$(1\,\mathrm{u})\,c^2/k = 1.08095438(62) \times 10^{13}\,\mathrm{K}$
1 m^{-1}	$(1\,\mathrm{m}^{-1})\,c = 299\,792\,458\,\mathrm{Hz}$	$(1\,\mathrm{m}^{-1})\,hc/k = 1.43877736(83) \times 10^{-2}\,\mathrm{K}$
1 Hz	$(1\,\mathrm{Hz}) = 1\,\mathrm{Hz}$	$(1\,\mathrm{Hz})\,h/k = 4.7992447(28) \times 10^{-11}\,\mathrm{K}$
1 K	$(1\,\mathrm{K})\,k/h = 2.0836612(12) \times 10^{10}\,\mathrm{Hz}$	$(1\,\mathrm{K}) = 1\,\mathrm{K}$

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