# 8. DEFINTIONS AND SYMBOLS FOR UNITS

## The International System of Units (SI)

The International System of units (SI) was adopted by the 11th General Conference on Weights and Measures (CGPM) in 1960. It is a coherent system of units built from seven *SI base units*, one for each of the seven dimensionally independent base quantities: they are the metre, kilogram, second, ampere, kelvin, mole, and candela, for the dimensions length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity, respectively. The *SI derived units* are expressed as products of powers of the base units, analogous to the corresponding relations between physical quantities but with numerical factors equal to unity.

In the International System there is only one SI unit for each physical quantity. This is either the appropriate SI base unit itself or the appropriate SI derived unit. However, any of the approved decimal prefixes, called *SI prefixes*, may be used to construct decimal multiples or submultiples of SI units.

It is recommended that only SI units be used in science and technology (with SI prefixes where appropriate). Where there are special reasons for making an exception to this rule, it is recommended always to define the units used in terms of SI units.

## Definitions of the SI Base Units

***Metre***: The metre is the length of path travelled by light in vaccum during a time interval of 1/299 792 458 of a second (17th CGPM, 1983).

***Kilogram***: The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram (3rd CGPM, 1901).

***Second***: 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 (13th CGPM, 1967).

***Ampere***: The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible ciruclar cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ newton per metre of length (9th CGPM, 1948).

***Kelvin***: The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (13th CGPM, 1967).

***Mole***: 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. 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 (14th CGPM, 1971).

*Examples of the use of the mole*

1 mol of $H_2$ contains about $6.022 \times 10^{23}$ $H_2$ molecules, or $12.044 \times 10^{23}$ H atoms
1 mol of HgCl has a mass of 236.04 g
1 mol of $Hg_2Cl_2$ has a mass of 472.08 g
1 mol of $Hg_2^{2+}$ has a mass of 401.18 g and a charge of 192.97 kC
1 mol of $Fe_{0.91}S$ has a mass of 82.88 g
1 mol of $e^-$ has a mass of 548.60 μm and a charge of $-96.49$ kC
1 mol of photons whose frequency is $5 \times 10^{14}$ Hz has energy of about 199.5 kJ

***Candela***: The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ hertz and that has a radiant intensity in that direction of (1/683) watt per steradian (16th CGPM, 1979).

## Names and Symbols for the SI Base Units

The symbols listed here are internationally agreed and should not be changed in other languages or scripts.

| Physical quantity | Name of SI unit | Symbol for SI unit |
|---|---|---|
| Length | metre | m |
| Mass | kilogram | kg |
| Time | second | s |
| Electric current | ampere | A |
| Thermodynamic temperature | kelvin | K |
| Amount of substance | mole | mol |
| Luminous intensity | candela | cd |

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## SI Derived Units with Special Names and Symbols

| Physical quantity | Name of SI unit | Symbol for SI unit | Expression in terms of SI base units | |
|---|---|---|---|---|
| Frequency[a] | hertz | Hz | $\mathrm{s^{-1}}$ | |
| Force | newton | N | $\mathrm{m\,kg\,s^{-2}}$ | |
| Pressure, stress | pascal | Pa | $\mathrm{N\,m^{-2}}$ | $= \mathrm{m^{-1}\,kg\,s^{-2}}$ |
| Energy, work, heat | joule | J | $\mathrm{N\,m}$ | $= \mathrm{m^{2}\,kg\,s^{-2}}$ |
| Power, radiant flux | watt | W | $\mathrm{J\,s^{-1}}$ | $= \mathrm{m^{2}\,kg\,s^{-3}}$ |
| Electric charge | coulomb | C | $\mathrm{A s}$ | |
| Electric potential, electromotive force | volt | V | $\mathrm{J\,C^{-1}}$ | $= \mathrm{m^{2}\,kg\,s^{-3}A^{-1}}$ |
| Electric resistance | ohm | Ω | $\mathrm{V\,A^{-1}}$ | $= \mathrm{m^{2}\,kg\,s^{-3}A^{-2}}$ |
| Electric conductance | siemens | S | $\Omega^{-1}$ | $= \mathrm{m^{-2}\,kg^{-1}\,s^{3}\,A^{2}}$ |
| Electric capacitance | farad | F | $\mathrm{C\,V^{-1}}$ | $= \mathrm{m^{-2}\,kg^{-1}\,s^{4}\,A^{2}}$ |
| Magnetic flux density | tesla | T | $\mathrm{V\,s\,m^{-2}}$ | $= \mathrm{kg\,s^{-2}\,A^{-1}}$ |
| Magnetic flux | weber | Wb | $\mathrm{V\,s}$ | $= \mathrm{m^{2}\,kg\,s^{-2}\,A^{-1}}$ |
| Inductance | henry | H | $\mathrm{V\,A^{-1}\,s}$ | $= \mathrm{m^{2}\,kg\,s^{-2}\,A^{-2}}$ |
| Celsius temperature[b] | degree Celsius | °C | K | |
| Luminous flux | lumen | lm | cd sr | |
| Illuminance | lux | lx | $\mathrm{cd\,sr\,m^{-2}}$ | |
| Activity[c] (radioactive) | becquerel | Bq | $\mathrm{s^{-1}}$ | |
| Absorbed dose[c] (of radiation) | gray | Gy | $\mathrm{J\,kg^{-1}}$ | $= \mathrm{m^{2}\,s^{-2}}$ |
| Dose equivalent[c] (dose equivalent index) | sievert | Sv | $\mathrm{J\,kg^{-1}}$ | $= \mathrm{m^{2}\,s^{-2}}$ |
| Plane angle[d] | radian | rad | 1 | $= \mathrm{m\,m^{-1}}$ |
| Solid angle[d] | steradian | sr | 1 | $= \mathrm{m^{2}\,m^{-2}}$ |

[a] For radial (angular) frequency and for angular velocity the unit rad $\mathrm{s^{-1}}$, or simply $\mathrm{s^{-1}}$, should be used, and this may *not* be simplified to Hz. The unit Hz should be used *only* for frequency in the sense of cycles per second.

[b] The Celsius temperature $\theta$ is defined by the equation $\theta/{}^{\circ}\mathrm{C} = T/\mathrm{K} - 273.15$.

The SI unit of Celsius temperature is the degree Celsius, °C, which is euqal to the kelvin, K. °C should be treated as a single symbol,with no space between the ° sign and the letter C. (The symbol °K, and the symbol °, should no longer be used).

[c] The units becquerel, gray and sievert are admitted for reasons of safeguarding human health.

[d] The units radian and steradian are described as ‘SI supplementary units’. However, in chemistry, as well as in physics, they are usually treated as dimensionless derived units, and this was recognized by CIPM in 1980. Since they are then of dimension 1, this leaves open the possiblity of including them or omitting them in expressions of SI derived units. In practice this means that rad and sr may be used when appropriate and may be omitted if clarity is not lost thereby.

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## SI Derived Units for Other Quantities

This table gives examples of other SI derived units; the list is merely illustrative.

| Physical quantity | Expression in terms of SI base units | |
|---|---|---|
| Area | $\mathrm{m^2}$ | |
| volume | $\mathrm{m^3}$ | |
| Speed, velocity | $\mathrm{m\ s^{-1}}$ | |
| Angular velocity | $\mathrm{s^{-1}}$, $\mathrm{rad\ s^{-1}}$ | |
| Acceleration | $\mathrm{m\ s^{-2}}$ | |
| Moment of force | $\mathrm{N\ m}$ | $= \mathrm{m^2\ kg\ s^{-2}}$ |
| Wavenumber | $\mathrm{m^{-1}}$ | |
| Density, mass density | $\mathrm{kg\ m^{-3}}$ | |
| Specific volume | $\mathrm{m^3\ kg^{-1}}$ | |
| Amount concentraion[a] | $\mathrm{mol\ m^{-3}}$ | |
| Molar volume | $\mathrm{m^3\ mol^{-1}}$ | |
| Heat capacity, entropy | $\mathrm{J\ K^{-1}}$ | $= \mathrm{m^2\ kg\ s^{-2}\ K^{-1}}$ |
| Molar heat capacity, molar entropy | $\mathrm{J\ K^{-1}\ mol^{-1}}$ | $= \mathrm{m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}}$ |
| Specific heat capacity, specific entropy | $\mathrm{J\ K^{-1}\ kg^{-1}}$ | $= \mathrm{m^2 s^{-2}\ K^{-1}}$ |
| Molar energy | $\mathrm{J\ mol^{-1}}$ | $= \mathrm{m^2\ kg\ s^{-2}\ mol^{-1}}$ |
| Specific energy | $\mathrm{J\ Kg^{-1}}$ | $= \mathrm{m^2 s^{-2}}$ |
| Energy density | $\mathrm{J\ m^{-3}}$ | $= \mathrm{m^{-1}\ kg\ s^{-2}}$ |
| Surface tension | $\mathrm{N\ m^{-1}} = \mathrm{J\ m^{-2}}$ | $= \mathrm{kg\ s^{-2}}$ |
| Heat flux density, irradiance | $\mathrm{W\ m^{-2}}$ | $= \mathrm{kg\ s^{-3}}$ |
| Thermal conductivity | $\mathrm{W\ m^{-1}\ K^{-1}}$ | $= \mathrm{m\ kg\ s^{-3}\ K^{-1}}$ |
| Kinematic viscosity, diffusion coefficient | $\mathrm{m^2\ s^{-1}}$ | |
| Dynamic viscosity | $\mathrm{N\ s\ m^{-2}} = \mathrm{Pa\ s}$ | $= \mathrm{m^{-1}\ kg\ s^{-1}}$ |
| Electric charge density | $\mathrm{C\ m^{-3}}$ | $= \mathrm{m^{-3}\ s\ A}$ |
| Electric current density | $\mathrm{A\ m^{-2}}$ | |
| Conductivity | $\mathrm{S\ m^{-1}}$ | $= \mathrm{m^{-3}\ kg^{-1}\ s^3\ A^2}$ |
| Molar conductivity | $\mathrm{S\ m^2\ mol^{-1}}$ | $= \mathrm{kg^{-1}\ mol^{-1} s^3\ A^2}$ |
| Permittivity | $\mathrm{F\ m^{-1}}$ | $= \mathrm{m^{-3}\ kg^{-1}\ s^{-4}\ A^2}$ |
| Permeability | $\mathrm{H\ m^{-1}}$ | $= \mathrm{m\ kg\ s^{-2}\ A^{-2}}$ |
| Electric field strength | $\mathrm{V\ m^{-1}}$ | $= \mathrm{m\ kg\ s^{-3}\ A^{-1}}$ |
| Magnetic field strength | $\mathrm{A\ m^{-1}}$ | |
| Luminance | $\mathrm{cd\ m^{-2}}$ | |
| Exposure (X and $\gamma$ rays) | $\mathrm{C\ kg^{-1}}$ | $= \mathrm{kg^{-1}\ s\ A}$ |
| Absorbed dose rate | $\mathrm{Gy\ s^{-1}}$ | $= \mathrm{m^2\ s^{-3}}$ |

[a] The words 'amount concentration' are an abbreviation for 'amount-of-substance concentration'. When there is not likely to be any ambiguity this quantity may be called simply 'concentration'.

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## SI Prefixes

To signify decimal multiples and submultiples of SI units the following prefixes may be used.

| Submultiple | Prefix | Symbol | Multiple | Prefix | Symbol |
|---|---|---|---|---|---|
| $10^{-1}$ | deci | d | 10 | deca | da |
| $10^{-2}$ | centi | c | $10^2$ | hecto | h |
| $10^{-3}$ | milli | m | $10^3$ | kilo | k |
| $10^{-6}$ | micro | µ | $10^6$ | mega | M |
| $10^{-9}$ | nano | n | $10^9$ | giga | G |
| $10^{-12}$ | pico | p | $10^{12}$ | tera | T |

| Submultiple | Prefix | Symbol | Multiple | Prefix | Symbol |
|---|---|---|---|---|---|
| $10^{-15}$ | femto | f | $10^{15}$ | peta | P |
| $10^{-18}$ | atto | a | $10^{18}$ | exa | E |
| $10^{-21}$ | zepto | z | $10^{21}$ | zetta | Z |
| $10^{-24}$ | yocto | y | $10^{24}$ | yotta | Y |

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Prefix symbols should be printed in roman (upright) type with no space between the prefix and the unit symbol.

*Example* kilometre, km

When a prefix is used with a unit symbol, the combination is taken as a new symbol that can be raised to any power without the use of parentheses.

*Examples* $1\ \mathrm{cm}^3 = (0.01\ \mathrm{m})^3 = 10^{-6}\ \mathrm{m}^3$
$1\ \mu\mathrm{s}^{-1} = (10^{-6}\ \mathrm{s})^{-1} = 10^{-6}\ \mathrm{s}^{-1}$
$1\ \mathrm{V/cm} = 100\ \mathrm{V/m}$
$1\ \mathrm{mmol/dm}^3 = 1\ \mathrm{mol\ m}^{-3}$

A prefix should never be used on its own, and prefixes are not to be combined into comnpound prefixes.

*Example* pm, not μμm

The names and symbols of decimal multiples and submultiples of the SI base unit of mass, the kg, which already contains a prefix, are constructed by adding the appropriate prefix to the word gram and symbol g.

*Examples* mg, not μkg; Mg, not kkg

The SI prefixes are not to be used with °C.

ISO has recommended standard representations of the prefix symbols for use with limited character sets.

## Units in Use Together with the SI

These units are not part of the SI, but it is recognized that they will continue to be used in appropriate contexts. SI prefixes may be attached to some of these units, such as millilitre, ml; millibar, mbar; megaelectronvolt, MeV; kilotonne, kt. A more extensive list of non-SI units, with conversion factors to the corresponding SI units, is given in the appendix, Conversion of Units.

| Physical quantity | Name of unit | Symbol for unit | Value in SI units |
|---|---|---|---|
| Time | minute | min | 60 s |
| Time | hour | h | 3600 s |
| Time | day | d | 86 400 s |
| Plane angle | degree | ° | $(\pi/180)$ rad |
| Plane angle | minute | ′ | $(\pi/10\,800)$ rad |
| Plane angle | second | ″ | $(\pi/648\,000)$ rad |
| Length | ångström[a] | Å | $10^{-10}$ m |
| Area | barn | b | $10^{-28}\ \mathrm{m}^2$ |
| Volume | litre | l, L | $\mathrm{dm}^3 = 10^{-3}\ \mathrm{m}^3$ |
| Mass | tonne | t | $\mathrm{Mg} = 10^3$ kg |
| Pressure | bar[a] | bar | $10^5\mathrm{Pa} = 10^5\ \mathrm{N\ m}^{-2}$ |
| Energy | electronvolt[b] | $\mathrm{eV}(= e \times \mathrm{V})$ | $\approx 1.60218 \times 10^{-19}$ J |
| Mass | unified atomic mass unit[b,c] | $\mathrm{u}(= m_a(^{12}\mathrm{C})/12$ | $\approx 1.66054 \times 10^{-27}$ kg |

[a] The ångström and the bar are approved by CIPM for 'temporary use with SI units', until CIPM makes a further recommendation. However, they should not be introduced where they are not used at present.

[b] The values of these units in terms of the corresponding SI units are not exact, since they depend on the values of the physical constants $e$ (for the electronvolt) and $N_A$ (for the unified atomic mass unit), which are determined by experiment. See appendix, Fundamental Constants.
[c] The unified atomic mass unit is also sometimes called the dalton, with symbol Da, although the name and symbol have not been approved by CGPM.
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## Atomic Units

For the purposes of quantum mechanical calculations of electronic wavefuntions, it is convenient to regard certain fundamental constants (and combinations of such constants) as though they were units. They are customarily called *atomic units* (abbreviated: au), and they may be regarded as forming a coherent system of units for the calculation of electronic properties in theoretical chemistry, although there is no authority from CGPM for treating them as units. The first five atomic units in the table below have special names and symnbols. Only four of these are independent; all others may be derived by multiplication and devision in the usual way, and the table includes a number of examples.

The relation of atomic units to the corresponding SI units involves the values of the fundamental physical constants, and is therefore not exact. The numerical values in the table are based on the estimates of the appendix, Fundamental Constants. The numerical results of calculations in theoretical chemistry are frequently quoted in atomic units, or as numerical values in the form (*physical quantity*)/(*atomic unit*), so that the reader may make the conversion using the current best estimates of the physical constants.

| Physical quantity | Name of unit | Symbol for unit | Value of unit in SI |
|---|---|---|---|
| mass | electron rest mass | $m_e$ | $9.109\,3897\,(54)\times10^{-31}$ kg |
| charge | elementary charge | $e$ | $1.602\,177\,33\,(49)\times10^{-19}$ C |
| action | Planck constant/2π[a] | $\hbar$ | $1.054\,572\,66\,(63)\times10^{-34}$ J s |
| length | bohr[a] | $a_0$ | $5.291\,772\,49\,(24)\times10^{-11}$ m |
| energy | hartree[a] | $E_h$ | $4.359\,7482\,(26)\times10^{-18}$ J |
| time | | $\hbar/E_h$ | $2.418\,884\,3341\,(29)\times10^{-17}$ s |
| velocity[b] | | $a_0E_h/\hbar$ | $2.187\,691\,42\,(10)\times10^{6}$ m s$^{-1}$ |
| force | | $E_h/a_0$ | $8.238\,7295\,(25)\times10^{-8}$ N |
| momentum, linear | | $\hbar/a_0$ | $1.992\,8534\,(12)\times10^{-24}$ N s |
| electric current | | $eE_h/\hbar$ | $6.623\,6211\,(20)\times10^{-3}$ A |
| electric field | | $E_h/ea_0$ | $5.142\,2082\,(15)\times10^{11}$ V m$^{-1}$ |
| electric dipole moment | | $ea_0$ | $8.478\,3579\,(26)\times10^{-30}$ C m |
| magnetic flux density | | $\hbar/ea_0^2$ | $2.350\,518\,08\,(71)\times10^{5}$ T |
| magnetic dipole moment[c] | | $e\hbar/m_e$ | $1.854\,803\,08\,(62)\times10^{-23}$ J T$^{-1}$ |

[a] $\hbar = h/2\pi$; $a_0 = 4\pi\varepsilon_0\hbar^2/m_e e^2$; $E_h = \hbar^2/m_3 a_0^2$.
[b] The numerical value of the speed of light, when expressed in atomic units, is equal to the reciprocal of the fine structure constant $\alpha$; $c/(\text{au of velocity}) = c\hbar/a_0E_h = \alpha^{-1} \approx 137.035\,9895\,(61)$.
[c] The atomic unit of magnetic dipole moment is twice the Bohr magneton, $\mu_B$.
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## Dimensionless Quantities

Values of dimensionless physical quanitites, more properly called 'quantities of dimension one', are often expressed in terms of mathematically exactly defined values denoted by special symbols or abbreviations, such as %( per cent) and ppm (part per million). These symbols are then treated as units, and are used as such in calculations.

### Fractions (Relative Values, Yields, Efficiencies)

Fractions such as relative uncertainty, mole fraction $x$ (also called amount fraction, or number fraction), mass fraction $w$, and volume fraction $\phi$, are sometimes expressed in terms of the sumbols summarized in the table below.

| Name | Symbol | Value | Examples |
|---|---|---|---|
| percent | % | $10^{-2}$ | The isotopic abundance of carbon-13 expressed as a mole fraction is $x = 1.1\%$ |
| part per million | ppm | $10^{-6}$ | The relative uncertainty in the Planck constant $h(= 6.626\,0755(40) \times 10^{-34}$ J s) is 0.60 ppm<br>The mass fration of impurities in a sample of copper was found to be less than 3 ppm, $w < 3$ppm |

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These multiples of the unit one are not part of the SI and ISO recommends that these symbols should never be used. They are also frequently used as units of 'concentration' without a clear indication of the type of fraction implied (e.g. mole fraction, mass fraction or volume fraction). To avoid ambiguity they should only be used in a context where the meaning of the quantity is carefully defined. Even then, the use of an appropriate SI unit ratio may be preferred.

### Deprecated Usage

Adding extra labels to ppm and similar symbols, such as ppmv (meaning ppm by volume) should be avoided. Qualifying labels may be added to symbols for physical quantities, but never to units.

The symbols % and ppm should not be used in combination with other units. In table headings and in labelling the axes of graphs the use of % and ppm in the denominator is to be avoided. Although one would write $x(^{13}\text{C}) = 1.1\%$, the notation $100\,x$ is to be preferred to $x/\%$ in tables and graphs.

The further symbols listed in the table below are also to be found in the literature, but their use is to be deprecated. Note that the names and symbols for $10^{-9}$ and $10^{-12}$ in this table are based on the American system of names. In other parts of the world a billion sometimes stands for $10^{12}$ and a trillion for $10^{18}$. Note also that the symbol ppt is sometimes used for part per thousand, and sometimes for part per trillion.

To avoid ambiguity the symbols ppb, ppt and pphm should not be used.

| Name | Symbol | Value | Examples |
|---|---|---|---|
| part per hundred | pph | $10^{-2}$ | (Exactly equivalent to percent, %) |
| part per thousand | ppt | $10^{-3}$ | Atmospheric carbon dioxide is depleted in carbon-13 mass fraction by 7‰ (or 7 ppt) relative to ocean water |
| permille[a] | ‰ | $10^{-3}$ | |
| part per hundred million | pphm | $10^{-8}$ | The mass fraction of impurity in the metal was less than 5 pphm |
| part per billion | ppb | $10^{-9}$ | The air quality standard for ozone is a volume fraction of $\phi = 120$ ppb |
| part per trillion | ppt | $10^{-12}$ | The natural background volume fraction of NO in air was found to be $\phi = 140$ ppt |
| part per quadrillion | ppq | $10^{-15}$ | |

[a] The permille is also spelled per mille, per mill, permil or pro mille.

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# 9. FUNDAMENTAL PHYSICAL CONSTANTS

The following values were recommended by the CODATA Task Group on Fundamental Constants in 1986. For each constant the standard deviation uncertainty in the least significant digits is given in parentheses.