1.4 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 defintions of the SI base units are given in section 1.4.1. 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 (see table 1.4.2) or the appropriate SI derived unit (see tables 1.4.3 and 1.4.4). However, any of the approved decimal prefixes, called *SI prefixes*, may be used to construct decimal multiples or submultiples of SI units (see table 1.4.5).

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.

Reference: Bureau International des Poids et Mesures, Le Systeme International d'Unités (SI), 6^{th} French and English Edition, BIPM, Sèvres 1991.

1.4.1 Definitions of the SI base units

metre

The metre is the length of path travelled by light in vacuum 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 round state of the caesium-133 atom (13th CGPM, 1967).

ampere

The ampere is that constant current which, if maintained in two straight parallel conductors if infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-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 DGPM, 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 6.022×10^{23} H_2 molecules, or 12.044×10^{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^+ 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 μg and a charge of -96.49 kC
1 mol of photons whose frequency is 5×10^{14} Hz has energy of about 199.5 kJ

See also section 1.3.7 (v).

candela

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

1.4.2 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. Symbols for units should be printed in roman (upright) type. They should remain unaltered in the plural, and should not be followed by a full stop except at the end of a sentence.

Example: r = 10 cm, not cm. or cms

Symbols for units should be printed in lower case letters, unless they are derived from a personal name when they should begin with a capital letter. (An exception is the symbol for the litre, which may be either L or l.)

Physical quantity	*Symbol for quantity*	*Name of SI unit*	*Symbol for SI unit*
length	l	metre	m
mass	m	kilogram	kg
time	t	second	s
elecric current	I	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

1.4.3 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[1]	hertz	Hz	s^{-1}	
force	newton	N	$m\ kg\ s^{-2}$	
pressure, stress	pascal	Pa	$N\ m^{-2}$	$= m^{-1}\ kg\ s^{-2}$
energy, work, heat	joule	J	N m	$= m^{2}\ kg\ s^{-2}$
power, radiant flux	watt	W	$J\ s^{-1}$	$= m^{2}\ kg\ s^{-3}$
electric charge	coulomb	C	A s	
electric potential, electromotive force	volt	V	$J\ C^{-1}$	$= m^{2}\ kg\ s^{-3}\ A^{-1}$
electric resistance	ohm	Ω	$V\ A^{-1}$	$= m^{2}\ kg\ s^{-3}\ A^{-2}$
electric conductance	siemens	S	Ω^{-1}	$= m^{-2}\ kg^{-1}\ s^{3}\ A^{2}$
electric capacitance	farad	F	$C\ V^{-1}$	$= m^{-2}\ kg^{-1}\ s^{4}\ A^{2}$
magnetic flux density	tesla	T	$V\ s\ m^{-2}$	$= kg\ s^{-2}\ A^{-1}$
magnetic flux	weber	Wb	V s	$= m^{2}\ kg\ s^{-2}\ A^{-1}$
inductance	henry	H	$V\ A^{-1}\ s$	$= m^{2}\ kg\ s^{-2}\ A^{-2}$
Celsius temeperature[2]	degree Celsius	°C	K	
luminous flux	lumen	lm	cd sr	
illuminance	lux	lx	$cd\ sr\ m^{-2}$	

(1) For radial (angular) frequency and for angular velocity the unit rad s^{-1}, or simply 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.

(2) The Celsius temperature θ is defined by the equation

$$\theta/°C = T/K - 273.15$$

The SI unit of Celsius temperature is the degree Celsius, °C, which is equal 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.)

Physical quantity	*Name of SI unit*	*Symbol for SI unit*	*Expression in terms of SI base units*	
activity[3] (radioactive)	becquerel	Bq	s^{-1}	
adsorbed dose[3] (of radiation)	gray	Gy	$J\ kg^{-1}$	$= m^2\ s^{-2}$
dose equivalent[3] (dose equivalent index)	sievert	Sv	$J\ kg^{-1}$	$= m^2\ s^{-2}$
plane angle[4]	radian	rad	1	$= m\ m^{-1}$
solid angle[4]	steradian	sr	1	$= m^2\ m^{-2}$

(3) The units becquerel, gray and sievert are admitted for reasons of safeguarding human health.

(4) The units radian and steradian are describe 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 possibility 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.

1.4.4 SI derived units for other quantities

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

Physical quantity	*Expression in terms of SI base units*	
area	m^2	
volume	m^3	
speed, velocity	$m\ s^{-1}$	
angular velocity	s^{-1}, rad s^{-1}	
acceleration	$m\ s^{-2}$	
moment of force	N m	$= m^2\ kg\ s^{-2}$
wavenumber	m^{-1}	
density, mass density	$kg\ m^{-3}$	
specific volume	$m^3\ kg^{-1}$	
amount concentration[5]	$mol\ m^{-3}$	
molar volume	$m^3\ mol^{-1}$	
heat capacity, entropy	$J\ K^{-1}$	$= m^2\ kg\ s^{-2}\ K^{-1}$
molar heat capacity, molar entropy	$J\ K^{-1}\ mol^{-1}$	$= m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
specific heat capacity, specific entropy	$J\ K^{-1}\ kg^{-1}$	$= m^2\ s^{-2}\ K^{-1}$
molar energy	$J\ mol^{-1}$	$= m^2\ kg\ s^{-2}\ mol^{-1}$
specific energy	$J\ kg^{-1}$	$= m^2\ s^{-2}$
energy density	$J\ m^{-3}$	$= m^{-1}\ kg\ s^{-2}$
surface tension	$N\ m^{-1} = J\ m^{-2} = kg\ s^{-2}$	
heat flux density, irradiance	$W\ m^{-2}$	$= kg\ s^{-3}$
thermal conductivity	$W\ m^{-1}\ K^{-1}$	$= m\ kg\ s^{-3}\ K^{-1}$

(5) 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'.

Physical quantity	*Expression in terms of SI base units*	
kinematic viscosity, diffusion coefficient	$m^2\ s^{-1}$	
dynamic viscosity	$N\ s\ m^{-2} = Pa\ s$	$= m^{-1}\ kg\ s^{-1}$
electric charge density	$C\ m^{-3}$	$= m^{-3}\ s\ A$
electric current density	$A\ m^{-2}$	
conductivity	$S\ m^{-1}$	$= m^{-3}\ kg^{-1}\ s^3\ A^2$
molar conductivity	$S\ m^2\ mol^{-1}$	$= kg^{-1}\ mol^{-1}\ s^3\ A^2$
permittivity	$F\ m^{-1}$	$= m^{-3}\ kg^{-1}\ s^4\ A^2$
permeability	$H\ m^{-1}$	$= m\ kg\ s^{-2}\ A^{-2}$
electric field strength	$V\ m^{-1}$	$= m\ kg\ s^{-3}\ A^{-1}$
magnetic field strength	$A\ m^{-1}$	
luminance	$cd\ m^{-2}$	
exposure (X and γ rays)	$C\ kg^{-1}$	$= kg^{-1}\ s\ A$
absorbed dose rate	$Gy\ s^{-1}$	$= m^2\ s^{-3}$

1.4.5 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
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}	yotto	Y

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 compound prefixes.

Example pm, not $\mu\mu$m

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.

1.4.6 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 chapter 5.

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[6]	Å	10^{-10} m
area	barn	b	10^{-28} m^2
volume	litre	l, L	dm^3 = 10^{-3} m^3
mass	tonne	t	Mg = 10^3 kg
pressure	bar[1]	bar	10^5 Pa = 10^5 N m^{-2}
energy	electronvolt[7]	eV (= e×V)	≈ 1.60218×10^{-19} J
mass	unified atomic mass unit[2,8]	u(= $m_a(^{12}C)/12$)	≈ 1.66054×10^{-27} kg

(6) 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.

(7) 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.

(8) 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.