The International System of Units (SI)

The International System of Units (abbreviated to SI) was established by the 11th General Conference on Weights and Measures (CGPM) in 1960. It is the modern metric system of measurement used throughout the World, see e.g. NIST (2008).

There are, according to NIST (2008), seven SI base quantities:

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

* In the US spelt "meter".

Any SI derived quantity, Q, can be expressed in terms of these SI base units by multiplication and division, i.e.:

$$Q = Cl^{\alpha}m^{\beta}t^{\gamma}I^{\delta}T^{\epsilon}n^{\zeta}I_v^{\eta}$$

Its dimension is then defined to be:

$$dim(Q) = \mathrm{L}^{\alpha}\mathrm{M}^{\beta}\mathrm{T}^{\gamma}\mathrm{I}^{\delta}\Theta^{\epsilon}\mathrm{N}^{\zeta}\mathrm{J}^{\eta}$$

where L, M, T, I, Θ, N and J are the dimensions of the corresponding SI base quantities

Definitions of each of the SI units are given in SI Unit definitions.

Examples of SI derived units include:

Derived quantity	SI derived unit	Symbol
area	square metre	m^2
mass density	kilogram per cubic metre	$\mathrm{kg/m}^3$
current density	ampere per square metre	$\mathrm{A/m}^2$
luminance	candela per square metre	$\mathrm{cd/m}^2$

These can also be expressed using negative powers, e.g. current density is equivalently measured in $\mathrm{A\,m}^{-2}$, which can also be written as $\mathrm{A} \cdot \mathrm{m}^{-2}$. There are specific rules about how SI units should be written, see here.

Quantities can be expressed in terms of these base units using 'scientific', i.e. 'exponent' notation, e.g. the mass of an electron is approximately 9.1×10^{-31} kg. Alternatively, the SI system has a series of prefixes defining decimal multiples and decimal divisions of the base unit, e.g. a millimetre can be written as 0.001 m = 1×10^{-3} m = 1 mm, see SI prefixes.

Certain SI derived units have special names and symbols, see SI derived units with special names and symbols.

There are some units that are outside the SI but are so commonly used that they are widely accepted, see units commonly accepted for use with the SI. These include units of time such as hours and minutes and units relevant in specific disciplines such as the electron volt. Some non-SI units are commonly used in certain fields and according to NIST (2008) are also acceptable for use with the SI, as long as their use is not extended beyond fields in which they are already used. Nearly all of these are defined by reference to their value in SI units.

There are also some specialised units that are given by the International Organisation for Standardisation (ISO) or the International Electrotechnical Commission (IEC) which NIST also think are compatible for use with the SI for similar reasons, e.g. the octave, phon and sone and some units used in information technology including the baud (Bd), bit (bit), erlang (E), hartley (Hart), and Shannon (Sh).

In some instances, physicists also use quantities expressed in terms of fundamental constants of nature, such as the speed of light in a vacuum. These are sometimes used in conjunction with the SI.

There are a large number of other units that are used in some circumstances, e.g. pints, quarts, inches, ounces etc. as per Imperial weights and measures. Some of these are defined by reference to SI units (or in some cases are special names for SI units or multiples or submultiples of such units that are not accepted for use with the SI), whilst others may be converted to SI units based on values of experimental measurements. The Nematrian website provides users with a large number of unit conversion functions that can be used to convert from one set of units to another.

SI Unit definitions

[SIUnitDefinitions]

Current definitions (2019) of each of the SI base units are set out below, following refinements implemented on 20 May 2019 which linked all of the definitions to fundamental constants of nature, see here.

Metre: The metre is the SI unit of length. It is the distance travelled by light in a vacuum during a time interval of 1/299792458 of a second.

Kilogram: The kilogram is the SI unit of mass. It is defined by setting Plank's constant to exactly $6.62607015 \times 10^{-34}$ joule second. It used to be defined (immediately prior to 20 May 2019) as the mass of the international prototype of the kilogram.

Second: The second is the SI unit of time. It is the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

Ampere: The ampere is the SI unit of electrical current. It is defined by setting the elementary charge e to be exactly $1.602176634 \times 10^{-19}$ coulomb. It used to be defined (immediately prior to 20 May 2019) as the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newtons per meter of length.

Kelvin: The kelvin is the SI unit of thermodynamic temperature. It is defined by setting the Boltzmann constant k to be exactly 1.380649 x 10^{-23} joule per kelvin. It used to be defined (immediately prior to 20 May 2019) as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

Mole: The mole is the SI unit of amount of atomic substance. It is defined by setting the Avogadro constant N_A to be exactly 6.02214076 x 10^{23} reciprocal mole. It used to be defined (immediately prior to 20 May 2019) as the amount of 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.

Candela: The candela is SI unit of luminous intensity. It is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.

Proposed refinements to definitions of the base units of the SI system

[SIUnitDefinitionsProposedRefinements]

As explained in SI unit definitions the kilogram used to be defined by reference to the mass of a specific material artefact, i.e. the international prototype kilogram. The definitions of the ampere, mole and candela then depended on the kilogram. Other base unit definitions that had previously referred to specific material artefacts (e.g. the metre) had been altered so that they refered directly to fundamental constants of nature.

The 23rd (2007) and 24th (2011) meetings of the CIPM included resolutions that aimed to redefine the kilogram by reference to a fundamental constant of nature, and to redefine the mole and candela to link more directly to such constants. Definitions were agreed by CIPM (2011) but without some of the precise numerical values being then selected.

On 20 May 2019 the following exact numerical values were adopted, linking all the fundamental SI units to constants of nature:

- the ground state hyperfine splitting frequency of the caesium 133 atom is exactly 9192631770 hertz
- the speed of light in vacuum c is exactly 299792458 metre per second
- the Planck constant h is exactly 6.62607015 x 10^{-34} joule second
- the elementary charge e is exactly 1.602176634 x 10^{-19} coulomb
- the Boltzmann constant k is exactly 1.380649 x 10^{-23} joule per kelvin
- the Avogadro constant N_A is exactly 6.02214076 x 10^{23} reciprocal mole
- the luminous efficacy K_{cd} of monochromatic radiation of frequency 5.4 x 10^{14} is exactly 683 lumen per watt

Such definitions do, of course, presuppose that fundamental constants of nature really are fundamental, a topic that has been the subject of some speculation over many years, see e.g. Barrow (2003). These speculations generally revolve around what might be the case if *dimensionless* constants such as the fine structure constant varied across the universe. Changes merely in *dimensional* physical constants, such as the speed of light are generally considered to be less operationally meaningful as such a world would be *observationally indistinguishable* from our world. A measurement system that is sometimes referred to in such a context involves Planck units.

SI prefixes

[SIUnitPrefixes]

As explained in Introduction to SI units, a prefix may be added to a SI base unit that indicates the exponent (power base ten) to apply to the base unit. The prefixes are set out below. In case you can't easily remember these prefixes, the table also contains links to the corresponding Nematrian conversion functions that you can use to convert units with a prefix to base units or vice versa:

Prefix	Symbol	Factor
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca*	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

* In the US spelt "deka"

An exception is the kilogram (spelt kilogramme in some locations), the SI base unit for mass, which for historical reasons already includes a 'kilo' prefix. Prefixes for it are formed by adjusting this prefix and applying it to the gram.

SI derived units with special names

[SIDerivedUnitsWithSpecialNames]

There are, according to NIST (2008), seven base quantities in the International System of Units (SI units), see Introduction to SI units. Other units are derived from these. However some derived units have special names and symbols:

Quantity	Special name	Special symbol	In terms of other SI units	In terms of SI base units
plane angle	radian[1]	rad		m/m
solid angle	steradian[1]	sr		m^2/m^2
frequency	hertz[2]	Hz		s^{-1}

force	newton	N		$\mathrm{m \cdot kg \cdot s^{-2}}$
pressure, stress	pascal	Pa	$\mathrm{N/m^2}$	$\mathrm{m^{-1} \cdot kg \cdot s^{-2}}$
energy, work, amount of heat	joule	J	$\mathrm{N \cdot m}$	$\mathrm{m^2 \cdot kg \cdot s^{-2}}$
power, radiant flux	watt	W	$\mathrm{J/s}$	$\mathrm{m^2 \cdot kg \cdot s^{-3}}$
electric charge, amount of electricity	coulomb	C		$\mathrm{s \cdot A}$
electric potential difference, electromotive force, voltage	volt	V	$\mathrm{W/A}$	$\mathrm{m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}}$
capacitance	farad	F	$\mathrm{C/V}$	$\mathrm{m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2}$
electric resistance	ohm	Ω	$\mathrm{V/A}$	$\mathrm{m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}}$
electric conductance	siemens	S	$\mathrm{A/V}$	$\mathrm{m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2}$
magnetic flux	weber	Wb	$\mathrm{V \cdot s}$	$\mathrm{m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}}$
magnetic flux density	tesla	T	$\mathrm{Wb/m^2}$	$\mathrm{kg \cdot s^{-2} \cdot A^{-1}}$
inductance	henry	H	$\mathrm{Wb/A}$	$\mathrm{m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}}$
Celsius temperature	degree Celsius[3]	°C		K
luminous flux	lumen	lm	$\mathrm{cd \cdot sr}$	cd
illuminance	lux	lx	$\mathrm{lm/m^2}$	$\mathrm{m^{-2} \cdot cd}$
Activity referred to a radionuclide[4]	becquerel	Bq		$\mathrm{s^{-1}}$
absorbed dose, specific energy (imparted), kerma	gray	Gy	$\mathrm{J/kg}$	$\mathrm{m^2 \cdot s^{-2}}$
dose equivalent, ambient dose equivalent, directional dose equivalent, personal dose equivalent	sievert	Sv	$\mathrm{J/kg}$	$\mathrm{m^2 \cdot s^{-2}}$
catalytic activity	katal	kat		$\mathrm{s^{-1} \cdot mol}$

Notes:
[1] The radian and steradian are special names for the number one that are often used to convey information about the quantity concerned. In practice (and especially in photometry) the symbols rad and sr are used where appropriate.

[2] The hertz is normally only used for periodic phenomena. Likewise the becquerel is normally only used for stochastic phenomena relevant to the applicable radionuclide.

[3] The degree Celsius is the special name for the kelvin when used to express Celsius temperatures. The two are equal in size, so a temperature difference is the same in either scale. By definition, the quantity in Celsius temperature (°C, symbol t) is defined by reference to the quantity in thermodynamic temperature (K, symbol T) by the equation $t = T - T_0$ where $T_0 = 273.15$ K by definition. T_0 is exactly 0.01 K below the thermodynamic temperature of the triple point of water

[4] Loosely referred to as the level of radioactivity of the radionuclide.

Rules for writing SI units

[SIUnitsRulesForWriting]

As noted in Introduction to SI units there are specific rules about how SI units should be written. These include:

- Values are written as a number followed by a space (representing a multiplication sign) and a unit symbol, e.g. 2.4 kg or 14×10^5 J. This convention also applies to the per cent sign (%). Exceptions are the symbols for plane angular degrees, minutes and seconds (°, ′ and ″), which are placed immediately after the number with no intervening space.

- Symbols for derived units formed by multiplication are joined with a centre dot (·) or a (non-break) space, for example, "N·m" or "N m".

- Symbols for derived units formed by division are joined with a solidus (/), or given as a negative exponent. For example, "metre per second" can be written "m/s", "m s^{-1}" or as "m· s^{-1}". Only one solidus should be used; e.g., "kg/(m·s^2)" but "kg/m/s^2" is ambiguous and should not be used.

- Symbols are mathematical entities, not abbreviations, so do not have an appended period/full stop, i.e. “.”.

- Symbols are written in upright (Roman) type (e.g. m for metres), so as to differentiate from the italic type generally used for quantities (e.g. *m* for mass). The consensus of international standards bodies is that this rule should be applied irrespective of the font used for any surrounding text.

- Symbols for units are written in lower case (e.g., "m", "s", "mol"), except for symbols derived from the name of a person. For example, the unit of pressure is named after Blaise Pascal, and is written "Pa", even though the unit itself is written "pascal" (see below). The one exception is the litre, whose original symbol "l" is too similar to the numeral "1" or the uppercase letter "i" (for some typefaces), in some English-speaking countries. The American National Institute of Standards and Technology recommends that "L" is used instead, see NIST (2008). This usage is common in USA, Canada and Australia (but not elsewhere).

- A prefix is part of the unit, and its symbol is prepended to the unit symbol without a separator (e.g. "G" in "GHz"). Compound prefixes are not allowed. All symbols of prefixes larger than 10^3 (kilo) are uppercase.

- The 10th resolution of the General Conference on Weights and Measures (CGPM)* in 2003 declared that "the symbol for the decimal marker shall be either the point on the line or the comma on the line." In practice, the decimal point is used in English-speaking countries and most of Asia, and the comma in most continental European languages. Spaces may be used as a thousands separator (1 000 000) in contrast to commas or periods (1,000,000 or 1.000.000) in order to reduce confusion resulting from the variation between these forms in different countries. In print, the space used for this purpose is typically narrower than that between words (a ‘thin’ space). As the Nematrian website is primarily English-speaking, it generally uses the decimal point as the symbol for the decimal marker. It also generally avoids spaces within numbers, so that they are easier to copy and paste between programs.

- Any line-break inside a number, inside a compound unit, or between a number and its unit should be avoided.

- When writing dimensionless quantities, the terms 'ppb' (parts per billion) and 'ppt' (parts per trillion) are recognised but SI recommends avoiding these terms, since the value of billion and trillion can vary from language to language. No alternative has been suggested by the International Bureau of Weights and Measures (BIPM)*.

- Names of units follow the grammatical rules associated with common nouns. In English and in French they start with a lowercase letter (e.g. newton, hertz), even when the symbol for the unit begins with a capital letter (see above). This also applies to 'degrees Celsius', since 'degree' is the unit. In German however, names of units, start with a capital letter. Names of units are pluralised using the normal English grammar rules. For example "henries" is the plural of "henry". However, the lux, hertz, and siemens are exceptions; they are the same in singular and plural form. This rule applies only to the full names of units, not to their symbols, so two 1 kg masses have a mass of 2 kg not 2 kgs.

- The official US spellings for deca, metre, and litre are deka, meter, and liter, respectively. The Nematrian unit conversion functions accept either spelling.

* The Metre Convention signed in 1875 established three international organisations to oversee the metric standards, i.e. (1) the General Conference on Weights and Measures (Conférence générale des poids et mesures or CGPM) which meets every four to six years with delegates from all member states, (2) the International Bureau of Weights and Measures (Bureau international des poids et mesures or BIPM), an international metrology centre at Sèvres in France; and (3) the International Committee for Weights and Measures (Comité international des poids et mesures or CIPM), an administrative committee which meets annually at the BIPM.

Units commonly accepted alongside SI units

[Nematrian website page: UnitsCommonlyAcceptedForUseWithSI, © Nematrian 2015]

As explained in Introduction to SI units, there are some units that are commonly accepted alongside SI units even though they do not specifically form part of the SI itself. These include:

Commonly used units (accepted for use with the SI), which are defined by reference to their value in SI units:

Name	**Symbol**	**Definition and value in SI Units**
minute (time)	min	1 min = 60 s
hour (time)	h	1 h = 60 min = 3600 s
Day	d	1 d =24 h = 86400 s
Degree	°	1° = $\pi/180$ rad
minute (angle)	'	1' = (1/60)° = $\pi/10800$ rad
second (angle)	"	1" =(1/3600)° = $\pi/648000$ rad
Hectare	ha	1 ha = 1 hm^2 = 10^4 m^2, is used to measure agrarian area
litre*	L, l	1 L = 1 dm^3 = 10^{-3} m^3
metric ton	T	1 T = 10^3 kg
Tonne	T	another name for metric ton
Neper**	Np	Used to measure power ratios. Uses a logarithmic scale involving natural logarithms
Bel**	B	Used to measure power ratios. Uses a logarithmic scale involving logarithms to base 10. Note: 1 B = 10 dB.
Decibel**	dB	Used to measure power ratios. Uses a logarithmic scale involving logarithms to base 10. A ratio of 10 is a 10 dB change, i.e. if two amounts (of power) differ by N decibels then they are in the ratio $10^{N(0.1)}$.

* In the US spelt “liter” and symbol is “L”.

** These measure (power) ratios. The underlying numerical values are rarely required, although for acoustics it is common to use 0 dB to refer to a sound pressure of .0002 microbar or 20 micropascals (although this is not accepted for use alongside SI units). In electronics dB may be combined with a suffix, e.g. “m” for “milliwatt”, to make, “dBm”, so that zero dBm equals one milliwatt, but such quantities are again not accepted for use alongside SI units. When dB is applied to voltage, e.g. dBu or dBV, it is necessary to square the amplitude, to convert voltage ratios to power ratios.

Another unit accepted for use with the SI is the per cent sign (%) which in this context can be thought of as a special way of saying 0.01, i.e. 1×10^{-2}.

Commonly used units (accepted for use with the SI), the values of which need to be obtained experimentally:

Name	Symbol	Definition and (approximate) value in SI Units
Electronvolt (or electron volt)	eV	The electron volt is the kinetic energy acquired by an electron in passing through a potential difference of 1 V in vacuum, and is approximately $1.602176487 \times 10^{-19}$ J according to the 2006 CODATA recommended value.
astronomical unit	ua	The astronomical unit is approximately equal to the mean Earth-Sun distance. It is the radius of an unperturbed circular Newtonian orbit about the Sun of a particle having infinitesimal mass, moving with a mean motion of 0.01720209895 radians per day (also known as the Gaussian constant), and has a value of $1.49597870691 \times 10^{11}$ m according to NIST (2008).
unified atomic mass unit	u	The unified atomic mass unit is equal to 1/12 times the mass of a free carbon 12 atom, at rest and in its ground state, and is $1.660538782 \times 10^{-27}$ kg according to the 2006 CODATA recommended value.
Dalton	Da	The dalton (Da) and the unified atomic mass (u) are alternative names (and symbols) for the same unit

Terms accepted for use with the SI in certain fields / countries due to established practice, or deemed acceptable for use with the SI by NIST (2008):

Name	Symbol	Definition and value in SI Units
nautical mile		1 nautical mile = 1852 m
Knot		1 nautical mile per hour = (1852/3600) m/s
Angstrom	Å	1 Å = 0.1 nm = 10^{-10} m
Barn	b	1 b = 100 fm^2 = 10^{-28} m^2
Bar	bar	1 bar = 0.1 MPa = 100 kPa = 1000 hPa = 10^5 Pa
millimeter of mercury	mmHg	1 mmHg ≈ 133.322 Pa
curie*	Ci	1 Ci = 3.7×10^{10} Bq
roentgen*	R	1 R = 2.58×10^{-4} C/kg
rad*	rad**	1 rad = 1 cGy = 10^{-2} Gy
rem*	rem	1 rem = 1 cSv = 10^{-2} Sv

* Technically only accepted in the US via NIST (2008) rather than by the SI generally.

** If there is a risk of confusion with the symbol for radian then rd may be used instead.