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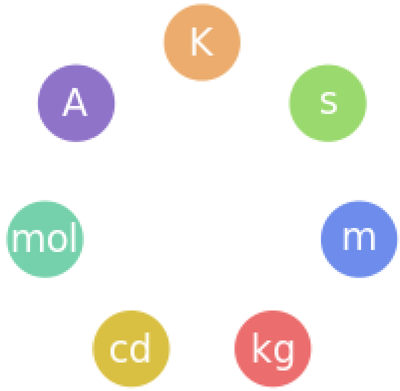
International System of Units

The **International System of Units** (abbreviated as **SI**, from the French Système international (d'unités)) is the modern form of the metric system, and is the most widely used system of measurement. It comprises a coherent system of units of measurement built on seven base units (ampere, kelvin, second, metre, kilogram, candela, mole) and a set of twenty decimal prefixes to the unit names and unit symbols that may be used when specifying multiples and fractions of the units. The system also specifies names for 22 derived units for other common physical quantities like lumen, watt, etc.



The SI base units

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

The base units, except for one, are derived from invariant constants of nature, such as the speed of light and triple point of water, which can be readily observed and measured with great accuracy. The kilogram standard of mass is a physical artefact certified in 1889, consisting of a cylinder of platinum–iridium, which ostensibly has the same mass (weight) as one litre of water at the freezing point. Its stability has been a matter of significant concern, resulting in recent proposals to change the definition to one derived from some invariant constant of nature.[1]

The derived units may be defined in terms of base units and/or other derived units in arbitrary combinations. They are adopted to facilitate measurement in diverse fields of endeavor. SI is intended to be an evolving system, so prefixes and units are created and unit definitions are modified through international agreement as the technology of measurement progresses and the precision of measurements improves. The last new derived unit was defined in 1999.

The reliability of the SI system depends not only on the precise measurement of standards for the base units in terms of various physical constants of nature, but also on precise determination of those constants. The set of constants used periodically changes as more stable constants are found, or ones which may be more precisely measured. One significant consequence is that in 1983, the metre was defined to be the distance that light travels in vacuum for an exact fraction of a second (about a 300 millionth) so that the speed of light is now an exactly defined constant of nature,[2] and will not change.

The motivation for the development of the SI was the diversity of units that had sprung up within the centimetre–gram–second (CGS) systems (specifically the inconsistency between the systems of electrostatic units and electromagnetic units) and the lack of coordination between the various disciplines that used them. The General Conference on Weights and Measures (French: Conférence générale des poids et mesures – CGPM), which was established by the Metre Convention of 1875, brought together many international organisations to establish the definitions and standards of a new system and standardise the rules for writing and presenting measurements. The system was published in 1960 as a result of an initiative that began in 1948. It is based on the metre–kilogram–second system of units (MKS) rather than any variant of the CGS. Since then, the SI has been adopted by all developed countries except the United States.[3]

Contents

Units and prefixes

The International System of Units consists of a set of base units, a set of coherent derived units, and a set of decimal-based multipliers that are used as prefixes.[4]:103–106 Coherent units are derived units that contain no numerical factor other than 1—quantities such as standard gravity and density of water are absent from their definitions. For example: N = kg × m /s^2 which says *one* newton is the force required to accelerate a mass of *one* kilogram by *one* metre per second squared. Since the SI units of mass and acceleration are kg and m⋅s^{-2} respectively and $F \propto m \times a$, the units of force (and hence of newtons) is formed by multiplication to give kg⋅m⋅s^{-2}. Since the newton is part of a coherent set of units, the constant of proportionality is 1.

While the base and specified derived units are coherent, they are not necessarily independent or disjoint: for example, anything that could be specified in terms of siemens, could just as well be specified in terms of ohms, because ohms and siemens are inverses of each other. And both ohms and siemens could be replaced with a combination of amperes and volts, because those quantities bear a defined relationship to each other.[5] Other useful derived quantities can be specified in terms of the SI base and derived units that have no named units in the SI system, such as acceleration, which as defined in SI units as m/s^2

Base units

The SI base units are the building blocks of the system and all other units are derived from them. When Maxwell first introduced the concept of a coherent system, he identified three quantities that could be used as base units: mass, length and time. Giorgi later identified the need for an electrical base unit. The unit of electric current was chosen for SI. Another three base units (for temperature, substance and luminous intensity) were added later

SI base units [6]:23[7][8]

Unit name	Unit symbol	Dimension symbol	Quantity name	Definition [n 1]
metre	m	L	length	▪ **Prior** (1793): $\frac{1}{10\,000\,000}$ of the meridian through Paris between the North Pole and the Equator.FG ▪ **Interim** (1960): 1 650 763.73 wavelengths in a vacuum of the radiation corresponding to the transition between the $2p^{10}$ and $5d^{5}$ quantum levels of the krypton-86 atom. ▪ **Current** (1983): The distance travelled by light in a vacuum in $\frac{1}{299\,792\,458}$ second.
kilogram[n 2]	kg	M	mass	▪ **Prior** (1793): The **grave** was defined as being the weight [mass] of one litre of pure water at its freezing point.FG ▪ **Current** (1889): The mass of a small squat cylinder of ~47 cubic centimetres of platinum-iridium alloy kept in a laboratory in France. Also, in practice, any of numerous official replicas of it.[9][10]
second	s	T	time	▪ **Prior**: $\frac{1}{86\,400}$ of a day of 24 hours of 60 minutes of 60 seconds ▪ **Interim** (1956): $\frac{1}{31\,556\,925.9747}$ of the tropical year for 1900 January 0 at 12 hours ephemeris time. ▪ **Current** (1967): 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.
ampere	A	I	electric current	▪ **Prior** (1881): A tenth of the electromagnetic CGS unit of current. The [CGS] electromagnetic unit of current is that current, flowing in an arc 1 cm long of a circle 1 cm in radius, that creates a field of one oersted at the centre.[11] IEC ▪ **Current** (1946): The 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} newtons per metre of length.
kelvin	K	Θ	thermodynamic temperature	▪ **Prior** (1743): The **centigrade scale** is obtained by assigning 0 °C to the freezing point of water and 100 °C to the boiling point of water. ▪ **Interim** (1954): The triple point of water (0.01 °C) defined to be exactly 273.16 K.[n 3] ▪ **Current** (1967): $\frac{1}{273.16}$ of the thermodynamic temperature of the triple point of water
mole	mol	N	amount of substance	▪ **Prior** (1900): A stoichiometric quantity which is the equivalent mass in grams of Avogadro's number of molecules of a substance.ICAW ▪ **Current** (1967): The amount of substance of a system which contains as many elementary entities[n 4] as there are atoms in 0.012 kilogram of carbon-12.

candela	cd	J	luminous intensity	▪ **Prior** (1946): The value of the new candle is such that the brightness of the full radiator at the temperature of solidification of platinum is 60 new candles per square centimetre. ▪ **Current** (1979): The luminous intensity in a given direction, of a source that emits monochromatic radiation of frequency 5.4×10^{14} hertz and that has a radiant intensity in that direction of $\frac{1}{683}$ watt per steradian. Note: both old and new definitions are approximately the luminous intensity of a whale blubber candle burning modestly bright, in the late 19th century called a "candlepower" or a "candle".

Notes

1. Interim definitions are given here only when there has been a *significant* difference in the definition.
2. Despite the prefix "kilo-", the kilogram is the base unit of mass. The kilogram, not the gram, is used in the definitions of derived units. Nonetheless, units of mass are *named* as if the gram were the base unit.
3. In 1954 the unit of thermodynamic temperature was known as the "degree Kelvin" (symbol °K; "Kelvin" spelt with an upper-case "K"). It was renamed the "kelvin" (symbol "K"; "kelvin" spelt with a lower case "k") in 1967.
4. 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.

The **Prior** definitions of the various base units in the above table were made by the following authorities:

- **FG** = French Government
- **IEC** = International Electrotechnical Commission
- **ICAW** = International Committee on Atomic Weights

All other definitions result from resolutions by either CGPM or the CIPM and are catalogued in the *SI Brochure*.

The early metric systems defined a unit of weight as a base unit, while the SI defines an analogous unit of mass. In everyday use, these are mostly interchangeable, but in scientific contexts the difference matters. Mass, strictly the inertial mass, represents a quantity of matter. It relates the acceleration of a body to the applied force via Newton's law, $F = m \times a$: force equals mass times acceleration. In SI units, if you apply a force of 1 N (newton) to a mass of 1 kg, it will accelerate at 1 m/s^2. This is true whether the object is floating in space or in a gravity field e.g. at the Earth's surface. Weight is the force exerted on a body by a gravitational field, and hence its weight depends on the strength of the gravitational field. Weight of a 1 kg mass at the Earth's surface is $m \times g$; mass times the acceleration due to gravity which at the earth's surface is 9.81 newtons, and at the surface of Mars is about 3.5 newtons. Weight is not an accurate base unit for precision measurement because the constant representing acceleration due to gravity is local and varies over the surface of the earth, because the earth does not have uniform density or radius in all directions. It also varies with altitude or depth (distance from earth's center).

Derived units

The derived units in the SI are formed by powers, products or quotients of the base units and are unlimited in number.[4]:103[6]:3 Derived units are associated with derived quantities, for example velocity is a quantity that is derived from the base quantities of time and length, so in SI the derived unit is metres per second (symbol m/s). The dimensions of derived units can be expressed in terms of the dimensions of the base units.

Derived units may themselves be used in combination with the names and symbols for base units and for other derived units to express the units of other derived quantities. For example, the SI unit of force is the newton (N), the SI unit of pressure is the pascal (Pa)—and the pascal can be defined as one newton per square metre (N/m^2).[12]

Named units derived from SI base units[6]:3

Name	Symbol	Quantity	In other SI units	In SI base units
radian[note 1]	rad	angle		$(m \cdot m^{-1})$
steradian	sr	solid angle		$(m^2 \cdot m^{-2})$
hertz	Hz	frequency		s^{-1}
newton	N	force, weight		$kg \cdot m \cdot s^{-2}$
pascal	Pa	pressure, stress	N/m^2	$kg \cdot m^{-1} \cdot s^{-2}$
joule	J	energy, work, heat	N·m	$kg \cdot m^2 \cdot s^{-2}$
watt	W	power, radiant flux	J/s	$kg \cdot m^2 \cdot s^{-3}$
coulomb	C	electric charge or quantity of electricity		s·A
volt	V	voltage (electrical potential), emf	W/A	$kg \cdot m^2 \cdot s^{-3} \cdot A^{-1}$
farad	F	capacitance	C/V	$kg^{-1} \cdot m^{-2} \cdot s^4 \cdot A^2$
ohm	Ω	resistance, impedance, reactance	V/A	$kg \cdot m^2 \cdot s^{-3} \cdot A^{-2}$
siemens	S	electrical conductance	Ω^{-1}	$kg^{-1} \cdot m^{-2} \cdot s^3 \cdot A^2$
weber	Wb	magnetic flux	V·s	$kg \cdot m^2 \cdot s^{-2} \cdot A^{-1}$
tesla	T	magnetic flux density	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
henry	H	inductance	Wb/A	$kg \cdot m^2 \cdot s^{-2} \cdot A^{-2}$
degree Celsius	°C	temperature relative to 273.15 K		K
lumen	lm	luminous flux	cd·sr	cd
lux	lx	illuminance	lm/m^2	$m^{-2} \cdot cd$
becquerel	Bq	radioactivity (decays per unit time)		s^{-1}
gray	Gy	absorbed dose (of ionizing radiation)	J/kg	$m^2 \cdot s^{-2}$
sievert	Sv	equivalent dose (of ionizing radiation)	J/kg	$m^2 \cdot s^{-2}$
katal	kat	catalytic activity		$mol \cdot s^{-1}$

Notes

1. The radian and steradian are now considered dimensionless derived units.
2. The table ordering is such that any derived unit is based on base or derived units that precede it.

Prefixes

Prefixes are added to unit names to produce multiple and sub-multiples of the original unit. All multiples are integer powers of ten, and above a hundred or below a hundredth all are integer powers of a thousand. For example, *kilo-* denotes a multiple of a thousand and *milli-* denotes a multiple of a thousandth, so there are one thousand millimetres to the metre and one thousand metres to the kilometre. The prefixes are never combined, so for example a millionth of a metre is a *micrometre*, not a millimillimetre. Multiples of the kilogram are named as if the gram were the base unit, so a millionth of a kilogram is a *milligram*, not a microkilogram.[4]:122[13]:14

Standard prefixes for the SI units of measure

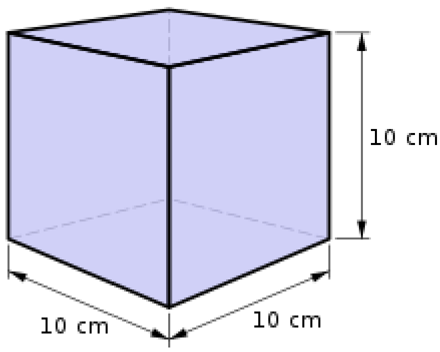
Multiples	**Prefix name**		**deca**	**hecto**	**kilo**	**mega**	**giga**	**tera**	**peta**	**exa**	**zetta**	**yotta**
	Prefix symbol		da	h	k	M	G	T	P	E	Z	Y
	Factor	10^0	10^1	10^2	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}	10^{21}	10^{24}
Submultiples	**Prefix name**		**deci**	**centi**	**milli**	**micro**	**nano**	**pico**	**femto**	**atto**	**zepto**	**yocto**
	Prefix symbol		d	c	m	μ	n	p	f	a	z	y
	Factor	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}	10^{-21}	10^{-24}

Non-SI units accepted for use with SI

The SI is capable of describing most useful and measurable physical quantities, but many non-SI units still appear in the scientific, technical, and commercial literature. Some units are deeply embedded in history and culture. The CIPM recognised and acknowledged such traditions by compiling a list of non-SI units accepted for use with SI, which are grouped as follows:[4]:123–129[13]:7–11[Note 1]

- **Non-SI units accepted for use with the SI**

  Certain units of time, angle, and legacy non-SI metric units have a long history of consistent use. Most societies have used the solar day and its non-decimal subdivisions as a basis of time and, unlike the foot or the pound, these were the same regardless of where they were being measured. The radian, being $\frac{1}{2\pi}$ of a revolution, has mathematical advantages but it is cumbersome for navigation, and, as with time, the units used in navigation have a large degree of consistency around the world. The tonne, litre, and hectare were adopted by the CGPM in 1879 and have been retained as units that may be used alongside SI units, having been given unique symbols. The catalogued units are

  The litre is classed as a non-SI unit accepted for use with the SI. Being one thousandth of a cubic metre, the litre is not a coherent unit of measure with respect to SI.

  minute, hour, day, degree of arc, minute of arc, second of arc, hectare, litre, tonne, astronomical unit and [deci]bel

- **Non-SI units whose values in SI units must be obtained experimentally** (Table 7).

  Physicists often use units of measure that are based on natural phenomena, particularly when the quantities associated with these phenomena are many orders of magnitude greater than or less than the equivalent SI unit. The most common ones have been catalogued in the SI Brochure together with consistent symbols and accepted values, but with the caveat that their values in SI units need to be measured.

  electronvolt (symbol eV), and dalton/unified atomic mass unit (Da or u)

- **Other non-SI units** (Table 8):

  A number of non-SI units that had never been formally sanctioned by the CGPM have continued to be used across the globe in many spheres including health care and navigation. As with the units of measure in Tables 6 and 7, these have been catalogued by the CIPM in the SI Brochure to ensure consistent usage, but with the recommendation that authors who use them should define them wherever they are used.

  bar, millimetre of mercury, ångström, nautical mile, barn, knot and neper

In the interests of standardising health-related units of measure used in the nuclear industry, the 12th CGPM (1964) accepted the continued use of the curie (symbol Ci) as a non-SI unit of activity for radionuclides;[4]: 152 the becquerel, sievert and gray were adopted in later years. Similarly, the millimetre of mercury (symbol mmHg) was retained for measuring blood pressure.[4]:127

Sphygmomanometer – the traditional device that measures blood pressure using mercury in a manometer. Pressures are recorded in "millimetres of mercury" – a non-SI unit

- **Non-SI units associated with the CGS and the CGS-Gaussian system of units** (Table 9)

  The SI manual also catalogues a number of legacy units of measure that are used in specific fields such as geodesy and geophysics or are found in the literature, particularly in classical and relativistic electrodynamics where they have certain advantages: The units that are catalogued are:

  erg, dyne, poise, stokes, stilb, phot, gal, maxwell, gauss, and oersted.

Common notions of the metric units

The basic units of the metric system, as originally defined, represented common quantities or relationships in nature. They still do – the modern precisely defined quantities are refinements of definition and methodology, but still with the same magnitudes. In cases where laboratory precision may not be required or available, or where approximations are good enough, the original definitions may suffice.[14]

- A second is 1/60 of a minute, which is 1/60 of an hour, which is 1/24 of a day, so a second is 1/86400 of a day; a second is the time it takes a dense object to freely fall 4.9 metres from rest.
- The metre is close to the length of a pendulum that has a period of 2 seconds; most dining tabletops are about 0.75 metre high; a very tall human (basketball forward) is about 2 metres tall.
- The kilogram is the weight of a litre of cold water; a cubic centimetre or millilitre of water weighs a gram (we need no be too concerned about the difference between mass and weight); a 1-euro coin, 7.5 g; a Sacagawea US 1-dollar coin, 8.1 g; a UK 50-pence coin, 8.0 g.
- A candela is about the luminous intensity of a moderately bright candle, or 1 candle power; a 60 W tungsten-filamen incandescent light bulb has a luminous intensity of about 64 candela.
- A mole of a substance has a mass that is its molecular weight expressed in units of grams; the mass of a mole of table salt is 58.4 g.
- A temperature difference of one kelvin is the same as one degree centigrade: 1/100 of the temperature differential between the freezing and boiling points of water at sea level; the absolute temperature in kelvins is the temperature in degrees Celsius plus about 273; human body temperature is about 37 °C or 310 K.
- A 60 W incandescent light bulb consumes 0.5 amperes at 120 V (US mains voltage) and about 0.27 amperes at 220 V (European mains voltage).

Lexicographic conventions

Unit names

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, pascal), even when the symbol for the unit begins with a capital letter. This also applies to "degrees Celsius", since "degree" is the unit.[15][16] The official British and American spellings for certain SI units differ – British English, as well as Australian, Canadian and New Zealand English, uses the spelling *deca-*, *metre*, and *litre* whereas American English uses the spelling *deka-*, *meter*, and *liter*, respectively.[6]:3

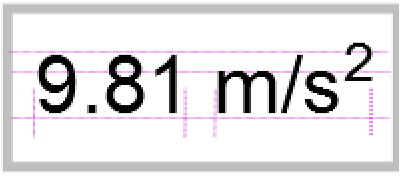
Unit symbols and the values of quantities

Although the writing of unit names is language-specific, the writing of unit symbols and the values of quantities is consistent across all languages and therefore the SI Brochure has specific rules in respect of writing them.[4]:130–135 The guideline produced by the National Institute of Standards and Technology (NIST)[17] clarifies language-specific areas in respect of American English that were left open by the SI Brochure, but is otherwise identical to the SI Brochure.[18]

General rules

General rules[Note 2] for writing SI units and quantities apply to text that is either handwritten or produced using an automated process:

- The value of a quantity is written as a number followed by a space (representing a multiplication sign) and a unit symbol; e.g., 2.21 kg, 7.3×10^2 m^2, 22 K. This rule explicitly includes the percent sign (%)[4]:134 and the symbol for degrees of temperature (°C).[4]: 133 Exceptions are the symbols for plane angular degrees, minutes, and seconds (°, ′, and ″), which are placed immediately after the number with no intervening space.
- Symbols are mathematical entities, not abbreviations, and as such do not have an appended period/full stop (.), unless the rules of grammar demand one for another reason, such as denoting the end of a sentence.
- A prefix is part of the unit, and its symbol is prepended to the unit symbol without a separator (e.g., k in km, M in MPa, G in GHz). Compound prefixes are not allowed.
- Symbols for derived units formed by multiplication are joined with a centre dot (·) or a non-breaking space; e.g., N·m or N m.
- Symbols for derived units formed by division are joined with a solidus (/), or given as a negative exponent. E.g., the "metre per second" can be written m/s, m s^{-1}, m·s^{-1}, or $\frac{m}{s}$. Only one solidus should be used; e.g., kg/(m·s^2) and kg·m^{-1}·s^{-2} are acceptable, but kg/m/s^2 is ambiguous and unacceptable.
- The first letter of symbols for units derived from the name of a person is written in upper case; otherwise, they are written in lower case. E.g., the unit of pressure is named after Blaise Pascal, so its symbol is written "Pa", but the symbol for mole is written "mol". Thus, "T" is the symbol for tesla, a measure of magnetic field strength, and "t" the symbol for tonne, a measure of mass. Since 1979, the litre may exceptionally be written using either an uppercase "L" or a lowercase "l", a decision prompted by the similarity of the lowercase letter "l" to the numeral "1", especially with certain typefaces or English-style handwriting. The American NIST recommends that within the United States "L" be used rather than "l".



Acceleration due to gravity
The lowercase letters (neither "metres" nor "seconds" were named after people), the space between the value and the units, and the superscript "2" to denote "squared".

- Symbols of units do not have a plural form; e.g., 25 kg, not 25 kgs.
- Uppercase and lowercase prefixes are not interchangeable. E.g., the quantities 1 mW and 1 MW represent two different quantities; the former is the typical power requirement of a hearing aid (1 milliwatt or 0.001 watts), and the latter the typical power requirement of a suburban train (1 megawatt or 1 000 000 watts).
- The symbol for the decimal marker is either a point or comma on the line. In practice, the decimal point is used in most English-speaking countries and most of Asia, and the comma in most of Latin America and in continental European countries.[19]
- Spaces should be used as a thousands separator (1 000 000) in contrast to commas or periods (1,000,000 or 1.000.000) to reduce confusion resulting from the variation between these forms in different countries.
- Any line-break inside a number, inside a compound unit, or between number and unit should be avoided. Where this is not possible, line breaks should coincide with thousands separators.
- Since the value of "billion" and "trillion" can vary from language to language, the dimensionless terms "ppb" (parts per billion) and "ppt" (parts per trillion) should be avoided. No alternative is suggested in the SI Brochure.

Printing SI symbols

The rules covering printing of quantities and units are part of ISO 80000-1:2009.[20]

Further rules[Note 2] are specified in respect of production of text using printing presses, word processors, typewriters and the like.

International System of Quantities

SI Brochure

The CGPM publishes a brochure which defines and presents SI.[4] Its official version is in French, in line with the Metre Convention.[4]:102 It leaves some scope for local interpretation, particularly regarding names and terms in different languages.[21][6]

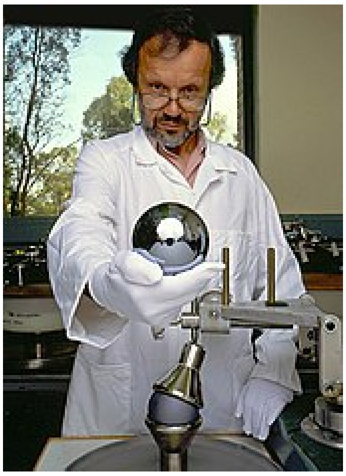
The writing and maintenance of the CGPM brochure is carried out by one of the committees of the International Committee for Weights and Measures (CIPM). The definitions of the terms "quantity", "unit", "dimension" etc. that are used in the *SI Brochure* are those given in the International vocabulary of metrology.[22]

Cover of brochure *The International System of Units*

The quantities and equations that define the SI units are now referred to as the *International System of Quantities* (ISQ). The system is based on the seven base quantities of the SI. Other quantities such as area, pressure, and electrical resistance are derived from these base quantities by clear non-contradictory equations. The ISQ defines the quantities that are measured with the SI units.[23] The ISQ is defined in the international standard ISO/IEC 80000, and was finalised in 2009 with the publication of ISO 80000-1.[24]

Realisation of units

Metrologists carefully distinguish between the definition of a unit and its realisation. The definition of each base unit of the SI is drawn up so that it is unique and provides a sound theoretical basis on which the most accurate and reproducible measurements can be made. The realisation of the definition of a unit is the procedure by which the definition may be used to establish the value and associated uncertainty of a quantity of the same kind as the unit. A description of the *mise en pratique*[Note 3] of the base units is given in an electronic appendix to the SI Brochure.[26][4]:168–169


Silicon sphere for the Avogadro project used for measuring the Avogadro constant to a relative standard uncertainty of 2×10^{-8} or less, held by Achim Leistner.[25]

The published *mise en pratique* is not the only way in which a base unit can be determined: the SI Brochure states that "any method consistent with the laws of physics could be used to realise any SI unit."[4]:111 In the current (2016) exercise to overhaul the definitions of the base units, various consultative committees of the CIPM have required that more than one *mise en pratique* shall be developed for determining the value of each unit. In particular:

- At least three separate experiments be carried out yielding values having a relative standard uncertainty in the determination of the kilogram of no more than 5×10^{-8} and at least one of these values should be better than 2×10^{-8}. Both the Watt balance and the Avogadro project should be included in the experiments and any differences between these be reconciled.[27][28]
- When the kelvin is being determined, the relative uncertainty of the Boltzmann constant derived from two fundamentally different methods such as acoustic gas thermometry and dielectric constant gas thermometry be better than one part in 10^{-6} and that these values be corroborated by other measurements.[29]

Evolution of the SI

Changes to the SI

The BIPM has described SI as "the modern metric system".[4]:95 Changing technology has led to an evolution of the definitions and standards that has followed two principal strands – changes to SI itself, and clarification of how to use units of measure that are not part of SI but are still nevertheless used on a worldwide basis.

Since 1960 the CGPM has made a number of changes to the SI to meet the needs of specific fields, notably chemistry and radiometry. These are mostly additions to the list of named derived units, and include the *mole* (symbol mol) for an amount of substance, the *pascal* (symbol Pa) for pressure, the *siemens* (symbol S) for electrical conductance, the *becquerel* (symbol Bq) for "activity referred to a radionuclide", the *gray* (symbol Gy) for ionizing radiation, the *sievert* (symbol Sv) as the unit of dose equivalent radiation, and the *katal* (symbol kat) for catalytic activity.[4]:156[30][4]:156[4]:158[4]:159[4]:165

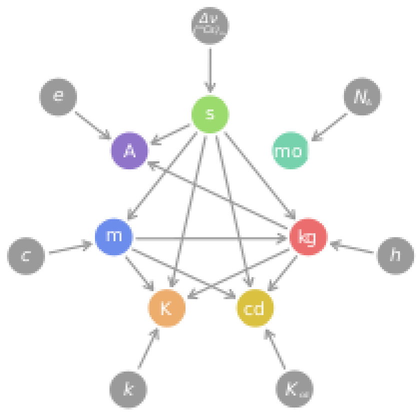
Acknowledging the advancement of precision science at both large and small scales, the range of defined prefixes pico- (10^{-12}) to tera- (10^{12}) was extended to 10^{24} to 10^{24}.[4]:152[4]:158[4]:164

The 1960 definition of the standard metre in terms of wavelengths of a specific emission of the krypton 86 atom was replaced with the distance that light travels in a vacuum in exactly $\frac{1}{299\,792\,458}$ second, so that the speed of light is now an exactly specified constant of nature.

A few changes to notation conventions were also made to alleviate lexicographic ambiguities.

Proposed redefinitions

After the metre was redefined in 1960, the kilogram remained the only SI base unit that relied on a specific physical artefact, the international prototype of the kilogram (IPK), for its definition and thus the only unit that was still subject to periodic comparisons of national standard kilograms with the IPK.[31] During the 2nd and 3rd Periodic Verification of National Prototypes of the Kilogram, a significant divergence in weight between the IPK and all of its official copies stored around the world had occurred: the copies had all noticeably gained weight with respect to the IPK. During *extraordinary verifications* carried out in 2014 preparatory to redefinition of metric standards, continuing divergence was not confirmed. Nonetheless, the residual and irreducible instability of a physical IPK undermines the reliability of the entire metric system to precision measurement from small (atomic) to large (astrophysical) scales.



Dependencies of proposed SI unit definitions (in colour) and seven physical constants (in grey) with fixed numerical values. Unlike the current (2014) definition, the base units are derived from one or more constants of nature.

The existing proposals are:

- In addition to the speed of light, four constants of nature – the Planck constant, an elementary charge, the Boltzmann constant and the Avogadro number – be defined to have exact values.
- The International prototype kilogram be retired
- The current definitions of the kilogram, ampere, kelvin and mole be revised.
- The wording of base unit definitions should change emphasis from explicit unit to explicit constant definitions.

The redefinitions are expected to be adopted at the 26th CGPM in November 2018.[32] The CODATA task group on fundamental constants has announced special submission deadlines for data to compute the values that will be announced at this event.[33]

History

The improvisation of units

The units and unit magnitudes of the metric system which became the SI were improvised piecemeal from everyday physical quantities starting in the mid-18th century. Only later were they moulded into an orthogonal coherent decimal system of measurement.

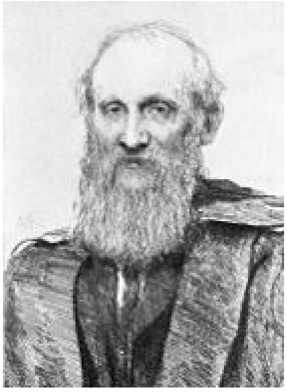
Stone marking the Austro-Hungarian/Italian border at Pontebba displaying myriametres, a unit of 10 km used in Central Europe in the 19th century (but since deprecated).[34]

The degree centigrade as a unit of temperature resulted from the scale devised by Swedish astronomer Anders Celsius in 1742. His scale counter-intuitively designated 100 as the freezing point of water and 0 as the boiling point. Independently, In 1743, the French physicist Jean-Pierre Christin described a scale with 0 as the freezing point of water and 100 the boiling point. The scale became known as the centi-grade, or 100 gradations of temperature, scale.

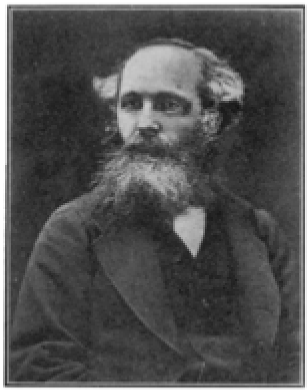
The metric system was developed from 1791 onwards by a committee of the French Academy of Sciences, commissioned to create a unified and rational system of measures.[35] The group, which included preeminent French men of science[36]:89 used the same principles for relating length, volume, and mass that had been proposed by the English clergyman John Wilkins in 1668[37][38] and the concept of using the Earth's meridian as the basis of the definition of length, originally proposed in 1670 by the French abbot Mouton.[39][40]

Carl Friedrich Gauss

In March 1791, the Assembly adopted the committee's proposed principles for the new decimal system of measure including the metre defined to be 1/10,000,000th of the length of the quadrant of earth's meridian passing through Paris, and authorised a survey to precisely establish the length of the meridian. In July 1792, the committee proposed the names *metre*, *are*, *litre* and *grave* for the units of length, area, capacity, and mass, respectively. The committee also proposed that multiples and submultiples of these units were to be denoted by decimal-based prefixes such as *centi* for a hundredth and *kilo* for a thousand.[41]:82



Thomson



Maxwell

William Thomson (Lord Kelvin) and James Clerk Maxwell played a prominent role in the development of the principle of coherence and in the naming of many units of measure.[42][43][44][45][46]

Later, during the process of adoption of the metric system, the Latin *gramme* and *kilogramme*, replaced the former provincial terms *gravet* (1/1000 *grave*) and *grave*. In June 1799, based on the results of the meridian survey, the standard *mètre des Archives* and *kilogramme des Archives* were deposited in the French National Archives. Subsequently that year, the metric system was adopted by law in France.[47] [48] The French system was short-lived due to it's unpopularity. Napoleon ridiculed it, and in 1812, introduced a replacement system, the *mesures usuelles* or "customary measures" which restored many of the old units, but redefined in terms of the metric system.

During the first half of the 19th century there was little consistency in the choice of preferred multiples of the base units: typically the myriametre (10 000 metres) was in widespread use in both France and parts of Germany, while the kilogram (1000 grams) rather than the myriagram was used for mass.[34]

In 1832, the German mathematician Carl Friedrich Gauss, assisted by Wilhelm Weber, implicitly defined the second as a base unit when he quoted the Earth's magnetic field in terms of millimetres, grams, and seconds.[42] Prior to this, the strength of the Earth's magnetic field had only been described in relative terms. The technique used by Gauss was to equate the torque induced on a suspended magnet of known mass by the Earth's magnetic field with the torque induced on an equivalent system under gravity. The resultant calculations enabled him to assign dimensions based on mass, length and time to the magnetic field.[49][50]

A candlepower as a unit of illuminance was originally defined by an 1860 English law as the light produced by a pure spermaceti candle weighing 1⁄6 pound (76 grams) and burning at a specified rate. Spermaceti, a waxy substance found in the heads of sperm whales, was once used to make high-quality candles. At this time the French standard of light was based upon the illumination from a Carcel oil lamp. The unit was defined as that illumination emanating from a lamp burning pure rapeseed oil at a defined rate. It was accepted that ten standard candles were about equal to one Carcel lamp.

Metre Convention

A French-inspired initiative for international cooperation in metrology led to the signing in 1875 of the Metre Convention also called Treaty of the Metre by 17 nations.[51][36]:353–354 Initially the convention only covered standards for the metre and the kilogram. In 1921, the Metre Convention was extended to include all physical units, including the ampere and others thereby enabling the CGPM to address inconsistencies in the way that the metric system had been used.[43][4]:96

CGPM vocabulary

French	English	Pages[4]
étalons	[Technical] standard	5, 95
prototype	prototype [kilogram/metre]	5,95
noms spéciaux	[Some derived units have] special names	16,106
mise en pratique	*mise en pratique* [Practical realisation] [Note 4]	82, 171

A set of 30 prototypes of the metre and 40 prototypes of the kilogram,[Note 5] in each case made of a 90% platinum-10% iridium alloy, were manufactured by British metallurgy specialty firm and accepted by the CGPM in 1889. One of each was selected at random to become the International prototype metre and International prototype kilogram that replaced the *mètre des Archives* and *kilogramme des Archives* respectively. Each member state was entitled to one of each of the remaining prototypes to serve as the national prototype for that country.[52]

The treaty also established a number of international organisations to oversee the keeping of international standards of measurement.[53] [54]

The cgs and MKS systems

In the 1860s, James Clerk Maxwell, William Thomson (later Lord Kelvin) and others working under the auspices of the British Association for the Advancement of Science, built on Gauss' work and formalised the concept of a coherent system of units with base units and derived units christened the centimetre–gram–second system of units in 1874. The principle of coherence was successfully used to define a number of units of measure based on the CGS, including the erg for energy, the dyne for force, the barye for pressure, the poise for dynamic viscosity and the stokes for kinematic viscosity.[45]

Closeup of the National Prototype Metre, serial number 27, allocated to the United States

In 1879, the CIPM published recommendations for writing the symbols for length, area, volume and mass, but it was outside its domain to publish recommendations for other quantities. Beginning in about 1900, physicists who had been using the symbol "μ"(mu) for "micrometre" or "micron", "λ"(lambda) for "microlitre", and "γ" (gamma) for "microgram" started to use the symbols "μm", "μL" and "μg".[55]

At the close of the 19th century three different systems of units of measure existed for electrical measurements: a CGS-based system for electrostatic units, also known as the Gaussian or ESU system, a CGS-based system for electromechanical units (EMU) and an International system based on units defined by the Metre Convention.[56] for electrical distribution systems. Attempts to resolve the electrical units in terms of length, mass, and time using dimensional analysis was beset with difficulties—the dimensions depended on whether one used the ESU or EMU systems.[46] This anomaly was resolved in 1901 when Giovanni Giorgi published a paper in which he advocated using a fourth base unit alongside the existing three base units. The fourth unit could be chosen to be electric current, voltage, or electrical resistance.[57] Electric current with named unit 'ampere' was chosen as the base unit, and the other electrical quantities derived from it according to the laws of physics. This became the foundation of the MKS system of units.

In the late 19th and early 20th centuries, a number of non-coherent units of measure based on the gram/kilogram, centimetre/metre and second, such as the *Pferdestärke* (metric horsepower) for power,[58][Note 6] the darcy for permeability[59] and "millimetres of mercury" for barometric and blood pressure were developed or propagated, some of which incorporated standard gravity in their definitions.[60]

At the end of the Second World War, a number of different systems of measurement were in use throughout the world. Some of these systems were metric system variations; others were based on customary systems of measure, like the U.S customary system and Imperial system of the UK and British Empire.

The *Practical system of units*

In 1948, the 9th CGPM commissioned a study to assess the measurement needs of the scientific, technical, and educational communities and "to make recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Metre Convention".[61] This working document was *Practical system of units of measurement*. Based on this study, the 10th CGPM in 1954 defined an international system derived from six base units including units of temperature and optical radiation in addition to those for the MKS system mass, length, and time units and Giorgi's current unit. Six base units were recommended: the metre, kilogram, second, ampere, degree Kelvin, and candela.

The 9th CGPM also approved the first formal recommendation for the writing of symbols in the metric system when the basis of the rules as they are now known was laid down.[62] These rules were subsequently extended and now cover unit symbols and names, prefix symbols and names, how quantity symbols should be written and used and how the values of quantities should be expressed.[4]:104,130

Birth of the SI

In 1960, the 11th CGPM synthesized the results of the 12 year study into a set of 16 resolutions. The system was named the *International System of Units*, abbreviated SI from the French name, *Le Système International d'Unités*.[4]:110[63]

See also

- Introduction to the metric system
- Outline of the metric system
- List of international common standards
- Metre–tonne–second system of units

Organisations

- Institute for Reference Materials and Measurements

Standards and conventions

- Conventional electrical unit
- Coordinated Universal Time (UTC)
- Unified Code for Units of Measure

Notes

1. This grouping reflects the 2014 revision of the 8th Edition of the SI Brochure (2006).
2. Except where specifically noted, these rules are common to both the SI Brochure and the NIST brochure.
3. This term is a translation of the official [French] text of the SI Brochure
4. The 8th edition of the SI Brochure (2008) notes that [at that time of publication] the term "*mise en pratique*" had not been fully defined.
5. The text "*Des comparaisons périodiques des étalons nationaux avec les prototypes internationaux*" (English: the periodic comparisons of national standards with the international prototypes) in article 6.3 of the Metre Convention (h

ttp://www.bipm.org/utils/common/documents/official/metre-convention.pdf) distinguishes between the words "standard" (OED: "The legal magnitude of a unit of measure or weight" (http://www.oed.com/view/Entry/188962?rskey=CZQ845&result=1#eid)) and "prototype" (OED: "an original on which something is modelled" (http://www.oed.com/view/Entry/153327?rskey=G9OW8z&result=1#eid)).

6. *Pferd* is German for "horse" and *Stärke* is German for "strength" or "power". The Pferdestärke is the power needed to raise 75 kg against gravity at the rate of one metre per second. (1 PS = 0.985 HP).

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5. Ohm's law: ohm = volt / ampere usually represented as *E* = *I* × *R*, where *E* is electromotive force or voltage (unit: volt), *I* is current (unit: ampere), and *R* is resistance (unit: ohm).
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Further reading

- International Union of Pure and Applied Chemistry (1993). *Quantities, Units and Symbols in Physical Chemistry*, 2nd edition, Oxford: Blackwell Science. ISBN 0-632-03583-8. Electronic version.
- Unit Systems in Electromagnetism
- MW Keller *et al.* Metrology Triangle Using a Watt Balance, a Calculable Capacitor, and a Single-Electron Tunneling Device
- "The Current SI Seen From the Perspective of the Proposed New SI". Barry N. Taylor. Journal of Research of the National Institute of Standards and Technology, Vol. 116, No. 6, Pgs. 797–807, Nov–Dec 2011.
- B. N. Taylor, Ambler Thompson, *International System of Units (SI)*, National Institute of Standards and Technology 2008 edition, ISBN 1437915582.

External links

Official

- BIPM Bureau International des Poids et Mesures (SI maintenance agency) (home page)
  - BIPM brochure (SI reference)
- ISO 80000-1:2009 *Quantities and units – Part 1: General*
- NIST Official Publications
  - NIST Special Publication 330, 2008 Edition: The International System of Units (SI)
  - NIST Special Publication 811, 2008 Edition: Guide for the Use of the International System of Units
  - NIST Special Pub 814: Interpretation of the SI for the United States and Federal Government Metric Conversion Policy
- Rules for SAE Use of SI (Metric) Units
- International System of Units at Curlie (based on DMOZ)

- EngNet Metric Conversion Chart Online Categorised Metric Conversion Calculator
- U.S. Metric Association. 2008. A Practical Guide to the International System of Units

History

- LaTeX SIunits package manual gives a historical background to the SI system.

Research

- *The metrological triangle*
- Recommendation of ICWM 1 (CI-2005)

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