

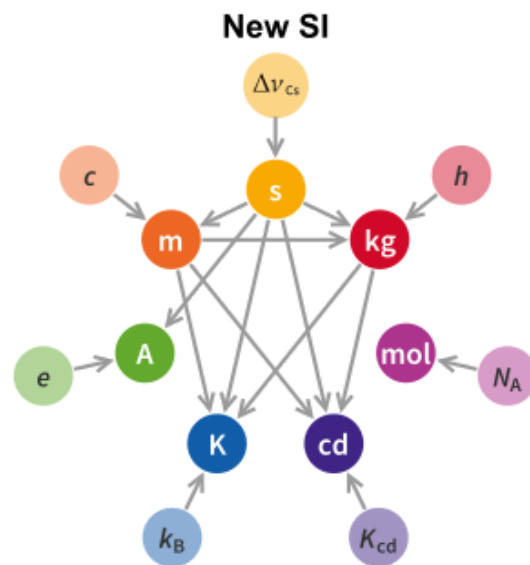
2019 redefinition of SI base units

A **redefinition of SI base units** is scheduled to come into force on 20 May 2019.^{[1][2]} The **kilogram**, **ampere**, **kelvin**, and **mole** will then be defined by setting exact numerical values for the **Planck constant** (h), the **elementary electric charge** (e), the **Boltzmann constant** (k), and the **Avogadro constant** (N_A), respectively. The metre and **candela** are already defined by **physical constants**, subject to correction to their present definitions. The new definitions aim to improve the SI without changing the size of any units, thus ensuring continuity with existing measurements.^{[3][4]} In November 2018, the 26th **General Conference on Weights and Measures** (CGPM) unanimously approved these changes,^{[5][6]} which the **International Committee for Weights and Measures** (CIPM) had proposed earlier that year.^{[7]:23}

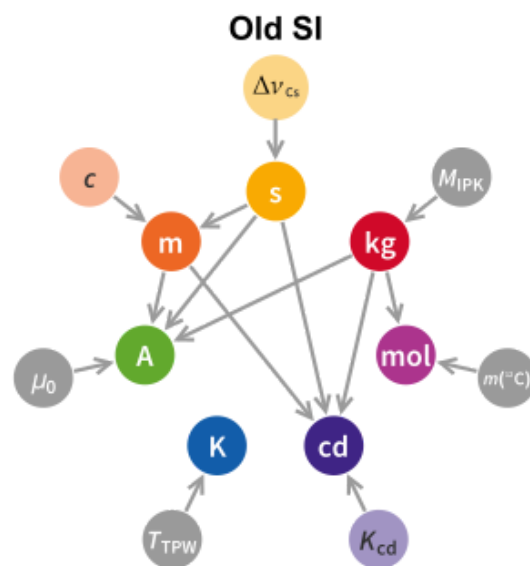
The previous major change of the metric system was in 1960 when the **International System of Units** (SI) was formally published. The SI is a **coherent system** structured around seven base units whose definitions are unconstrained by that of any other unit and another twenty-two named units derived from these base units. The **metre** was redefined in terms of the **wavelength** of a spectral line of a **krypton-86** radiation,^[Note 1] making it derivable from universal natural phenomena, but the kilogram remained defined in terms of a physical prototype, leaving it the only artefact upon which the SI unit definitions depend.

The **metric system** was originally conceived as a system of measurement that was derivable from unchanging phenomena,^[8] but practical limitations necessitated the use of artefacts (the **prototype metre** and **prototype kilogram**) when the metric system was first introduced in France in 1799. Although designed for long-term stability, the masses of the kilogram prototype and its secondary copies have shown small variations over time relative to each other, and they are not thought to be adequate for the increasing accuracy demanded by science, prompting a search for a suitable replacement. Also, some units were defined based on measurements that are difficult to precisely realise in a laboratory, such as the definition of the **kelvin** in terms of the **triple point of water**. With the 2019 redefinition, the SI is for the first time wholly derivable from natural phenomena, with most units based on fundamental physical constants.

A number of authors have published criticisms of the revised definitions – including that the proposal had failed to address the impact of breaking the link between the definition of the **dalton**^[Note 2] and the definitions of the **kilogram**, the **mole**, and the **Avogadro constant**



The SI system after the 2019 redefinition: Dependence of base unit definitions on physical constants with fixed numerical values and on other base units.



The SI system after 1983, but before the 2019 redefinition: Dependence of base unit definitions on other base units (for example, the metre is defined as the distance travelled by light in a specific fraction of a second), with the constants of nature and artefacts used to define them (such as the mass of the IPK for the kilogram).

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Background

The basic structure of SI was developed over a period of about 170 years (1791 to 1960). Since 1960, technological advances have made it possible to address various weaknesses in SI, such as the dependence on an artefact to define the kilogram.

Development of SI

During the early years of the French Revolution the leaders of the French National Constituent Assembly decided to introduce a completely new system of measurement based on the principles of logic and natural phenomena. Specifically, the metre was defined as one ten-millionth of the distance from the North Pole to the Equator, and the kilogram as the mass of one thousandth of a cubic metre of pure water. Although these definitions were chosen so that nobody would "own" the units, they could not be measured with sufficient convenience or precision for practical use. Instead, realisations were created in the form of the *mètre des Archives* and *kilogramme des Archives* which were a "best attempt" at fulfilling these principles.^[9]

In 1875, by which time the use of the metric system had become widespread in Europe and in Latin America, twenty industrially developed nations met for the Convention of the Metre. The result was the signing of the Treaty of the Metre under which three bodies were set up to take custody of the international prototype kilogram and metre and to regulate comparisons with national prototypes.^{[10][11]} They were:

- CGPM (General Conference on Weights and Measures, *Conférence générale des poids et mesures*) – The Conference meets every four to six years and consists of delegates of the nations who had signed the convention. It discusses and examines the arrangements required to ensure the propagation and improvement of the International System of Units and it endorses the results of new fundamental metrological determinations.
- CIPM (International Committee for Weights and Measures, *Comité international des poids et mesures*) – The Committee consists of eighteen eminent scientists, each from a different country, nominated by the CGPM. The CIPM meets annually and is tasked to advise the CGPM. The CIPM has set up a number of sub-committees, each charged with a particular area of interest. One of these, the Consultative Committee for Units (CCU), amongst other things, advises the CIPM on matters concerning units of measurement.^[12]
- BIPM (International Bureau for Weights and Measures, *Bureau international des poids et mesures*) – The Bureau provides safe keeping of the international prototype kilogram and metre, provides laboratory facilities for regular comparisons of the national prototypes with the international prototype and is the secretariat for the CIPM and the CGPM.

The first CGPM (1889) formally approved the use of 40 prototype metres and 40 prototype kilograms from the British firm Johnson Matthey as the standards mandated by the Convention of the Metre.^[13] One of each of these was nominated by lot as the international prototypes, other copies were retained by the CGPM as working copies, and the rest were distributed to member nations for use as their national prototypes. At regular intervals the national prototypes were compared with and recalibrated against the international prototype.^[14]

In 1921 the Convention of the Metre was revised and the mandate of the CGPM was extended to provide standards for all units of measure, not just mass and length. In the ensuing years, the CGPM took on responsibility for providing standards of electric current (1946), luminosity (1946), temperature (1948), time (1956), and molar mass (1971).^[15]

The 9th CGPM (1948) instructed the CIPM "to make recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Metre Convention"^[16]

The recommendations based on this mandate were presented to the 11th CGPM (1960) where they were formally accepted and given the name "*Système International d'Unités*" and its abbreviation "SI".^[17]

Impetus for change

Changing the underlying principles behind the definition of the SI base units is not without precedent. The 11th CGPM (1960) defined the SI metre in terms of the wavelength of krypton-86 radiation, replacing the pre-SI metre bar. The 13th CGPM (1967) replaced the original definition of the second (which was based on Earth's average rotation during 1750–1892)^[18] with a definition based on the frequency of the radiation emitted between two hyperfine levels of the ground state of the caesium-133 atom. And the 17th CGPM (1983) replaced the 1960 definition of the metre with one based on the second, by giving an exact definition of the speed of light in units of metres per second.^[19]

Over the years, drifts of up to 2×10^{-8} kilograms per annum in the national prototype kilograms relative to the international prototype kilogram have been detected. There was no way of determining whether the national prototypes were gaining mass or whether the IPK was losing mass.^[21] Newcastle University metrologist Peter Cumpson has since identified mercury vapour absorption or carbonaceous contamination as possible causes of this drift.^{[22][23]} At the 21st meeting of the CGPM (1999), national laboratories were urged to investigate ways of breaking the link between the kilogram and a specific artefact.

Independently of this drift having been identified, the Avogadro project and development of the Kibble balance (known as a "watt balance" before 2016) promised methods of indirectly measuring mass with a very high precision. These projects provided tools that would enable alternative means of redefining the kilogram.^[24]

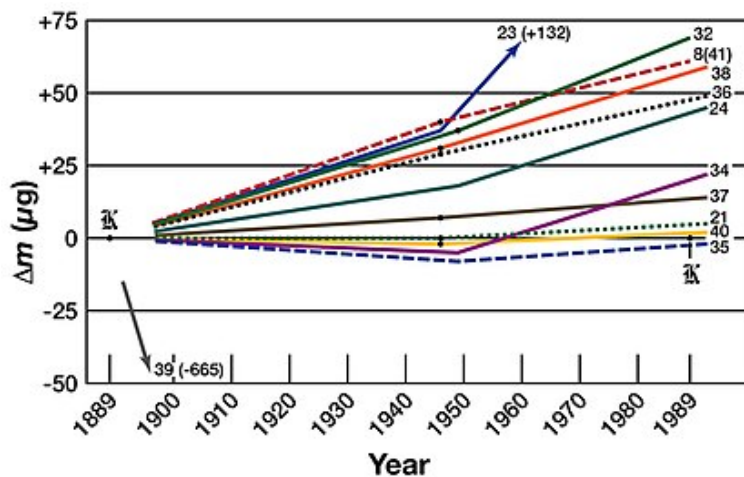
A report published in 2007 by the Consultative Committee for Thermometry (CCT) to the CIPM noted that their current definition of temperature has proved to be unsatisfactory for temperatures below 20 K (-253 °C ; -424 °F) and for temperatures above 1,300 K ($1,030\text{ °C}$; $1,880\text{ °F}$). The committee was of the view that the Boltzmann constant provided a better basis for temperature measurement than did the triple point of water, as it overcame these difficulties.^[25]

At its 23rd meeting (2007), the CGPM mandated the CIPM to investigate the use of natural constants as the basis for all units of measure rather than the artefacts that were then in use. The following year this was endorsed by the International Union of Pure and Applied Physics (IUPAP).^[26] At a meeting of the CCU held in Reading, United Kingdom, in September 2010, a resolution^[27] and draft changes to the SI brochure that were to be presented to the next meeting of the CIPM in October 2010 were agreed to in principle.^[28] The CIPM meeting of October 2010 found that "the conditions set by the General Conference at its 23rd meeting have not yet been fully met."^[Note 4] For this reason the CIPM does not propose a revision of the SI at the present time";^[30] however, the CIPM presented a resolution for consideration at the 24th CGPM (17–21 October 2011) to agree to the new definitions in principle, but not to implement them until the details have been finalised.^[31] This resolution was accepted by the conference,^[32] and in addition the CGPM moved the date of the 25th meeting forward from 2015 to 2014.^{[33][34]} At the 25th meeting (18–20 November 2014), it was found that "despite [the progress in the necessary requirements] the data do not yet appear to be sufficiently robust for the CGPM to adopt the revised SI at its 25th meeting",^[35] thus postponing the revision to the next meeting in 2018. Measurements accurate enough to meet the conditions were available in 2017, and the redefinition^[36] was adopted at the 26th CGPM (13–16 November 2018).

Redefinition

Following the successful 1983 redefinition of the metre in terms of an exact numerical value for the speed of light, the BIPM's Consultative Committee for Units (CCU) recommended, and the BIPM proposed, that four further constants of nature should be defined to have exact values. These are:

- The Planck constant h is exactly $6.626\,070\,15 \times 10^{-34}$ joule-second (Js).
- The elementary charge e is exactly $1.602\,176\,634 \times 10^{-19}$ coulomb (C).
- The Boltzmann constant k is exactly $1.380\,649 \times 10^{-23}$ joule per kelvin (JK^{-1}).



Mass drift over time of national prototypes K21–K40, plus two of the International Prototype Kilogram's (IPK's) sister copies: K32 and K8(41).^[Note 3] All mass changes are relative to the IPK.^[20]

- The Avogadro constant N_A is exactly $6.022\,140\,76 \times 10^{23}$ reciprocal mole (mol^{-1}).

These constants were described in the 2006 version of the SI manual, but in that version the latter three were defined as "constants to be obtained by experiment" rather than as "defining constants".

The redefinition retains unchanged the numerical values associated with the following constants of nature:

- The speed of light c is exactly 299 792 458 metres per second ($\text{m}\cdot\text{s}^{-1}$).
- The ground state hyperfine structure transition frequency of the caesium-133 atom $\Delta\nu_{\text{Cs}}$ is exactly 9 192 631 770 hertz (Hz).
- The luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} Hz is exactly 683 lumens per watt ($\text{lm}\cdot\text{W}^{-1}$).

The seven definitions above are rewritten below with the derived units (joule, coulomb, hertz, lumen, and watt) expressed in terms of the seven base units (second, metre, kilogram, ampere, kelvin, mole, and candela), according to the updated 9th edition of the SI Brochure (2018).^[4] In the list that follows, the symbol sr stands for the dimensionless unit steradian.

- $h = 6.626\,070\,15 \times 10^{-34} \text{ kg}\cdot\text{m}^2\cdot\text{s}^{-1}$
- $e = 1.602\,176\,634 \times 10^{-19} \text{ A}\cdot\text{s}$
- $k = 1.380\,649 \times 10^{-23} \text{ kg}\cdot\text{m}^2\cdot\text{K}^{-1}\cdot\text{s}^{-2}$
- $N_A = 6.022\,140\,76 \times 10^{23} \text{ mol}^{-1}$
- $c = 299\,792\,458 \text{ m}\cdot\text{s}^{-1}$
- $\Delta\nu_{\text{Cs}} = \Delta\nu(^{133}\text{Cs})_{\text{hfs}} = 9\,192\,631\,770 \text{ s}^{-1}$
- $K_{\text{cd}} = 683 \text{ cd}\cdot\text{sr}\cdot\text{s}^3\cdot\text{kg}^{-1}\cdot\text{m}^{-2}$

As part of the redefinition, the international prototype kilogram was retired and definitions of the kilogram, the ampere, and the kelvin were replaced. The definition of the mole was revised.

These changes have the effect of redefining the SI base units, though the definitions of the SI derived units in terms of the base units remain the same.

Impact on base unit definitions

Following the CCU proposal, the text of the definitions of all the base units was either refined or rewritten changing the emphasis from explicit-unit to explicit-constant type definitions.^[38] Explicit-unit type definitions define a unit in terms of a specific example of that unit – for example in 1324 Edward II defined the inch as being the length of three barleycorns^[39] and since 1889 the kilogram has been defined as being the mass of the International Prototype Kilogram. In explicit-constant definitions, a constant of nature is given a specified value and the definition of the unit emerges as a consequence. For example, in 1983, the speed of light was defined to be exactly 299 792 458 metres per second and, since the second had been independently defined, the length of the metre could thus be derived.

The previous^[19] (as of 2018) and 2019^{[4][37]} definitions are given below

Second

The new definition of the second is effectively the same as the previous one, the only difference being that the conditions under which the definition applies are more rigorously defined.

- **Previous definition:** 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.
- **2019 definition:** The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\text{Cs}}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1} .

Metre

The new definition of the metre is effectively the same as the previous one, the only difference being that the additional rigour in the definition of the second will propagate to the metre.

- **Previous definition:** The metre is the length of the path travelled by light in vacuum during a time interval of $\frac{1}{299\,792\,458}$ of a second.
- **2019 definition:** The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit $\text{m}\cdot\text{s}^{-1}$, where the second is defined in terms of the caesium

frequency $\Delta\nu_{CS}$.

Kilogram

The definition of the kilogram changed fundamentally – the previous definition defined the kilogram as being the mass of the international prototype kilogram, which is an artefact and not a constant of nature,^[41] whereas the new definition relates it to the equivalent mass of the energy of a photon given its frequency via the Planck constant.



A Kibble balance, which is being used to measure the Planck constant in terms of the international prototype kilogram.^[40]

- **Previous definition:** The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
- **2019 definition:** The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,15 \times 10^{-34}$ when expressed in the unit Js, which is equal to $\text{kgm}^2\cdot\text{s}^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{CS}$.

A consequence of this change is that the new definition of the kilogram is dependent on the definitions of the second and the metre.

Ampere

The definition of the ampere underwent a major revision – the previous definition, which is difficult to realise with high precision in practice, was replaced by a definition that is more intuitive and easier to realise.

- **Previous definition:** The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.
- **2019 definition:** The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602\,176\,634 \times 10^{-19}$ when expressed in the unit C, which is equal to As, where the second is defined in terms of $\Delta\nu_{CS}$.

Since the previous definition contained a reference to force, which has the dimensions MLT^{-2} , it follows that in the previous SI the kilogram, metre, and second, the base units representing these dimensions, had to be defined before the ampere could be defined. Other consequences of the previous definition were that in SI the value of vacuum permeability (μ_0) was fixed at exactly $4\pi \times 10^{-7} \text{ H}\cdot\text{m}^{-1}$.^[42] Since the speed of light in vacuum (c) is also fixed, it followed from the relationship

$$c^2 = \frac{1}{\mu_0 \epsilon_0}$$

that the vacuum permittivity (ϵ_0) had a fixed value, and from

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}},$$

that the impedance of free space (Z_0) likewise had a fixed value.^[43]

A consequence of the revised definition is that the ampere no longer depends on the definitions of the kilogram and the metre, but does still depend on the definition of the second. In addition, the numerical values of the vacuum permeability, vacuum permittivity, and impedance of free space, which were exact before the redefinition, will be subject to experimental error after the redefinition.^[44]

Kelvin

The definition of the kelvin underwent a fundamental change. Rather than using the triple point of water to fix the temperature scale, the new definition uses the energy equivalent as given by Boltzmann's equation

- **Previous definition:** The kelvin, unit of thermodynamic temperature is $\frac{1}{273.16}$ of the thermodynamic temperature of the triple point of water.
- **2019 definition:** The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\,649 \times 10^{-23}$ when expressed in the unit JK^{-1} , which is equal to $\text{kgm}^2\cdot\text{s}^{-2}\cdot\text{K}^{-1}$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{CS}$.

One consequence of this change is that the new definition makes the definition of the kelvin depend on the definitions of the second, the metre, and the kilogram.

Mole

The previous definition of the mole linked it to the kilogram. The revised definition breaks that link by making a mole a specific number of entities of the substance in question.

- **Previous definition:** The mole is the amount of substance of a system that 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.
- **2019 definition:**^{[7]:22} The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.022\,140\,76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A , when expressed in the unit mol^{-1} and is called the Avogadro number.^{[7][45]} The amount of substance, symbol n , of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.

One consequence of this change is that the current defined relationship between the mass of the ^{12}C atom, the dalton, the kilogram, and the Avogadro number will no longer be valid. One of the following must change:

- The mass of a ^{12}C atom is exactly 12 dalton.
- The number of dalton in a gram is exactly the numerical value of the Avogadro number: (i.e., $1 \text{ g/Da} = 1 \text{ mol} \cdot N_A$).

The wording of the ninth SI Brochure^{[4][Note 5]} implies that the first statement remains valid, which means that the second is no longer true. The molar mass constant, while still with great accuracy remaining 1 g/mol, is no longer exactly equal to that. Draft Resolution A, which was voted on at the 26th CGPM, only stated that "the molar mass of carbon 12, $M(^{12}\text{C})$, is equal to $0.012 \text{ kg} \cdot \text{mol}^{-1}$ within a relative standard uncertainty equal to that of the recommended value of $N_A h$ at the time this Resolution was adopted, namely 4.5×10^{-10} , and that in the future its value will be determined experimentally", which makes no reference to the dalton and is consistent with either statement.

Candela

The new definition of the candela is effectively the same as the current definition, with the only difference being that the additional rigour in the definition of the second and metre will propagate to the candela.

- **Previous definition:** The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of $\frac{1}{683}$ watt per steradian.
- **2019 definition:** The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd} , to be 683 when expressed in the unit $\text{lm} \cdot \text{W}^{-1}$, which is equal to $\text{cd} \cdot \text{sr} \cdot \text{W}^{-1}$, or $\text{cd} \cdot \text{sr} \cdot \text{kg}^{-1} \cdot \text{m}^{-2} \cdot \text{s}^3$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{\text{CS}}$.

Impact on reproducibility

All seven of the base units will be defined in terms of defined constants^[Note 6] and universal physical constants.^{[Note 7][46]} Seven constants are needed to define the seven base units, but there is not a direct correspondence between each specific base unit and a specific constant: aside from the second and the mole, more than one of the seven constants contributes to the definition of any given base unit.

When the New SI was first designed, there were more than six suitable physical constants from which the designers could choose. For example, once length and time had been established, the universal gravitational constant G could, from a dimensional point of view, be used to define mass.^[Note 8] It should be noted that in practice G can be measured only with a relative uncertainty of the order of 10^{-5} ,^[Note 9] which would have resulted in upper limit of the kilogram's reproducibility being around 10^{-5} whereas the current international prototype kilogram can be measured with a reproducibility of 1.2×10^{-8} .^[44] The choice of physical constants was made on the basis of minimal uncertainty associated with measuring the constant and the degree of independence of the constant in respect of other constants that were being used. Although the BIPM has developed a standard *mise en pratique* (practical technique)^[47] for each type of measurement, the *mise en pratique* used to make the measurement is not part of the measurement's definition – it is merely an assurance that the measurement can be done without exceeding the specified maximum uncertainty



A near-perfect sphere of ultra-pure silicon – part of the Avogadro project, an International Avogadro Coordination project to determine the Avogadro number.^[40]

Uncertainty of fundamental physical constants

Fundamental physical constants are often interdependent. This implies that the most precise estimate of a fundamental physical constant often can be determined by directly measuring other fundamental physical constants, from which the value can be calculated. The uncertainty in these constants is then determined from the uncertainty of the others by the propagation of uncertainty. Constants whose value is fixed, for determining the units in which they are expressed, do not have an uncertainty associated with them, so they do not contribute any extra uncertainty to the value calculated for the constant. One of the reasons that the SI unit system will be changed is that determination of values can often be greatly improved if expressed in terms of the revised unit definitions. This is due to the dependence of their values on physical constants.

The following table catalogues the notable changes in determination of fundamental physical constants. The constants are expressed in direct measurements and fixed constants to minimise and determine the uncertainty. Some constants in that expression do not contribute significantly to the final uncertainty; only the significant factors are noted. The value of the relative uncertainty using the data of CODATA of 2014 is given, and is expressed in the relative uncertainty of the significant factors, noted with $u_r(\text{constant})$. An approximately equals sign (\approx) is used if an uncertainty is only approximated by the expression due to insignificant factors or linear approximation.

Constant	Symbol	Previous definition			2019 def	
		Relation to directly measured and fixed constants	Significant factor(s) in uncertainty	Relative uncertainty	Relation to directly measured and fixed constants	Significant factor(s) in uncertainty
Mass of $\text{IPK}^{\text{[Note 10]}}$	$m(\mathcal{K})$	1 kg	None	Exact	$m(\mathcal{K})$	$m(\mathcal{K})$
Planck constant	h	$\frac{8\alpha}{c\mu_0 K_J^2}$	K_J^2	$1.2 \times 10^{-8} \approx 2u_{\text{r}}(K_J)$	h	None
Josephson constant	K_J	K_J	K_J	$6.1 \times 10^{-9} = u_{\text{r}}(K_J)$	$\frac{2e}{h}$	None
Von Klitzing constant	R_K	$\frac{c\mu_0}{2\alpha}$	α	$2.3 \times 10^{-10} = u_{\text{r}}(\alpha)$	$\frac{h}{e^2}$	None
Elementary charge	e	$\frac{4\alpha}{c\mu_0 K_J}$	K_J	$6.1 \times 10^{-9} \approx u_{\text{r}}(K_J)$	e	None
Magnetic constant	μ_0	$4\pi \times 10^{-7} \text{ m}\cdot\text{kg}\cdot\text{s}^{-2}\cdot\text{A}^{-2}$	None	Exact	$\frac{2h\alpha}{ce^2}$	α
Vacuum permittivity	ϵ_0	$\frac{1}{c^2 \mu_0}$	None	Exact	$\frac{e^2}{2hc\alpha}$	α
Impedance of free space	Z_0	$c\mu_0$	None	Exact	$\frac{2h\alpha}{e^2}$	α
Electron mass	m_e	$\frac{16R_\infty}{c^2 \alpha \mu_0 K_J^2}$	K_J^2	$1.2 \times 10^{-8} \approx 2u_{\text{r}}(K_J)$	$\frac{2hR_\infty}{c\alpha^2}$	α^2
Electron molar mass	$M(\text{e})$	$A_{\text{r}}(\text{e})M_{\text{u}}$	$A_{\text{r}}(\text{e})$	$2.9 \times 10^{-11} = u_{\text{r}}(A_{\text{r}}(\text{e}))$	$\frac{2hR_\infty N_{\text{A}}}{c\alpha^2}$	α^2
Unified atomic mass unit or dalton	$m_{\text{u}} = 1 \text{ u}$ $= 1 \text{ Da}$	$\frac{16R_\infty}{c^2 \alpha \mu_0 K_J^2 A_{\text{r}}(\text{e})}$	K_J^2	$1.2 \times 10^{-8} \approx 2u_{\text{r}}(K_J)$	$\frac{2hR_\infty}{c\alpha^2 A_{\text{r}}(\text{e})}$	α^2
Molar mass constant	M_{u}	$0.001 \text{ kg}\cdot\text{mol}^{-1}$	None	Exact	$\frac{2hR_\infty N_{\text{A}}}{c\alpha^2 A_{\text{r}}(\text{e})}$	α^2
Avogadro constant	N_{A}	$\frac{c^2 \alpha \mu_0 K_J^2 A_{\text{r}}(\text{e}) M_{\text{u}}}{16R_\infty}$	K_J^2	$1.2 \times 10^{-8} \approx 2u_{\text{r}}(K_J)$	N_{A}	None
Atomic mass of carbon-12	$m(^{12}\text{C})$	$\frac{192R_\infty}{c^2 \alpha \mu_0 K_J^2 A_{\text{r}}(\text{e})}$	K_J^2	$1.2 \times 10^{-8} \approx 2u_{\text{r}}(K_J)$	$\frac{24hR_\infty}{c\alpha^2 A_{\text{r}}(\text{e})}$	α^2
Molar mass of carbon-12	$M(^{12}\text{C})$	$0.012 \text{ kg}\cdot\text{mol}^{-1}$	None	Exact	$\frac{24hR_\infty N_{\text{A}}}{c\alpha^2 A_{\text{r}}(\text{e})}$	α^2
Faraday constant	F	$\frac{c\alpha^2 K_J A_{\text{r}}(\text{e}) M_{\text{u}}}{4R_\infty}$	K_J, α^2	$6.2 \times 10^{-9} \approx u_{\text{r}}(K_J)$ <small>[Note 11]</small>	eN_{A}	None
Temperature of triple point of water	T_{TPW}	273.16 K	None	Exact	T_{TPW}	T_{TPW}
Molar gas constant	R	R	R	$5.7 \times 10^{-7} = u_{\text{r}}(R)$	kN_{A}	None
Boltzmann constant	k	$\frac{16RR_\infty}{c^2 \alpha \mu_0 K_J^2 A_{\text{r}}(\text{e}) M_{\text{u}}}$	R	$5.7 \times 10^{-7} \approx u_{\text{r}}(R)$	k	None
Stefan–Boltzmann constant	σ	$\frac{256\pi^5 R^4 R_\infty^4}{15c^7 \alpha^7 \mu_0 K_J^2 A_{\text{r}}(\text{e})^4 M_{\text{u}}^4}$	R^4	$2.3 \times 10^{-6} \approx 4u_{\text{r}}(R)$	$\frac{2\pi^5 k^4}{15h^3 c^2}$	None

(c = speed of light, α = fine-structure constant, R_∞ = Rydberg constant, $A_r(\text{e})$ = electron rest mass in atomic mass units.)

Acceptance

Much of the work done by the CIPM is delegated to consultative committees. The CIPM Consultative Committee for Units (CCU) has made the proposed changes while other committees have examined the proposal in detail and have made recommendations regarding their acceptance by the CGPM in 2014. The various consultative committees have laid down a number of criteria that must be met before they will support the CCU's proposal, including:

- For the redefinition of the kilogram, at least three separate experiments be carried out yielding values for the Planck constant having a relative expanded (95%) uncertainty of no more than 5×10^{-8} and at least one of these values should be better than 2×10^{-8} . Both the Kibble balance and the Avogadro project should be included in the experiments and any differences between these be reconciled.^{[48][49]}
- For the redefinition of the kelvin, the relative uncertainty of Boltzmann constant derived from two fundamentally different methods such as acoustic gas thermometry and dielectric constant gas thermometry be better than 10^{-6} and that these values be corroborated by other measurements.^[50]

As at March 2011, the International Avogadro Coordination (IAC) group had obtained an uncertainty of 3.0×10^{-8} and NIST had obtained an uncertainty of 3.6×10^{-8} in their measurements.^[24]

On 1 September 2012 the European Association of National Metrology Institutes (EURAMET) launched a formal project to reduce the relative difference between the Kibble balance and the silicon sphere approach to measuring the kilogram from $(17 \pm 5) \times 10^{-8}$ to within 2×10^{-8} .^[51]

As of March 2013 the proposed redefinition is known as the "New SI",^[3] but Mohr, in a paper following the CGPM proposal but predating the formal CCU proposal, suggested that since the proposed system makes use of atomic scale phenomena rather than macroscopic phenomena, it should be called the "Quantum SI System".^[52]

As of the 2014 CODATA recommended values of the fundamental physical constants (published in 2016, using data collected through the end of 2014), all measurements meet the CGPM's requirements and the way is clear to proceed with the redefinition and the next CGPM quadrennial meeting in late 2018.^{[53][54]}

On 20 October 2017, the 106th meeting of the International Committee for Weights and Measures (CIPM) formally accepted a revised Draft Resolution A calling for the redefinition of the SI, to be voted on at the 26th CGPM,^{[7]:17–23} The same day, in response to the CIPM's endorsement of the final values,^{[7]:22} the CODATA Task Group on Fundamental Constants published its 2017 recommended values for the four constants (with uncertainties) and proposed numerical values for the redefinition (without uncertainty).^[37] The vote, held on 16 November 2018 at the 26th CGPM, was unanimous from all attending national representatives in favour of the revised proposal. The new definitions will become effective on 20 May 2019.^[55]

Concerns

In 2010, Marcus Foster of the Commonwealth Scientific and Industrial Research Organisation published a wide-ranging critique of SI in which he raised numerous issues ranging from basic issues such as the absence of the symbol "kg" from most Western keyboards to the abstract issues such as inadequate formalism in the metrological concepts on which SI is based. The changes proposed in the New SI only addressed issues regarding the definition of the base units including new definitions of the candela and the mole – units that Foster argued were not true base units. Other issues raised by Foster fell outside the scope of the proposal.^[56]

Explicit-unit and explicit-constant definitions

Concerns have been expressed that the use of explicit-constant definitions of the unit being defined that are not related to an example of its quantity will have many adverse effects.^[57] Although this criticism applies to the proposed linking of the kilogram to the Planck constant h via a route that requires a knowledge of both special relativity and quantum mechanics,^[58] it does not apply to the proposed definition of the ampere, which is closer to an example of its quantity than is the current definition.^[59] Some observers have welcomed the proposal to base the definition of electric current on the charge of the electron rather than the current definition of a force between two parallel current-carrying wires; since the nature of the electromagnetic interaction between two bodies at the quantum electrodynamics level is somewhat different from the nature at classical electrodynamic levels, it is considered inappropriate to use classical electrodynamics to define quantities that exist at quantum electrodynamic levels.^[44]

Mass and the Avogadro constant

When the scale of the divergence between the IPK and national kilogram prototypes was reported in 2005, a debate arose on how best to redefine the kilogram – should the kilogram be defined in terms of the mass of the silicon-28 atom or should it be determined using the Kibble balance? The mass of a silicon atom could be determined using the Avogadro project and using the Avogadro number be linked directly to the kilogram.^[60]

Concern has also been expressed that the authors of the proposal had failed to address the impact of breaking the link between the mole, kilogram, the dalton (Da), and the Avogadro constant (N_A).^[Note 12] This direct link has caused many to argue that the mole is not a true physical unit, but, in the words of the Swedish philosopher Johansson, a "scaling factor".^{[66][61]}

The SI Brochure (8th edition) defines the dalton in terms of the mass of an atom of ^{12}C . It defines the Avogadro constant in terms of this mass and the kilogram, making it determined by experiment. The proposal fixes the Avogadro constant, and the draft of the Ninth SI Brochure^[4] retains the definition of dalton in terms of ^{12}C , with the effect that the link between the dalton and the kilogram will be broken.^{[62][63]}

In 1993, the International Union of Pure and Applied Chemistry (IUPAC) approved the use of the dalton as an alternative to the unified atomic mass unit with the qualification that the CGPM had not given its approval.^[64] This approval has since been given.^[65] Following the proposal to redefine the mole by fixing the value of the Avogadro constant, Brian Leonard of the University of Akron, writing in Metrologia proposed that the dalton (Da) be redefined such that $N_A = (\text{g/Da}) \text{ mol}^{-1}$, but that the unified atomic mass unit (m_u) retain its current definition based on the mass of ^{12}C , ceasing to exactly equal to the dalton. This would result in the dalton and the atomic mass unit potentially differing from each other with a relative uncertainty of the order of 10^{-10} .^[66] However, the draft of the ninth SI Brochure defines both the dalton (Da) and the unified atomic mass unit (u) as exactly $\frac{1}{12}$ of the mass of a free carbon-12 atom and not in relation to the kilogram,^[4] with the effect that instead the above equation will be inexact.

Temperature

Temperature is somewhat of an enigma – room temperature can be measured by means of expansion and contraction of a liquid in a thermometer, but high temperatures are often associated with a colour. Wojciech T. Chyla, approaching the structure of SI from a philosophical point of view in the Journal of the Polish Physical Society, argued that temperature is not a real base unit but is rather an average of the thermal energies of the individual particles that make up the body concerned.^[44] He noted that in many theoretical papers, temperature is represented by the quantities Θ or β where

$$\Theta = kT; \quad \beta = \frac{1}{kT}$$

and k is the Boltzmann constant.

However, Chyla acknowledged that in the macroscopic world temperature plays the role of a base unit as much of the theory of thermodynamics is based on temperature.

The Consultative Committee for Thermometry, part of the International Committee for Weights and Measures publishes a *mise en pratique* (practical technique), last updated in 1990, for measuring temperature which, at very low and at very high temperatures, makes great use of linking energy to temperature via the Boltzmann constant^{[67][68]}

Luminous intensity

Foster argued that "luminous intensity [the candela] is not a physical quantity, but a photobiological quantity that exists in human perception", thereby questioning whether the candela should be a base unit.^[56]

See also

- International System of Units– a system of units of measurement for base and derived physical quantities
- International Vocabulary of Metrology
- Physical constant– Universal and unchanging physical quantity
- SI base unit

Notes

1. The metre was redefined again in 1983 by fixing the value of the speed of light. That definition will remain in effect after 2019.

2. The dalton is not defined in the formal proposal to be voted upon by the CGPM, only in the (draft) *Ninth SI Brochure*
3. Prototype No. 8(41) was accidentally stamped with the number 41, but its accessories carry the proper number 8. Since there is no prototype marked 8, this prototype is referred to as 8(41).
4. In particular the CIPM was to prepare a detailed *mise en pratique* for each of the new definitions of the kilogram, ampere, kelvin and mole set by the 23rd CGPM^[29]
5. A footnote in Table 8 on non-SI units states: "The dalton (Da) and the unified atomic mass unit (u) are alternative names (and symbols) for the same unit, equal to 1/12 of the mass of a free carbon 12 atom, at rest and in its ground state."
6. Though the three quantities temperature, luminous intensity and amount of substance may be regarded from a fundamental physical perspective as derived quantities, these are perceptually independent quantities and have conversion constants defined that relate the historically defined units to the underlying physics.
7. The definition of the candela is atypical within the base units: translating physical measurements spectral intensity into units of candela also requires a model of the response of the human eye to different wavelengths of light known as the luminosity function and denoted by $V(\lambda)$, a function that is determined by the International Commission on Illumination (CIE).
8. The dimensions of G are $L^3M^{-1}T^{-2}$, so once standards have been established for length and for time, mass can in theory be deduced from G . Also, when fundamental constants as relations between these three units are set, the units can be deduced by a combination of these constants, for example as a linear combination Planck units
9. The following terms are defined in International vocabulary of metrology – Basic and general concepts and associated terms (http://www.bipm.org/utis/common/documents/jgm/JCGM_200_2012.pdf)
 - measurement reproducibility – definition 2.25
 - standard measurement uncertainty – definition 2.30
 - relative standard measurement uncertainty – definition 2.32
10. Technically, the mass of the International Prototype Kilogram is no longer a "physical constant", as the artefact is abandoned as a reference in the new SI.
11. Although the calculation of the uncertainty implies that the fine structure constant isn't a significant factor because of rounding errors, the uncertainty in fine structure constant does have an effect on the determined value.
12. The two quantities of the Avogadro constant N_A and the Avogadro number N_N are numerically the same, but while N_A has the unit mol^{-1} , N_N is a pure number

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Further reading

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External links

- [BIPM website on the New SI including a FAQ page.](#)

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