Bureau International
des Poids et Mesures

# The International System of Units (SI)

9th edition 2019

# The BIPM
# and the Metre Convention

The International Bureau of Weights and Measures (BIPM) was set up by the Metre Convention signed in Paris on 20 May 1875 by seventeen States during the final session of the diplomatic Conference of the Metre. This Convention was amended in 1921.

The BIPM has its headquarters near Paris, in the grounds (43 520 $\mathrm{m}^2$) of the Pavillon de Breteuil (Parc de Saint-Cloud) placed at its disposal by the French Government; its upkeep is financed jointly by the Member States of the Metre Convention.

The task of the BIPM is to ensure worldwide unification of measurements; its function is thus to:

- establish fundamental standards and scales for the measurement of the principal physical quantities and maintain the international prototype~~s~~;
- carry out comparisons of national and international standards;
- ensure the coordination of corresponding measurement techniques;
- carry out and coordinate measurements of the fundamental physical constants relevant to these activities.

The BIPM operates under the exclusive supervision of the International Committee for Weights and Measures (CIPM) which itself comes under the authority of the General Conference on Weights and Measures (CGPM) and reports to it on the work accomplished by the BIPM.

Delegates from all Member States of the Metre Convention attend the General Conference which, at present, meets every four years. The function of these meetings is to:

- discuss and initiate the arrangements required to ensure the propagation and improvement of the International System of Units (SI), which is the modern form of the metric system;
- confirm the results of new fundamental metrological determinations and various scientific resolutions of international scope;
- take all major decisions concerning the finance, organization and development of the BIPM.

The CIPM has eighteen members each from a different State: at present, it meets every year. The officers of this committee present an annual report on the administrative and financial position of the BIPM to the Governments of the Member States of the Metre Convention. The principal task of the CIPM is to ensure worldwide uniformity in units of measurement. It does this by direct action or by submitting proposals to the CGPM.

As of 20 May 2019, fifty nine States were Members of this Convention: Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Czech Republic, Denmark, Egypt, Finland, France, Germany, Greece, Hungary, India, Indonesia, Iran (Islamic Rep. of), Iraq, Ireland, Israel, Italy, Japan, Kazakhstan, Kenya, Korea (Republic of), Lithuania, Malaysia, Mexico, Montenegro, Netherlands, New Zealand, Norway, Pakistan, Poland, Portugal, Romania, Russian Federation, Saudi Arabia, Serbia, Singapore, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Thailand, Tunisia, Turkey, Ukraine, United Arab Emirates, United Kingdom, United States of America, and Uruguay.

Forty-two States and Economies were Associates of the General Conference: Albania, Azerbaijan, Bangladesh, Belarus, Bolivia, Bosnia and Herzegovina, Botswana, CARICOM, Chinese Taipei, Costa Rica, Cuba, Ecuador, Estonia, Ehiopia, Georgia, Ghana, Hong Kong (China), Jamaica, Kuwait, Latvia, Luxembourg, Macedonia (fmr Yugoslav Rep. of), Malta, Mauritius, Moldova (Republic of), Mongolia, Namibia, Oman, Panama, Paraguay, Peru, Philippines, Qatar, Seychelles, Sri Lanka, Sudan, Syrian Arab Republic, Tanzania (United Republic of), Viet Nam, Zambia, and Zimbawe

The activities of the BIPM, which in the beginning were limited to measurements of length and mass, and to metrological studies in relation to these quantities, have been extended to standards of measurement of electricity (1927), photometry and radiometry (1937), ionizing radiation (1960), time scales (1988) and to chemistry (2000). To this end the original laboratories, built in 1876 -1878, were enlarged in 1929; new buildings were constructed in 1963-1964 for the ionizing radiation laboratories, in 1984 for the laser work and in 1988 for a library and offices. In 2001 a new building for the workshop, offices and meeting rooms was opened.

Some forty-five physicists and technicians work in the BIPM laboratories. They mainly conduct metrological research, international comparisons of realizations of units and calibrations of standards. An annual report, the *Director's Report on the Activity and Management of the International Bureau of Weights and Measures*, gives details of the work in progress.

Following the extension of the work entrusted to the BIPM in 1927, the CIPM has set up bodies, known as Consultative Committees, whose function is to provide it with information on matters that it refers to them for study and advice. These Consultative Committees, which may form temporary or permanent working groups to study special topics, are responsible for coordinating the international work carried out in their respective fields and for proposing recommendations to the CIPM concerning units.

The Consultative Committees have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **31**, 97). They meet at irregular intervals. The president of each Consultative Committee is designated by the CIPM and is normally a member of the CIPM. The members of the Consultative Committees are metrology laboratories and specialized institutes, agreed by the CIPM, which send delegates of their choice. In addition, there are individual members appointed by the CIPM, and a representative of the BIPM (Criteria for membership of Consultative Committees, *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1996, **64**, 124). At present, there are ten such committees:

1. The Consultative Committee for Electricity and Magnetism (CCEM), new name given in 1997 to the Consultative Committee for Electricity (CCE) set up in 1927;
2. The Consultative Committee for Photometry and Radiometry (CCPR), new name given in 1971 to the Consultative Committee for Photometry (CCP) set up in 1933 (between 1930 and 1933 the CCE dealt with matters concerning photometry);
3. The Consultative Committee for Thermometry (CCT), set up in 1937;
4. The Consultative Committee for Length (CCL), new name given in 1997 to the Consultative Committee for the Definition of the Metre (CCDM), set up in 1952;
5. The Consultative Committee for Time and Frequency (CCTF), new name given in 1997 to the Consultative Committee for the Definition of the Second (CCDS) set up in 1956;
6. The Consultative Committee for Ionizing Radiation (CCRI), new name given in 1997 to the Consultative Committee for Standards of Ionizing Radiation (CCEMRI) set up in 1958 (in 1969 this committee established four sections: Section I (X- and $\gamma$-rays, electrons), Section II (Measurement of radionuclides), Section III (Neutron measurements), Section IV ($\alpha$-energy standards); in 1975 this last section was dissolved and Section II was made responsible for its field of activity);

7. The Consultative Committee for Units (CCU), set up in 1964 (this committee replaced the Commission for the System of Units set up by the CIPM in 1954);
8. The Consultative Committee for Mass and Related Quantities (CCM), set up in 1980;
9. The Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM), set up in 1993;
10. The Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV), set up un 1999.

The proceedings of the General Conference and the CIPM are published by the BIPM in the following series:

*Report of the meeting of the General Conference on Weights and Measures*;
*Report of the meeting of the International Committee for Weights and Measures*.

The CIPM decided in 2003 that the reports of meetings of the Consultative Committees should no longer be printed, but would be placed on the BIPM website, in their original language.

The BIPM also publishes monographs on special metrological subjects and, under the title The International System of Units (SI), this brochure, periodically updated, in which are collected all the decisions and recommendations concerning units.

The collection of the *Travaux et Mémoires du Bureau International des Poids et Mesures* (22 volumes published between 1881 and 1966) and the *Recueil de Travaux du Bureau International des Poids et Mesures* (11 volumes published between 1966 and 1988) ceased by a decision of the CIPM.

The scientific work of the BIPM is published in the open scientific literature and an annual list of publications appears in the *Director's Report on the Activity and Management of the International Bureau of Weights and Measures*.

Since 1965 *Metrologia*, an international journal published under the auspices of the CIPM, has printed articles dealing with scientific metrology, improvements in methods of measurement, work on standards and units, as well as reports concerning the activities, decisions and recommendations of the various bodies created under the Metre Convention.

# The International System of Units

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# Preface
# to the 9th edition

(to be completed)

# 1 Introduction

## 1.1 The SI and the defining constants

This brochure presents information on the definition and use of the International System of Units, universally known as the SI (from the French *Système international d'unités*), for which the General Conference on Weights and Measures (CGPM) has responsibility. In 1960 the 11th CGPM formally defined and established the SI and has subsequently revised it from time to time in response to the requirements of users and advances in science and technology. The most recent and perhaps the most significant revision of the SI since its establishment was made by the 26th CGPM (2018) and is documented in this 9th edition of the SI Brochure. The Metre Convention and its organs, the CGPM, the Comité International des Poids et Mesures (CIPM), the Bureau International des Poids et Mesures (BIPM), and the Consultative Committees are described in the preface.

The SI is a consistent system of units for use in all aspects of life, including international trade, manufacturing, security, health and safety, protection of the environment, and in the basic science that underpins all of these. The system of quantities underlying the SI and the equations relating them are based on the present description of nature and are familiar to all scientists, technologists and engineers.

The definition of the SI units is established in terms of a set of seven defining constants. The complete system of units can be derived from the fixed values of these defining constants, expressed in the units of the SI. These seven defining constants are the most fundamental feature of the definition of the entire system of units. These particular constants were chosen after having been identified as being the best choice, taking into account the previous definition of the SI, which is based on seven base units, and progress in science.

A variety of experimental methods described by the CIPM Consultative Committees may be used to realize the definitions. Descriptions of these realizations are also referred to as "mises en pratique". Realizations may be revised whenever new experiments are developed; for this reason advice on realizing the definitions is not included in this brochure but is available on the BIPM website.

## 1.2 Motivation for the use of defining constants to define the SI

Historically, SI units have been presented in terms of a set of – most recently seven – *base units*. All other units, described as *derived units,* are constructed as products of powers of the base units.

Different types of definitions for the base units have been used: specific properties of artefacts such as the mass of the international prototype (IPK) for the unit kilogram; a specific physical state such as the triple point of water for the unit kelvin; idealized experimental prescriptions as in the case of the ampere and the candela; or constants of nature such as the speed of light for the definition of the unit metre.

To be of any practical use, these units not only have to be defined, but they also have to be realized physically for dissemination. In the case of an artefact, the definition and the realization are equivalent – a path that was pursued by advanced ancient civilizations. Although this is simple and clear, artefacts involve the risk of loss, damage or change. The other types of unit definitions are increasingly abstract or idealized. Here, the realizations are separated conceptually from the definitions so that the units can, as a matter of principle, be realized independently at any place and at any time. In addition, new and superior realizations may be introduced as science and technologies develop, without the need to redefine the unit. These advantages – most obviously seen with the history of the definition of the metre from artefacts through an atomic reference transition to the fixed numerical value of the speed of light – led to the decision to define all units by using defining constants.

The choice of the base units was never unique, but grew historically and became familiar to users of the SI. This description in terms of base and derived units is maintained in the present definition of the SI, but has been reformulated as a consequence of adoption of the defining constants.

## 1.3 Implementation of the SI

The definitions of the SI units, as decided by the CGPM, represent the highest reference level for measurement traceability to the SI.

Metrology institutes around the world establish the practical realizations of the definitions in order to allow for traceability of measurements to the SI. The Consultative Committees provide the framework for establishing the equivalence of the realizations in order to harmonize traceability world-wide.

Standardization bodies may specify further details for quantities and units and rules for their application, where these are needed by interested parties. Whenever SI units are involved, these standards must refer to the definitions by the CGPM. Many such specifications are listed for example in the standards developed by the International Organization for Standardization and the International Electrotechnical Commission (ISO/IEC 80000 series of international standards).

Individual countries have established rules concerning the use of units by national legislation, either for general use or for specific areas such as commerce, health, public safety and education. In almost all countries, this legislation is based on the SI. The International Organization of Legal Metrology (OIML) is charged with the international harmonization of the technical specifications of this legislation.

# 2 The International System of Units

## 2.1 Defining the unit of a quantity

The value of a quantity is generally expressed as the product of a number and a unit. The unit is simply a particular example of the quantity concerned which is used as a reference, and the number is the ratio of the value of the quantity to the unit.

For a particular quantity different units may be used. For example, the value of the speed $v$ of a particle may be expressed as $v$ = 25 m/s or $v$ = 90 km/h, where metre per second and kilometre per hour are alternative units for the same value of the quantity speed.

Before stating the result of a measurement, it is essential that the quantity being presented is adequately described. This may be simple, as in the case of the length of a particular steel rod, but can become more complex when higher accuracy is required and where additional parameters, such as temperature, need to be specified.

When a measurement result of a quantity is reported, the ***estimated value*** of the measurand (the quantity to be measured), and the ***uncertainty*** associated with that value, are necessary. Both are expressed in the same unit.

## 2.2 Definition of the SI

As for any quantity, the value of a fundamental constant can be expressed as the product of a number and a unit.

The definitions below specify the exact numerical value of each constant when its value is expressed in the corresponding SI unit. By fixing the exact numerical value the unit becomes defined, since the product of the ***numerical value*** and the ***unit*** has to equal the ***value*** of the constant, which is postulated to be invariant.

The seven constants are chosen in such a way that any unit of the SI can be written either through a defining constant itself or through products or ratios of defining constants.

**The International System of Units, the SI, is the system of units in which**

- **the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta\nu_{\mathrm{Cs}}$ is 9 192 631 770 Hz,**
- **the speed of light in vacuum $c$ is 299 792 458 m/s,**
- **the Planck constant $h$ is 6.626 070 15 × $10^{-34}$ J s,**
- **the elementary charge $e$ is 1.602 176 634 × $10^{-19}$ C,**
- **the Boltzmann constant $k$ is 1.380 649 × $10^{-23}$ J/K,**
- **the Avogadro constant $N_{\mathrm{A}}$ is 6.022 140 76 × $10^{23}$ $\mathrm{mol}^{-1}$,**
- **the luminous efficacy of monochromatic radiation of frequency 540 × $10^{12}$ Hz, $K_{\mathrm{cd}}$, is 683 lm/W.**

where the hertz, joule, coulomb, lumen, and watt, with unit symbols Hz, J, C, lm, and W, respectively, are related to the units second, metre, kilogram, ampere, kelvin, mole, and candela, with unit symbols s, m, kg, A, K, mol, and cd, respectively, according to $\mathrm{Hz} = \mathrm{s}^{-1}$, $\mathrm{J} = \mathrm{kg\ m}^2\ \mathrm{s}^{-2}$, $\mathrm{C} = \mathrm{A\ s}$, $\mathrm{lm} = \mathrm{cd\ m}^2\ \mathrm{m}^{-2} = \mathrm{cd\ sr}$, and $\mathrm{W} = \mathrm{kg\ m}^2\ \mathrm{s}^{-3}$

The numerical values of the seven defining constants have no uncertainty.

**Table 1. The seven defining constants of the SI and the seven corresponding units they define**

| Defining constant | Symbol | Numerical value | Unit |
|---|---|---|---|
| hyperfine transition frequency of Cs | $\Delta\nu_{\mathrm{Cs}}$ | 9 192 631 770 | Hz |
| speed of light in vacuum | $c$ | 299 792 458 | $\mathrm{m\ s^{-1}}$ |
| Planck constant | $h$ | $6.626\ 070\ 15 \times 10^{-34}$ | J s |
| elementary charge | $e$ | $1.602\ 176\ 634 \times 10^{-19}$ | C |
| Boltzmann constant | $k$ | $1.380\ 649 \times 10^{-23}$ | $\mathrm{J\ K^{-1}}$ |
| Avogadro constant | $N_{\mathrm{A}}$ | $6.022\ 140\ 76 \times 10^{23}$ | $\mathrm{mol^{-1}}$ |
| luminous efficacy | $K_{\mathrm{cd}}$ | 683 | $\mathrm{lm\ W^{-1}}$ |

Preserving continuity, as far as possible, has always been an essential feature of any changes to the International System of Units. The numerical values of the defining constants have been chosen to be consistent with the earlier definitions in so far as advances in science and knowledge allow.

### 2.2.1 The nature of the seven defining constants

The nature of the defining constants ranges from fundamental constants of nature to technical constants.

The use of a constant to define a unit disconnects definition from realization. This offers the possibility that completely different or new and superior practical realizations can be developed, as technologies evolve, without the need to change the definition.

A technical constant such as $K_{\mathrm{cd}}$, the luminous efficacy of monochromatic radiation of frequency $540 \times 10^{12}$ Hz refers to a special application. In principle, its numerical value can be chosen freely, such as to include conventional physiological or other weighting factors. In contrast, the use of a fundamental constant of nature, in general, does not allow this choice because it is related to other constants through the equations of physics.

The set of seven defining constants has been chosen to provide a fundamental, stable and universal reference that simultaneously allows for practical realizations with the smallest uncertainties. The technical conventions and specifications also take historical developments into account.

Both the Planck constant $h$ and the speed of light in vacuum $c$ are properly described as fundamental. They determine quantum effects and space-time properties, respectively, and affect all particles and fields equally on all scales and in all environments.

The elementary charge $e$ corresponds to a coupling strength of the electromagnetic force via the fine-structure constant $\alpha = e^2/(2c\varepsilon_0 h)$ where $\varepsilon_0$ is the vacuum electric permittivity or electric constant. Some theories predict a variation of $\alpha$ over time. The experimental limits of the maximum possible variation in $\alpha$ are so low, however, that any effect on foreseeable practical measurements can be excluded.

The Boltzmann constant $k$ corresponds to a conversion factor between the quantities temperature (with unit kelvin) and energy (with unit joule), whereby the numerical value is obtained from historical specifications of the temperature scale. The temperature of a system scales with the thermal energy, but not necessarily with the internal energy of a system. In statistical physics the Boltzmann constant connects the entropy $S$ with the number $\Omega$ of quantum-mechanically accessible states, $S = k \ln \Omega$.

The caesium frequency $\Delta\nu_{\mathrm{Cs}}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, has the character of an atomic parameter, which may be affected by the environment, such as electromagnetic fields. However, the underlying transition is well understood, stable and a good choice as a reference transition under practical considerations. The choice of an atomic parameter like $\Delta\nu_{\mathrm{Cs}}$ does not disconnect definition and realization in the same way that $h$, $c$, $e$, or $k$ do, but specifies the reference.

The Avogadro constant $N_{\mathrm{A}}$ corresponds to a conversion factor between the quantity amount of substance (with unit mole) and the quantity for counting entities (with unit one, symbol 1). Thus it has the character of a constant of proportionality similar to the Boltzmann constant $k$.

The luminous efficacy of monochromatic radiation of frequency $540 \times 10^{12}$ Hz, $K_{\mathrm{cd}}$, is a technical constant that gives an exact numerical relationship between the purely physical characteristics of the radiant power stimulating the human eye (W) and its photobiological response defined by the luminous flux due to the spectral responsivity of a standard observer (lm) at a frequency of $540 \times 10^{12}$ hertz.

## 2.3 Definitions of the SI units

Prior to the definitions adopted in 2018, the SI was defined through seven *base units* from which the *derived units* were constructed as products of powers of the *base units.* Defining the SI by fixing the numerical values of seven defining constants has the effect that this distinction is, in principle, not needed, since all units, *base* as well as *derived units*, may be constructed directly from the defining constants. Nevertheless, the concept of base and derived units is maintained, not only because it is useful and historically well established, but also because it is necessary to maintain consistency with the International System of Quantities (ISQ) defined by the ISO/IEC 80000 series of Standards, which specify base and derived quantities to which the SI base and derived units necessarily correspond.

### 2.3.1 Base units

The base units of the SI are listed in Table 2.

**Table 2. SI base units**

| Base quantity | | Base unit | |
|---|---|---|---|
| Name | Typical symbol | Name | Symbol |
| time | *t* | second | s |
| length | *l*, *x*, *r*, etc. | metre | m |
| mass | *m* | kilogram | kg |
| electric current | *I*, *i* | ampere | A |
| thermodynamic temperature | *T* | kelvin | K |
| amount of substance | *n* | mole | mol |
| luminous intensity | $I_v$ | candela | cd |

The symbols for quantities are generally single letters of the Latin or Greek alphabets, printed in an italic font, and are *recommendations*.
The symbols for units are printed in an upright (roman) font and are *mandatory*, see chapter 5.

Starting from the definition of the SI in terms of fixed numerical values of the defining constants, definitions of each of the seven base units are deduced by using, as appropriate, one or more of these defining constants to give the following set of definitions:

**The second**

**The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\mathrm{Cs}}$, 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 $\mathrm{s}^{-1}$.**

This definition implies the exact relation $\Delta\nu_{\mathrm{Cs}} = 9\,192\,631\,770$ Hz. Inverting this relation gives an expression for the unit second in terms of the defining constant $\Delta\nu_{\mathrm{Cs}}$:

$$1\,\mathrm{Hz} = \frac{\Delta\nu_{\mathrm{Cs}}}{9\,192\,631\,770} \quad \text{or} \quad 1\,\mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu_{\mathrm{Cs}}}\,.$$

The effect of this definition is that the second is equal to the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the $^{133}$Cs atom.

The reference to an unperturbed atom is intended to make it clear that the definition of the SI second is based on an isolated caesium atom that is unperturbed by any external field, such as ambient black-body radiation.

The second, so defined, is the unit of proper time in the sense of the general theory of relativity. To allow the provision of a coordinated time scale, the signals of different primary clocks in different locations are combined, which have to be corrected for relativistic caesium frequency shifts (see section 2.3.6).

The CIPM has adopted various secondary representations of the second, based on a selected number of spectral lines of atoms, ions or molecules. The unperturbed frequencies of these lines can be determined with a relative uncertainty not lower than that of the realization of the second based on the $^{133}$Cs hyperfine transition frequency, but some can be reproduced with superior stability.

### The metre

**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 m s$^{-1}$, where the second is defined in terms of the caesium frequency $\Delta\nu_{\mathrm{Cs}}$.**

This definition implies the exact relation $c = 299\,792\,458$ m s$^{-1}$. Inverting this relation gives an exact expression for the metre in terms of the defining constants $c$ and $\Delta\nu_{\mathrm{Cs}}$:

$$1\,\mathrm{m} = \left(\frac{c}{299\ 792\ 458}\right)\mathrm{s} = \frac{9\,192\,631\,770}{299\ 792\ 458}\frac{c}{\Delta\nu_{\mathrm{Cs}}} \approx 30.663\ 319\frac{c}{\Delta\nu_{\mathrm{Cs}}}\,.$$

The effect of this definition is that one metre is the length of the path travelled by light in vacuum during a time interval with duration of 1/299 792 458 of a second.

### The kilogram

**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 × 10$^{-34}$ when expressed in the unit J s, which is equal to kg m$^2$ s$^{-1}$, where the metre and the second are defined in terms of $c$ and $\Delta\nu_{\mathrm{Cs}}$.**

This definition implies the exact relation $h = 6.626\,070\,15 \times 10^{-34}$ kg m$^2$ s$^{-1}$. Inverting this relation gives an exact expression for the kilogram in terms of the three defining constants $h$, $\Delta\nu_{\mathrm{Cs}}$ and $c$:

$$1\,\mathrm{kg} = \left(\frac{h}{6.626\,070\,15 \times 10^{-34}}\right)\mathrm{m}^{-2}\mathrm{s}$$

which is equal to

$$1\,\mathrm{kg} = \frac{(299\ 792\ 458)^2}{(6.626\ 070\ 15 \times 10^{-34})(9\ 192\ 631\ 770)}\frac{h\,\Delta\nu_{\mathrm{Cs}}}{c^2} \approx 1.475\,5214 \times 10^{40}\,\frac{h\,\Delta\nu_{\mathrm{Cs}}}{c^2}$$

The effect of this definition is to define the unit kg m$^2$ s$^{-1}$ (the unit of both the physical quantities action and angular momentum). Together with the definitions of the second and the metre this leads to a definition of the unit of mass expressed in terms of the Planck constant $h$.

The previous definition of the kilogram fixed the value of the mass of the international prototype of the kilogram, $m(\mathcal{K})$, to be equal to one kilogram exactly and the value of the Planck constant $h$ had to be determined by experiment. The present definition fixes the numerical value of $h$ exactly and the mass of the prototype has now to be determined by experiment.

The number chosen for the numerical value of the Planck constant in this definition is such that at the time of its adoption, the kilogram was equal to the mass of the international prototype, $m(\mathcal{K}) = 1$ kg, with a relative standard uncertainty of $1 \times 10^{-8}$, which was the standard uncertainty of the combined best estimates of the value of the Planck constant at that time.

Note that with the present definition, primary realizations can be established, in principle, at any point in the mass scale.

### The ampere

**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 × $10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{\mathrm{Cs}}$.**

This definition implies the exact relation $e = 1.602\,176\,634 \times 10^{-19}$ A s. Inverting this relation gives an exact expression for the unit ampere in terms of the defining constants $e$ and $\Delta\nu_{\mathrm{Cs}}$:

$$1\,\mathrm{A} = \left(\frac{e}{1.602\,176\,634 \times 10^{-19}}\right)\mathrm{s}^{-1}$$

which is equal to

$$1\,\mathrm{A} = \frac{1}{(9\,192\,631\,770)(1.602\,176\,634 \times 10^{-19})}\Delta\nu_{\mathrm{Cs}}e \approx 6.789\,687 \times 10^{8}\,\Delta\nu_{\mathrm{Cs}}e$$

The effect of this definition is that one ampere is the electric current corresponding to the flow of 1/(1.602 176 634 × $10^{-19}$) elementary charges per second.

The previous definition of the ampere was based on the force between two current carrying conductors and had the effect of fixing the value of the vacuum magnetic permeability $\mu_0$ (also known as the magnetic constant) to be exactly $4\pi \times 10^{-7}$ H $\mathrm{m}^{-1}$ = $4\pi \times 10^{-7}$ N $\mathrm{A}^{-2}$, where H and N denote the coherent derived units henry and newton, respectively. The new definition of the ampere fixes the value of $e$ instead of $\mu_0$. As a result, $\mu_0$ must be determined experimentally.

It also follows that since the vacuum electric permittivity $\varepsilon_0$ (also known as the electric constant), the characteristic impedance of vacuum $Z_0$, and the admittance of vacuum $Y_0$ are equal to $1/\mu_0 c^2$, $\mu_0 c$, and $1/\mu_0 c$, respectively, the values of $\varepsilon_0$, $Z_0$, and $Y_0$ must now also be determined experimentally, and are affected by the same relative standard uncertainty as $\mu_0$ since $c$ is exactly known. The product $\varepsilon_0\mu_0 = 1/c^2$ and quotient $Z_0/\mu_0 = c$ remain exact. At the time of adopting the present definition of the ampere, $\mu_0$ was equal to $4\pi \times 10^{-7}$ H/m with a relative standard uncertainty of $2.3 \times 10^{-10}$.

### The kelvin

**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 × $10^{-23}$ when expressed in the unit J $\mathrm{K}^{-1}$, which is equal to kg $\mathrm{m}^2$ $\mathrm{s}^{-2}$ $\mathrm{K}^{-1}$, where the kilogram, metre and second are defined in terms of $h$, $c$ and $\Delta\nu_{\mathrm{Cs}}$.**

This definition implies the exact relation $k = 1.380\,649 \times 10^{-23}$ kg $\mathrm{m}^2$ $\mathrm{s}^{-2}$ $\mathrm{K}^{-1}$. Inverting this relation gives an exact expression for the kelvin in terms of the defining constants $k$, $h$ and $\Delta\nu_{\mathrm{Cs}}$:

$$1\,\mathrm{K} = \left(\frac{1.380\,649}{k}\right) \times 10^{-23}\ \mathrm{kg\ m^2\ s^{-2}}$$

which is equal to

$$1\mathrm{K} = \frac{1.380\ 649 \times 10^{-23}}{\left(6.626\ 070\ 15 \times 10^{-34}\right)\left(9\ 192\ 631\ 770\right)} \frac{\Delta \nu_{\mathrm{Cs}} h}{k} \approx 2.266\ 6653 \frac{\Delta \nu_{\mathrm{Cs}} h}{k}$$

The effect of this definition is that one kelvin is equal to the change of thermodynamic temperature that results in a change of thermal energy $kT$ by 1.380 649 × $10^{-23}$ J.

The previous definition of the kelvin set the temperature of the triple point of water, $T_{\mathrm{TPW}}$, to be exactly 273.16 K. Due to the fact that the present definition of the kelvin fixes the numerical value of $k$ instead of $T_{\mathrm{TPW}}$, the latter must now be determined experimentally. At the time of adopting the present definition $T_{\mathrm{TPW}}$ was equal to 273.16 K with a relative standard uncertainty of 3.7 × $10^{-7}$ based on measurements of $k$ made prior to the redefinition.

As a result of the way temperature scales used to be defined, it remains common practice to express a thermodynamic temperature, symbol $T$, in terms of its difference from the reference temperature $T_0 = 273.15$ K, close to the ice point. This difference is called the Celsius temperature, symbol $t$, which is defined by the quantity equation

$$t = T - T_0\,.$$

The unit of Celsius temperature is the degree Celsius, symbol °C, which is by definition equal in magnitude to the unit kelvin. A difference or interval of temperature may be expressed in kelvin or in degrees Celsius, the numerical value of the temperature difference being the same in either case. However, the numerical value of a Celsius temperature expressed in degrees Celsius is related to the numerical value of the thermodynamic temperature expressed in kelvin by the relation

$$t/{}^{\circ}\mathrm{C} = T/\mathrm{K} - 273.15$$

(see 5.4.1 for an explanation of the notation used here).

The kelvin and the degree Celsius are also units of the International Temperature Scale of 1990 (ITS-90) adopted by the CIPM in 1989 in Recommendation 5 (CI-1989, PV, **57**, 115). Note that the ITS-90 defines two quantities $T_{90}$ and $t_{90}$ which are close approximations to the corresponding thermodynamic temperatures $T$ and $t$.

Note that with the present definition, primary realizations of the kelvin can, in principle, be established at any point of the temperature scale.

### The mole

**The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly 6.022 140 76 × $10^{23}$ 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.**

**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.**

This definition implies the exact relation $N_A = 6.022\,140\,76 \times 10^{23}\ \mathrm{mol}^{-1}$. Inverting this relation gives an exact expression for the mole in terms of the defining constant $N_A$:

$$1\,\mathrm{mol} = \left(\frac{6.022\,140\,76 \times 10^{23}}{N_\mathrm{A}}\right)$$

The effect of this definition is that the mole is the amount of substance of a system that contains $6.022\,140\,76 \times 10^{23}$ specified elementary entities.

The previous definition of the mole fixed the value of the molar mass of carbon 12, $M(^{12}\mathrm{C})$, to be exactly 0.012 kg/mol. According to the present definition $M(^{12}\mathrm{C})$ is no longer known exactly and must be determined experimentally. The value chosen for $N_A$ is such that at the time of adopting the present definition of the mole, $M(^{12}\mathrm{C})$ was equal to 0.012 kg/mol with a relative standard uncertainty of $4.5 \times 10^{-10}$.

The molar mass of any atom or molecule $X$ may still be obtained from its relative atomic mass from the equation

$$M(X) = A_\mathrm{r}(X)\,[M(^{12}\mathrm{C})/12] = A_\mathrm{r}(X)\,M_\mathrm{u}$$

and the molar mass of any atom or molecule $X$ is also related to the mass of the elementary entity $m(X)$ by the relation

$$M(X) = N_\mathrm{A}\,m(X) = N_\mathrm{A}\,A_\mathrm{r}(X)\,m_\mathrm{u}\,.$$

In these equations $M_u$ is the molar mass constant, equal to $M(^{12}\mathrm{C})/12$ and $m_u$ is the unified atomic mass constant, equal to $m(^{12}\mathrm{C})/12$. They are related to the Avogadro constant through the relation

$$M_\mathrm{u} = N_\mathrm{A}\,m_\mathrm{u}\,.$$

In the name “amount of substance”, the word “substance” will typically be replaced by words to specify the substance concerned in any particular application, for example “amount of hydrogen chloride, HCl”, or “amount of benzene, $C_6H_6$”. It is important to give a precise definition of the entity involved (as emphasized in the definition of the mole); this should preferably be done by specifying the molecular chemical formula of the material involved. Although the word “amount” has a more general dictionary definition, the abbreviation of the full name “amount of substance” to “amount” may be used for brevity. This also applies to derived quantities such as “amount-of-substance concentration”, which may simply be called “amount concentration”. In the field of clinical chemistry, the name “amount-of-substance concentration” is generally abbreviated to “substance concentration”.

**The candela**

**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, $K_{\mathrm{cd}}$, to be 683 when expressed in the unit $\mathrm{lm\,W^{-1}}$, which is equal to $\mathrm{cd\,sr\,W^{-1}}$, or $\mathrm{cd\,sr\,kg^{-1}\,m^{-2}\,s^{3}}$, where the kilogram, metre and second are defined in terms of $h$, $c$ and $\Delta\nu_{\mathrm{Cs}}$.**

This definition implies the exact relation $K_{\mathrm{cd}} = 683\ \mathrm{cd\,sr\,kg^{-1}\,m^{-2}\,s^{3}}$ for monochromatic radiation of frequency $\nu = 540 \times 10^{12}$ Hz. Inverting this relation gives an exact expression for the candela in terms of the defining constants $K_{\mathrm{cd}}$, $h$ and $\Delta\nu_{\mathrm{Cs}}$:

$$1\,\mathrm{cd} = \left(\frac{K_{\mathrm{cd}}}{683}\right)\mathrm{kg\ m^{2}\ s^{-3}\ sr^{-1}}$$

which is equal to

$$1\,\mathrm{cd} = \frac{1}{\left(6.626\ 070\ 15\times10^{-34}\right)\left(9\ 192\ 631\ 770\right)^{2}683}(\Delta\nu_{\mathrm{Cs}})^{2}\ h\,K_{\mathrm{cd}}$$

$$\approx 2.614\,830\times10^{10}\ (\Delta\nu_{\mathrm{Cs}})^{2}\ h\,K_{\mathrm{cd}}$$

The effect of this definition is that one candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × $10^{12}$ Hz and has a radiant intensity in that direction of (1/683) W/sr. The definition of the steradian is given below Table 4.

## 2.3.2 Practical realization of SI units

The highest-level experimental methods used for the realization of units using the equations of physics are known as primary methods. The essential characteristic of a primary method is that it allows a quantity to be measured in a particular unit by using only measurements of quantities that do not involve that unit. In the present formulation of the SI, the basis of the definitions is different from that used previously, so that new methods may be used for the practical realization of SI units.

Instead of each definition specifying a particular condition or physical state, which sets a fundamental limit to the accuracy of realization, a user is now free to choose any convenient equation of physics that links the defining constants to the quantity intended to be measured. This is a much more general way of defining the basic units of measurement. It is not limited by today’s science or technology; future developments may lead to different ways of realizing units to a higher accuracy. When defined this way, there is, in principle, no limit to the accuracy with which a unit might be realized. The exception remains the definition of the second, in which the original microwave transition of caesium must remain, for the time being, the basis of the definition. For a more comprehensive explanation of the realization of SI units see Appendix 2.

### 2.3.3 Dimensions of quantities

Physical quantities can be organized in a system of dimensions, where the system used is decided by convention. Each of the seven base quantities used in the SI is regarded as having its own dimension. The symbols used for the base quantities and the symbols used to denote their dimension are shown in Table 3.

**Table 3. Base quantities and dimensions used in the SI**

| Base quantity | Typical symbol for quantity | Symbol for dimension |
|---|---|---|
| time | $t$ | T |
| length | $l$, $x$, $r$, etc. | L |
| mass | $m$ | M |
| electric current | $I$, $i$ | I |
| thermodynamic temperature | $T$ | Θ |
| amount of substance | $n$ | N |
| luminous intensity | $I_\mathrm{v}$ | J |

All other quantities, with the exception of counts, are derived quantities, which may be written in terms of base quantities according to the equations of physics. The dimensions of the derived quantities are written as products of powers of the dimensions of the base quantities using the equations that relate the derived quantities to the base quantities. In general the dimension of any quantity $Q$ is written in the form of a dimensional product,

$$\dim Q = \mathsf{T}^{\alpha}\,\mathsf{L}^{\beta}\mathsf{M}^{\gamma}\,\mathsf{I}^{\delta}\,\Theta^{\varepsilon}\,\mathsf{N}^{\zeta}\,\mathsf{J}^{\eta}$$

where the exponents $\alpha$, $\beta$, $\gamma$, $\delta$, $\varepsilon$, $\zeta$ and $\eta$, which are generally small integers, which can be positive, negative, or zero, are called the dimensional exponents.

There are quantities $Q$ for which the defining equation is such that all of the dimensional exponents in the equation for the dimension of $Q$ are zero. This is true in particular for any quantity that is defined as the ratio of two quantities of the same kind. For example, the refractive index is the ratio of two speeds and the relative permittivity is the ratio of the permittivity of a dielectric medium to that of free space. Such quantities are simply numbers. The associated unit is the unit one, symbol 1, although this is rarely explicitly written (see 5.4.7).

There are also some quantities that cannot be described in terms of the seven base quantities of the SI, but have the nature of a count. Examples are a number of molecules, a number of cellular or biomolecular entities (for example copies of a particular nucleic acid sequence), or degeneracy in quantum mechanics. Counting quantities are also quantities with the associated unit one.

The unit one is the neutral element of any system of units – necessarily and present automatically. There is no requirement to introduce it formally by decision. Therefore, a formal traceability to the SI can be established through appropriate, validated measurement procedures.

Plane and solid angles, when expressed in radians and steradians respectively, are in effect also treated within the SI as quantities with the unit one (see section 5.4.8). The symbols rad and sr are written explicitly where appropriate, in order to emphasize that, for radians or steradians, the quantity being considered is, or involves the plane angle or solid angle respectively. For steradians it emphasizes the distinction between fluxes and intensities in radiometry and photometry for example. However, it is a long-established practice in mathematics and across all areas of science to make use of rad = 1 and sr = 1. For historical reasons the radian and steradian are treated as derived units, as described in section 2.3.4.

It is especially important to have a clear description of any quantity with unit one (see section 5.4.7) that is expressed as a ratio of quantities of the same kind (for example length ratios or amount fractions) or as a count (for example number of photons or decays).

### 2.3.4 Derived units

Derived units are defined as products of powers of the base units. When the numerical factor of this product is one, the derived units are called *coherent derived units*. The base and coherent derived units of the SI form a coherent set, designated the *set of coherent SI units*. The word “coherent” here means that equations between the numerical values of quantities take exactly the same form as the equations between the quantities themselves.

Some of the coherent derived units in the SI are given special names. Table 4 lists 22 SI units with special names. Together with the seven base units (Table 2) they form the core of the set of SI units. All other SI units are combinations of some of these 29 units.

It is important to note that any of the seven base units and 22 SI units with special names can be constructed directly from the seven defining constants. In fact, the units of the seven defining constants include both base and derived units.

The CGPM has adopted a series of prefixes for use in forming the decimal multiples and sub-multiples of the coherent SI units (see chapter 3). They are convenient for expressing the values of quantities that are much larger than or much smaller than the coherent unit. However, when prefixes are used with SI units, the resulting units are no longer coherent, because the prefix introduces a numerical factor other than one. Prefixes may be used with any of the 29 SI units with special names with the exception of the base unit kilogram, which is further explained in chapter 3.

**Table 4. The 22 SI units with special names and symbols**

| Derived quantity | Special name of unit | Unit expressed in terms of base units *(a)* | Unit expressed in terms of other SI units |
|---|---|---|---|
| plane angle | radian *(b)* | rad = m/m | |
| solid angle | steradian *(c)* | sr = $m^2/m^2$ | |
| frequency | hertz *(d)* | Hz = $s^{-1}$ | |
| force | newton | N = kg m $s^{-2}$ | |
| pressure, stress | pascal | Pa = kg $m^{-1}$ $s^{-2}$ | |
| energy, work, amount of heat | joule | J = kg $m^2$ $s^{-2}$ | N m |
| power, radiant flux | watt | W = kg $m^2$ $s^{-3}$ | J/s |
| electric charge | coulomb | C = A s | |

| | | | |
|---|---|---|---|
| electric potential difference (*e*) | volt | V = kg m$^2$ s$^{-3}$ A$^{-1}$ | W/A |
| capacitance | farad | F = kg$^{-1}$ m$^{-2}$ s$^4$ A$^2$ | C/V |
| electric resistance | ohm | Ω = kg m$^2$ s$^{-3}$ A$^{-2}$ | V/A |
| electric conductance | siemens | S = kg$^{-1}$ m$^{-2}$ s$^3$ A$^2$ | A/V |
| magnetic flux | weber | Wb = kg m$^2$ s$^{-2}$ A$^{-1}$ | V s |
| magnetic flux density | tesla | T = kg s$^{-2}$ A$^{-1}$ | Wb/m$^2$ |
| inductance | henry | H = kg m$^2$ s$^{-2}$ A$^{-2}$ | Wb/A |
| Celsius temperature | degree Celsius (*f*) | $^{\circ}$C = K | |
| luminous flux | lumen | lm = cd sr | cd sr |
| illuminance | lux | lx = cd sr m$^{-2}$ | lm/m$^2$ |
| activity referred to a radionuclide (*d, g*) | becquerel | Bq = s$^{-1}$ | |
| absorbed dose, kerma | gray | Gy = m$^2$ s$^{-2}$ | J/kg |
| dose equivalent | sievert (*h*) | Sv = m$^2$ s$^{-2}$ | J/kg |
| catalytic activity | katal | kat = mol s$^{-1}$ | |

(*a*) The order of symbols for base units in this Table is different from that in the 8th edition following a decision by the CCU at its 21st meeting (2013) to return to the original order in Resolution 12 of the 11th CGPM (1960) in which newton was written kg m s$^{-2}$, the joule as kg m$^2$ s$^{-2}$ and J s as kg m$^{-2}$ s$^{-1}$. The intention was to reflect the underlying physics of the corresponding quantity equations although for some more complex derived units this may not be possible.

(*b*) The radian is the coherent unit for plane angle. One radian is the angle subtended at the centre of a circle by an arc that is equal in length to the radius. It is also the unit for phase angle. For periodic phenomena, the phase angle increases by 2π rad in one period. The radian was formerly an SI supplementary unit, but this category was abolished in 1995.

(*c*) The steradian is the coherent unit for solid angle. One steradian is the solid angle subtended at the centre of a sphere by an area of the surface that is equal to the squared radius. Like the radian, the steradian was formerly an SI supplementary unit.

(*d*) The hertz shall only be used for periodic phenomena and the becquerel shall only be used for stochastic processes in activity referred to a radionuclide.

(*e*) Electric potential difference is also called “voltage” in many countries, as well as “electric tension” or simply “tension” in some countries.

(*f*) The degree Celsius is used to express Celsius temperatures. The numerical value of a temperature difference or temperature interval is the same when expressed in either degrees Celsius or in kelvin.

(*g*) Activity referred to a radionuclide is sometimes incorrectly called radioactivity.

(*h*) See CIPM Recommendation 2 on the use of the sievert (PV, 2002, **70**, 205).

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The seven base units and 22 units with special names and symbols may be used in combination to express the units of other derived quantities. Since the number of quantities is without limit, it is not possible to provide a complete list of derived quantities and derived units. Table 5 lists some examples of derived quantities and the corresponding coherent derived units expressed in terms of base units. In addition, Table 6 lists examples of coherent derived units whose names and symbols also include derived units. The complete set of SI units includes both the coherent set and the multiples and sub-multiples formed by using the SI prefixes.

### Table 5. Examples of coherent derived units in the SI expressed in terms of base units

| Derived quantity | Typical symbol of quantity | Derived unit expressed in terms of base units |
|---|---|---|
| area | $A$ | $\mathrm{m}^2$ |
| volume | $V$ | $\mathrm{m}^3$ |
| speed, velocity | $v$ | $\mathrm{m\ s}^{-1}$ |
| acceleration | $a$ | $\mathrm{m\ s}^{-2}$ |
| wavenumber | $\sigma$ | $\mathrm{m}^{-1}$ |
| density, mass density | $\rho$ | $\mathrm{kg\ m}^{-3}$ |
| surface density | $\rho_\mathrm{A}$ | $\mathrm{kg\ m}^{-2}$ |
| specific volume | $\upsilon$ | $\mathrm{m}^3\ \mathrm{kg}^{-1}$ |
| current density | $j$ | $\mathrm{A\ m}^{-2}$ |
| magnetic field strength | $H$ | $\mathrm{A\ m}^{-1}$ |
| amount of substance concentration | $c$ | $\mathrm{mol\ m}^{-3}$ |
| mass concentration | $\rho$, $\gamma$ | $\mathrm{kg\ m}^{-3}$ |
| luminance | $L_\mathrm{v}$ | $\mathrm{cd\ m}^{-2}$ |

### Table 6. Examples of SI coherent derived units whose names and symbols include SI coherent derived units with special names and symbols

| Derived quantity | Name of coherent derived unit | Symbol | Derived unit expressed in terms of base units |
|---|---|---|---|
| dynamic viscosity | pascal second | Pa s | $\mathrm{kg\ m}^{-1}\ \mathrm{s}^{-1}$ |
| moment of force | newton metre | N m | $\mathrm{kg\ m}^2\ \mathrm{s}^{-2}$ |
| surface tension | newton per metre | $\mathrm{N\ m}^{-1}$ | $\mathrm{kg\ s}^{-2}$ |
| angular velocity, angular frequency | radian per second | $\mathrm{rad\ s}^{-1}$ | $\mathrm{s}^{-1}$ |
| angular acceleration | radian per second squared | $\mathrm{rad/s}^2$ | $\mathrm{s}^{-2}$ |
| heat flux density, irradiance | watt per square metre | $\mathrm{W\ m}^2$ | $\mathrm{kg\ s}^{-3}$ |
| heat capacity, entropy | joule per kelvin | $\mathrm{J\ K}^{-1}$ | $\mathrm{kg\ m}^2\ \mathrm{s}^{-2}\ \mathrm{K}^{-1}$ |
| specific heat capacity, specific entropy | joule per kilogram kelvin | $\mathrm{J\ K}^{-1}\ \mathrm{kg}^{-1}$ | $\mathrm{m}^2\ \mathrm{s}^{-2}\ \mathrm{K}^{-1}$ |
| specific energy | joule per kilogram | $\mathrm{J\ kg}^{-1}$ | $\mathrm{m}^2\ \mathrm{s}^{-2}$ |
| thermal conductivity | watt per metre kelvin | $\mathrm{W\ m}^{-1}\ \mathrm{K}^{-1}$ | $\mathrm{kg\ m\ s}^{-3}\ \mathrm{K}^{-1}$ |
| energy density | joule per cubic metre | $\mathrm{J\ m}^{-3}$ | $\mathrm{kg\ m}^{-1}\ \mathrm{s}^{-2}$ |
| electric field strength | volt per metre | $\mathrm{V\ m}^{-1}$ | $\mathrm{kg\ m\ s}^{-3}\ \mathrm{A}^{-1}$ |
| electric charge density | coulomb per cubic metre | $\mathrm{C\ m}^{-3}$ | $\mathrm{A\ s\ m}^{-3}$ |
| surface charge density | coulomb per square metre | $\mathrm{C\ m}^{-2}$ | $\mathrm{A\ s\ m}^{-2}$ |
| electric flux density, electric displacement | coulomb per square metre | $\mathrm{C\ m}^{-2}$ | $\mathrm{A\ s\ m}^{-2}$ |
| permittivity | farad per metre | $\mathrm{F\ m}^{-1}$ | $\mathrm{kg}^{-1}\ \mathrm{m}^{-3}\ \mathrm{s}^4\ \mathrm{A}^2$ |
| permeability | henry per metre | $\mathrm{H\ m}^{-1}$ | $\mathrm{kg\ m\ s}^{-2}\ \mathrm{A}^{-2}$ |

| | | | |
|---|---|---|---|
| molar energy | joule per mole | $\mathrm{J\ mol^{-1}}$ | $\mathrm{kg\ m^{2}\ s^{-2}\ mol^{-1}}$ |
| molar entropy, molar heat capacity | joule per mole kelvin | $\mathrm{J\ K^{-1}\ mol^{-1}}$ | $\mathrm{kg\ m^{2}\ s^{-2}\ mol^{-1}\ K^{-1}}$ |
| exposure (x- and γ-rays) | coulomb per kilogram | $\mathrm{C\ kg^{-1}}$ | $\mathrm{A\ s\ kg^{-1}}$ |
| absorbed dose rate | gray per second | $\mathrm{Gy\ s^{-1}}$ | $\mathrm{m^{2}\ s^{-3}}$ |
| radiant intensity | watt per steradian | $\mathrm{W\ sr^{-1}}$ | $\mathrm{kg\ m^{2}\ s^{-3}}$ |
| radiance | watt per square metre steradian | $\mathrm{W\ sr^{-1}\ m^{-2}}$ | $\mathrm{kg\ s^{-3}}$ |
| catalytic activity concentration | katal per cubic metre | $\mathrm{kat\ m^{-3}}$ | $\mathrm{mol\ s^{-1}\ m^{-3}}$ |

It is important to emphasize that each physical quantity has only one coherent SI unit, even though this unit can be expressed in different forms by using some of the special names and symbols.

The converse, however, is not true, because in general several different quantities may share the same SI unit. For example, for the quantity heat capacity as well as for the quantity entropy the SI unit is joule per kelvin. Similarly, for the base quantity electric current as well as the derived quantity magnetomotive force the SI unit is the ampere. It is therefore important not to use the unit alone to specify the quantity. This applies not only to technical texts, but also, for example, to measuring instruments (i.e. the instrument read-out needs to indicate both the unit and the quantity measured).

In practice, with certain quantities, preference is given to the use of certain special unit names to facilitate the distinction between different quantities having the same dimension. When using this freedom, one may recall the process by which this quantity is defined. For example, the quantity torque is the cross product of a position vector and a force vector. The SI unit is newton metre. Even though torque has the same dimension as energy (SI unit joule), the joule is never used for expressing torque.

The International Electrotechnical Commission (IEC) has introduced the var (symbol: var) as a special name for the unit of reactive power. In terms of SI coherent units, the var is identical to the volt ampere.

The SI unit of frequency is hertz, the SI unit of angular velocity and angular frequency is radian per second, and the SI unit of activity is becquerel, implying counts per second. Although it is formally correct to write all three of these units as the reciprocal second, the use of the different names emphasizes the different nature of the quantities concerned. It is especially important to carefully distinguish frequencies from angular frequencies, because by definition their numerical values differ by a factor[1] of $2\pi$. Ignoring this fact may cause an error of $2\pi$. Note that in some countries, frequency values are conventionally expressed using “cycle/s” or “cps” instead of the SI unit Hz, although “cycle” and “cps” are not units in the SI. Note also that it is common, although not recommended, to use the term frequency for quantities expressed in rad/s. Because of this, it is recommended that quantities called “frequency”, “angular frequency”, and “angular velocity” always be given explicit units of Hz or rad/s and not $\mathrm{s^{-1}}$**.**

In the field of ionizing radiation, the SI unit becquerel rather than the reciprocal second is used. The SI units gray and sievert are used for absorbed dose and dose equivalent, respectively, rather than joule per kilogram. The special names becquerel, gray and sievert were specifically introduced because of the dangers to human health that might arise from mistakes involving the units reciprocal second and joule per kilogram, in case the latter units were incorrectly taken to identify the different quantities involved.

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[1] see ISO 80000-3 for details

Special care must be taken when expressing temperatures or temperature differences, respectively. A temperature difference of 1 K equals that of 1 $^{o}$C, but for an absolute temperature the difference of 273.15 K must be taken into account. The unit degree Celsius is only coherent when expressing temperature differences.

### 2.3.5 Units for quantities that describe biological and physiological effects

Four of the SI units listed in tables 2 and 4 include physiological weighting factors: candela, lumen, lux and sievert.

Lumen and lux are derived from the base unit candela. Like the candela, they carry information about human vision. The candela was established as a base unit in 1954, acknowledging the importance of light in daily life. Further information on the units and conventions used for defining photochemical and photobiological quantities is in Appendix 3.

Ionizing radiation deposits energy in irradiated matter. The ratio of deposited energy to mass is termed absorbed dose $D$. As decided by the CIPM in 2002, the quantity dose equivalent $H = Q\,D$ is the product of the absorbed dose $D$ and a numerical quality factor $Q$ that takes into account the biological effectiveness of the radiation and is dependent on the energy and type of radiation.

There are units for quantities that describe biological effects and involve weighting factors, which are not SI units. Two examples are given here:

Sound causes pressure fluctuations in the air, superimposed on the normal atmospheric pressure, that are sensed by the human ear. The sensitivity of the ear depends on the frequency of the sound, but it is not a simple function of either the pressure changes or the frequency. Therefore, frequency-weighted quantities are used in acoustics to approximate the way in which sound is perceived. They are used, for example, for measurements concerning protection against hearing damage. The effect of ultrasonic acoustic waves poses similar concerns in medical diagnosis and therapy.

There is a class of units for quantifying the biological activity of certain substances used in medical diagnosis and therapy that cannot yet be defined in terms of the units of the SI. This lack of definition is because the mechanism of the specific biological effect of these substances is not yet sufficiently well understood for it to be quantifiable in terms of physico-chemical parameters. In view of their importance for human health and safety, the World Health Organization (WHO) has taken responsibility for defining WHO International Units (IU) for the biological activity of such substances.

### 2.3.6 SI units in the framework of the general theory of relativity

The practical realization of a unit and the process of comparison require a set of equations within a framework of a theoretical description. In some cases, these equations include relativistic effects.

For frequency standards it is possible to establish comparisons at a distance by means of electromagnetic signals. To interpret the results, the general theory of relativity is required, since it predicts, among other things, a relative frequency shift between standards of about 1 part in $10^{16}$ per metre of altitude difference at the surface of the earth. Effects of this magnitude must be corrected for when comparing the best frequency standards.

When practical realizations are compared locally, i.e. in a small space-time domain, effects due to the space-time curvature described by the general theory of relativity can be neglected. When realizations share the same space-time coordinates (for example the same motion and acceleration or gravitational field), relativistic effects may be neglected entirely.

# 3 Decimal multiples and sub-multiples of SI units

Decimal multiples and submultiples ranging from $10^{24}$ to $10^{-24}$ are provided for use with the SI units. The names and symbols of these multiple and sub-multiple prefixes are presented in Table 7.

The SI prefixes refer strictly to powers of 10. They should not be used to indicate powers of 2 (for example, one kilobit represents 1000 bits and not 1024 bits). The names and symbols for prefixes to be used with powers of 2 are recommended as follows:

| | | |
|---|---|---|
| kibi | Ki | $2^{10}$ |
| mebi | Mi | $2^{20}$ |
| gibi | Gi | $2^{30}$ |
| tebi | Ti | $2^{40}$ |
| pebi | Pi | $2^{50}$ |
| exbi | Ei | $2^{60}$ |
| zebi | Zi | $2^{70}$ |
| yobi | Yi | $2^{80}$ |

Prefix symbols are printed in upright typeface, as are unit symbols, regardless of the typeface used in the surrounding text and are attached to unit symbols without a space between the prefix symbol and the unit symbol. With the exception of da (deca), h (hecto) and k (kilo), all multiple prefix symbols are upper-case letters and all sub-multiple prefix symbols are lowercase letters. All prefix names are printed in lowercase letters, except at the beginning of a sentence.

**Table 7. SI prefixes**

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

The grouping formed by a prefix symbol attached to a unit symbol constitutes a new inseparable unit symbol (forming a multiple or sub-multiple of the unit concerned) that can be raised to a positive or negative power and that can be combined with other unit symbols to form compound unit symbols.

*Examples*: pm (picometre), mmol (millimole), GΩ (gigaohm), THz (terahertz)

$2.3\ \mathrm{cm}^3 = 2.3\ (\mathrm{cm})^3 = 2.3\ (10^{-2}\ \mathrm{m})^3 = 2.3 \times 10^{-6}\ \mathrm{m}^3$

$1\ \mathrm{cm}^{-1} = 1\ (\mathrm{cm})^{-1} = 1\ (10^{-2}\ \mathrm{m})^{-1} = 10^2\ \mathrm{m}^{-1} = 100\ \mathrm{m}^{-1}$ .

Similarly prefix names are also inseparable from the unit names to which they are attached. Thus, for example, millimetre, micropascal and meganewton are single words.

Compound prefix symbols, i.e. prefix symbols formed by the juxtaposition of two or more prefix symbols, are not permitted. This rule also applies to two or more compound prefix names.

Prefix symbols can neither stand alone nor be attached to the number 1, the symbol for the unit one. Similarly, prefix names cannot be attached to the name of the unit one, that is, to the word “one”.

The kilogram is the only coherent SI unit, whose name and symbol, for historical reasons, include a prefix. Names and symbols for decimal multiples and sub-multiples of the unit of mass are formed by attaching prefix names and symbols to the unit name “gram” and the unit symbol “g” respectively. For example, $10^{-6}$ kg is written as milligram, mg, not as microkilogram, µkg.

# 4 Non-SI units that are accepted for use with the SI

The SI provides the internationally agreed reference in terms of which all other units are defined. The coherent SI units have the important advantage that unit conversions are not required when inserting particular values for quantities into quantity equations.

Nonetheless it is recognized that some non-SI units are widely used and are expected to continue to be used for many years. Therefore, the CIPM has accepted some non-SI units for use with the SI; these are listed in Table 8. If these units are used it should be understood that some advantages of the SI are lost. The SI prefixes can be used with several of these units, but not, for example, with the non-SI units of time.

The gal (symbol: Gal) is a non SI unit of acceleration employed in geodesy and geophysics to express acceleration due to gravity

1 Gal = 1 cm $s^{-2}$
= $10^{-2}$ m $s^{-2}$

**Table 8. Non-SI units accepted for use with the SI Units**

| Quantity | Name of unit | Symbol for unit | Value in SI units |
|---|---|---|---|
| time | minute | min | 1 min = 60 s |
| | hour | h | 1 h = 60 min = 3600 s |
| | day | d | 1 d = 24 h = 86 400 s |
| length | astronomical unit (*a*) | au | 1 au = 149 597 870 700 m |
| plane and phase angle | degree | $^\circ$ | $1^\circ = (\pi/180)$ rad |
| | minute | ′ | $1' = (1/60)^\circ = (\pi/10\,800)$ rad |
| | second (*b*) | ″ | $1'' = (1/60)' = (\pi/648\,000)$ rad |
| area | hectare (*c*) | ha | 1 ha = 1 $hm^2$ = $10^4$ $m^2$ |
| volume | litre (*d*) | l, L | 1 l = 1 L = 1 $dm^3$ = $10^3$ $cm^3$ = $10^{-3}$ $m^3$ |
| mass | tonne (*e*) | t | 1 t = $10^3$ kg |
| | dalton (*f*) | Da | 1 Da = 1.660 539 040 (20) × $10^{-27}$ kg |
| energy | electronvolt (*g*) | eV | 1 eV = 1.602 176 634 × $10^{-19}$ J |
| logarithmic ratio quantities | neper (*h*) | Np | see text |
| | bel (*h*) | B | |
| | decibel (*h*) | dB | |

(*a*) As decided at the XXVIII General Assembly of the International Astronomical Union (Resolution B2, 2012).

(*b*) For some applications such as in astronomy, small angles are measured in arcseconds (i.e. seconds of plane angle), denoted as or ″, milliarcseconds, microarcseconds and picoarcseconds, denoted mas, µas and pas, respectively, where arcsecond is an alternative name for second of plane angle.

(*c*) The unit hectare and its symbol ha, were adopted by the CIPM in 1879 (PV, 1879, 41). The hectare is used to express land area.

(*d*) The litre and the symbol lower-case l, were adopted by the CIPM in 1879 (PV, 1879, 41). The alternative symbol, capital L, was adopted by the 16th CGPM (1979, Resolution 6; CR, 101 and *Metrologia*, 1980, **16**, 56-57) in order to avoid the risk of confusion between the letter l (el) and the numeral 1 (one).

(*e*) The tonne and its symbol t, were adopted by the CIPM in 1879 (PV, 1879, 41). This unit is sometimes referred to as “metric ton” in some English-speaking countries.

(*f*) 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. This value of the dalton is the value recommended in the CODATA 2014 adjustment. It will be updated in the CODATA 2018 adjustment to take into accound the, now fixed, 2017 value of the Planck constant *h*. This will reduce the 2014 uncertainty by an order of magnitude.

(*g*) The electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of one volt in vacuum. The electronvolt is often combined with the SI prefixes.

(*h*) In using these units it is important that the nature of the quantity be specified and that any reference value used be specified.

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Table 8 also includes the units of logarithmic ratio quantities, the neper, bel and decibel. They are used to convey information on the nature of the logarithmic ratio quantity concerned. The neper, Np, is used to express the values of quantities whose numerical values are based on the use of the neperian (or natural) logarithm, $\ln = \log_e$. The bel and the decibel, B and dB, where 1 dB = (1/10) B, are used to express the values of logarithmic ratio quantities whose numerical values are based on the decadic logarithm, $\lg = \log_{10}$. The statement $L_X = m$ dB = $(m/10)$ B (where $m$ is a number) is interpreted to mean that $m = 10 \lg(X/X_0)$. The units neper, bel and decibel have been accepted by the CIPM for use with the International System, but are not SI units.

There are many more non-SI units, which are either of historical interest, or are still used in specific fields (for example, the barrel of oil) or in particular countries (the inch, foot and yard). The CIPM can see no case for continuing to use these units in modern scientific and technical work. However, it is clearly a matter of importance to be able to recall the relation of these units to the corresponding SI units and this will continue to be true for many years.

# 5 Writing unit symbols and names, and expressing the values of quantities

## 5.1 The use of unit symbols and names

General principles for the writing of unit symbols and numbers were first given by the 9th CGPM (1948, Resolution 7). These were subsequently elaborated by ISO, IEC and other international bodies. As a consequence, there now exists a general consensus on how unit symbols and names, including prefix symbols and names as well as quantity symbols should be written and used, and how the values of quantities should be expressed. Compliance with these rules and style conventions, the most important of which are presented in this chapter, supports the readability of scientific and technical papers.

## 5.2 Unit symbols

Unit symbols are printed in upright type regardless of the type used in the surrounding text. They are printed in lower-case letters unless they are derived from a proper name, in which case the first letter is a capital letter.

An exception, adopted by the 16th CGPM (1979, Resolution 6), is that either capital L or lower-case l is allowed for the litre, in order to avoid possible confusion between the numeral 1 (one) and the lower-case letter l (el).

A multiple or sub-multiple prefix, if used, is part of the unit and precedes the unit symbol without a separator. A prefix is never used in isolation and compound prefixes are never used.

Unit symbols are mathematical entities and not abbreviations. Therefore, they are not followed by a period except at the end of a sentence, and one must neither use the plural nor mix unit symbols and unit names within one expression, since names are not mathematical entities.

In forming products and quotients of unit symbols the normal rules of algebraic multiplication or division apply. Multiplication must be indicated by a space or a half-high (centred) dot (·), since otherwise some prefixes could be misinterpreted as a unit symbol. Division is indicated by a horizontal line, by a solidus (oblique stroke, /) or by negative exponents. When several unit symbols are combined, care should be taken to avoid ambiguities, for example by using brackets or negative exponents. A solidus must not be used more than once in a given expression without brackets to remove ambiguities.

It is not permissible to use abbreviations for unit symbols or unit names, such as sec (for either s or second), sq. mm (for either $\mathrm{mm}^2$ or square millimetre), cc (for either $\mathrm{cm}^3$ or cubic centimetre), or mps (for either m/s or metre per second). The use of the correct symbols for SI units, and for units in general, as listed in earlier chapters of this brochure, is mandatory. In this way ambiguities and misunderstandings in the values of quantities are avoided.

## 5.3 Unit names

Unit names are normally printed in upright type and they are treated like ordinary nouns. In English, the names of units start with a lower-case letter (even when the symbol for the unit begins with a capital letter), except at the beginning of a sentence or in capitalized material such as a title. In keeping with this rule, the correct spelling of the name of the unit with the symbol °C is “degree Celsius” (the unit degree begins with a lower-case d and the modifier Celsius begins with an upper-case C because it is a proper name).

Although the values of quantities are normally expressed using symbols for numbers and symbols for units, if for some reason the unit name is more appropriate than the unit symbol, the unit name should be spelled out in full.

When the name of a unit is combined with the name of a multiple or sub-multiple prefix, no space or hyphen is used between the prefix name and the unit name. The combination of prefix name and unit name is a single word (see chapter 3).

When the name of a derived unit is formed from the names of individual units by juxtaposition, either a space or a hyphen is used to separate the names of the individual units.

## 5.4 Rules and style conventions for expressing values of quantities

### 5.4.1 Value and numerical value of a quantity, and the use of quantity calculus

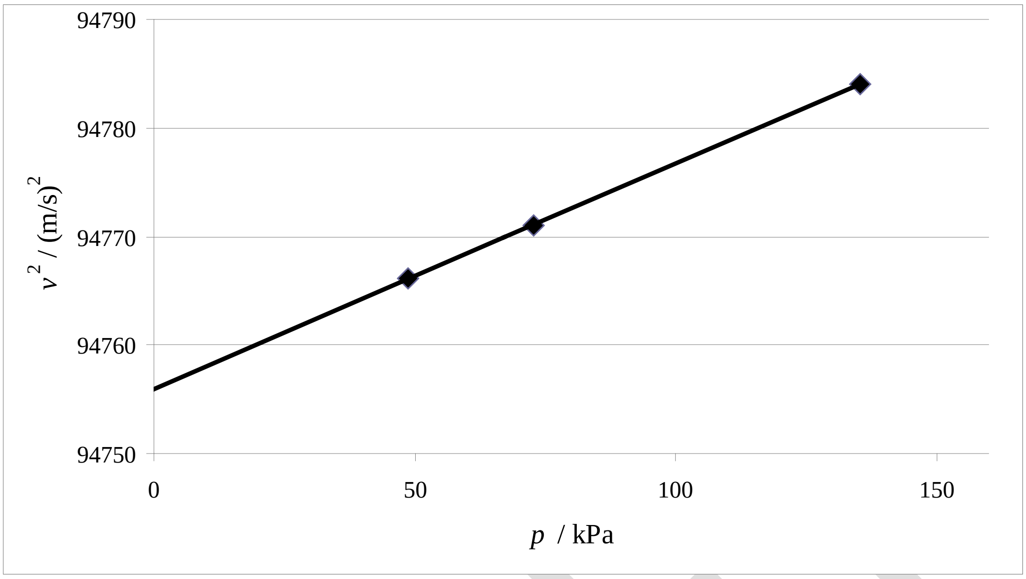
Symbols for quantities are generally single letters set in an italic font, although they may be qualified by further information in subscripts or superscripts or in brackets. For example, $C$ is the recommended symbol for heat capacity, $C_{\mathrm{m}}$ for molar heat capacity, $C_{\mathrm{m},\,p}$ for molar heat capacity at constant pressure, and $C_{\mathrm{m},V}$ for molar heat capacity at constant volume.

Recommended names and symbols for quantities are listed in many standard references, such as the ISO/IEC 80000 series *Quantities and units*, the IUPAP SUNAMCO Red Book *Symbols, Units and Nomenclature in Physics* and the IUPAC Green Book *Quantities, Units and Symbols in Physical Chemistry*. However, symbols for quantities are recommendations (in contrast to symbols for units, for which the use of the correct form is mandatory). In certain circumstances authors may wish to use a symbol of their own choice for a quantity, for example to avoid a conflict arising from the use of the same symbol for two different quantities. In such cases, the meaning of the symbol must be clearly stated. However, neither the name of a quantity, nor the symbol used to denote it, should imply any particular choice of unit.

Symbols for units are treated as mathematical entities. In expressing the value of a quantity as the product of a numerical value and a unit, both the numerical value and the unit may be treated by the ordinary rules of algebra. This procedure is described as the use of quantity calculus, or the algebra of quantities. For example, the equation $p$ = 48 kPa may equally be written as $p$/kPa = 48. It is common practice to write the quotient of a quantity and a unit in this way for a column heading in a table, so that the entries in the table are simply numbers. For example, a table of the velocity squared versus pressure may be formatted as shown below.

| $p$/kPa | $v^2/(\mathrm{m/s})^2$ |
|---|---|
| 48.73 | 94766 |
| 72.87 | 94771 |
| 135.42 | 94784 |

The axes of a graph may also be labelled in this way, so that the tick marks are labelled only with numbers, as in the graph below.



### 5.4.2 Quantity symbols and unit symbols

Unit symbols must not be used to provide specific information about the quantity and should never be the sole source of information on the quantity. Units are never qualified by further information about the nature of the quantity; any extra information on the nature of the quantity should be attached to the quantity symbol and not to the unit symbol.

For example:
The maximum electric potential difference is $U_{\mathrm{max}} = 1000$ V but not $U = 1000\ \mathrm{V}_{\mathrm{max}}$.
The mass fraction of copper in the sample of silicon is $w(\mathrm{Cu}) = 1.3 \times 10^{-6}$ but not $1.3 \times 10^{-6}$ w/w.
$m = 12.3$ g where $m$ is used as a symbol for the quantity mass, but $\varphi = 30°\ 22'\ 8''$, where $\varphi$ is used as a symbol for the quantity plane angle.

### 5.4.3 Formatting the value of a quantity

The numerical value always precedes the unit and a space is always used to separate the unit from the number. Thus the value of the quantity is the product of the number and the unit. The space between the number and the unit is regarded as a multiplication sign (just as a space between units implies multiplication). The only exceptions to this rule are for the unit symbols for degree, minute and second for plane angle, °, ′ and ″, respectively, for which no space is left between the numerical value and the unit symbol.

This rule means that the symbol °C for the degree Celsius is preceded by a space when one expresses values of Celsius temperature $t$.

t = 30.2 °C,
but not $t$ = 30.2°C,
nor $t$ = 30.2° C

Even when the value of a quantity is used as an adjective, a space is left between the numerical value and the unit symbol. Only when the name of the unit is spelled out would the ordinary rules of grammar apply, so that in English a hyphen would be used to separate the number from the unit.

a 10 kΩ resistor
a 35-millimeter film

In any expression, only one unit is used. An exception to this rule is in expressing the values of time and of plane angles using non-SI units. However, for plane angles it is generally preferable to divide the degree decimally. It is therefore preferable to write 22.20° rather than 22° 12′, except in fields such as navigation, cartography, astronomy, and in the measurement of very small angles.

$l$ = 10.234 m, but not
$l$ = 10 m 23.4 cm

### 5.4.4 Formatting numbers, and the decimal marker

The symbol used to separate the integral part of a number from its decimal part is called the decimal marker. Following a decision by the 22nd CGPM (2003, Resolution 10), the decimal marker “shall be either the point on the line or the comma on the line.” The decimal marker chosen should be that which is customary in the language and context concerned.

If the number is between +1 and −1, then the decimal marker is always preceded by a zero.

–0.234, but not –.234

Following the 9th CGPM (1948, Resolution 7) and the 22nd CGPM (2003, Resolution 10), for numbers with many digits the digits may be divided into groups of three by a space, in order to facilitate reading. Neither dots nor commas are inserted in the spaces between groups of three. However, when there are only four digits before or after the decimal marker, it is customary not to use a space to isolate a single digit. The practice of grouping digits in this way is a matter of choice; it is not always followed in certain specialized applications such as engineering drawings, financial statements and scripts to be read by a computer.

43 279.168 29,
but not 43,279.168,29

either 3279.1683
or 3 279.168 3

For numbers in a table, the format used should not vary within one column.

### 5.4.5 Expressing the measurement uncertainty in the value of a quantity

The uncertainty associated with an estimated value of a quantity should be evaluated and expressed in accordance with the document JCGM 100:2008 (GUM 1995 with minor corrections), *Evaluation of measurement data - Guide to the expression of uncertainty in measurement*. The standard uncertainty associated with a quantity $x$ is denoted by $u(x)$. One convenient way to represent the standard uncertainty is given in the following example:

$$m_\mathrm{n} = 1.674\,927\,471\,(21) \times 10^{-27}\ \mathrm{kg},$$

where $m_\mathrm{n}$ is the symbol for the quantity (in this case the mass of a neutron) and the number in parentheses is the numerical value of the standard uncertainty of the estimated value of $m_\mathrm{n}$ referred to the last digits of the quoted value; in this case $u(m_\mathrm{n}) = 0.000\,000\,21 \times 10^{-27}$ kg. If an expanded uncertainty $U(x)$ is used in place of the standard uncertainty $u(x)$, then the coverage probability $p$ and the coverage factor $k$ must be stated.

### 5.4.6 Multiplying or dividing quantity symbols, the values of quantities, or numbers

Examples:

$F = ma$ for force equals mass times acceleration

When multiplying or dividing quantity symbols any of the following methods may be used:

$ab$, $a\ b$, $a \cdot b$, $a \times b$, $a/b$, $\frac{a}{b}$, $a\ b^{-1}$.

(53 m/s) × 10.2 s
or (53 m/s)(10.2 s)

When multiplying the value of quantities either a multiplication sign × or brackets should be used, not a half-high (centred) dot. When multiplying numbers only the multiplication sign × should be used.

25 × 60.5
but not 25 · 60.5

(20 m)/(5 s) = 4 m/s

When dividing the values of quantities using a solidus, brackets are used to avoid ambiguity.

(a/b)/c, not a/b/c

$n = 1.51$,
but not $n = 1.51 \times 1$,
where $n$ is the quantity symbol for refractive index.

### 5.4.7 Stating quantity values being pure numbers

As discussed in Section 2.3.3, values of quantities with unit one, are expressed simply as numbers. The unit symbol 1 or unit name “one” are not explicitly shown. SI prefix symbols can neither be attached to the symbol 1 nor to the name “one”, therefore powers of 10 are used to express particularly large or small values.

Quantities that are ratios of quantities of the same kind (for example length ratios and amount fractions) have the option of being expressed with units (m/m, mol/mol) to aid the understanding of the quantity being expressed and also allow the use of SI prefixes, if this is desirable (µm/m, nmol/mol). Quantities relating to counting do not have this option, they are just numbers.

The internationally recognized symbol % (percent) may be used with the SI. When it is used, a space separates the number and the symbol %. The symbol % should be used rather than the name “percent”. In written text, however, the symbol % generally takes the meaning of “parts per hundred”. Phrases such as “percentage by mass”, “percentage by volume”, or “percentage by amount of substance” shall not be used; the extra information on the quantity should instead be conveyed in the description and symbol for the quantity.

The term “ppm”, meaning $10^{-6}$ relative value, or 1 part in $10^{6}$, or parts per million, is also used. This is analogous to the meaning of percent as parts per hundred. The terms “parts per billion” and “parts per trillion” and their respective abbreviations “ppb” and “ppt”, are also used, but their meanings are language dependent. For this reason the abbreviations ppb and ppt should be avoided.

In English-speaking countries, a billion is now generally taken to be $10^{9}$ and a trillion to be $10^{12}$; however, a billion may still sometimes be interpreted as $10^{12}$ and a trillion as $10^{18}$. The abbreviation ppt is also sometimes read as parts per thousand, adding further confusion.

### 5.4.8 Plane angles, solid angles and phase angles

The coherent SI unit for the plane angle and the phase angle is radian, unit symbol rad and that for the solid angle is steradian, unit symbol sr.

The plane angle, expressed in radian, between two lines originating from a common point is the length of circular arc $s$, swept out between the lines by a radius vector of length $r$ from the common point divided by the length of the radius vector, $\theta = s/r$ rad. The phase angle (often just referred to as the “phase”) is the argument of any complex number. It is the angle between the positive real axis and the radius of the polar representation of the complex number in the complex plane.

One radian corresponds to the angle for which $s = r$, thus 1 rad = 1. The measure of the right angle is exactly equal to the number $\pi/2$.

A historical convention is the degree. The conversion between radians and degrees follows from the relation $360° = 2\pi$ rad. Note that the degree, with the symbol °, is not a unit of the SI.

The solid angle, expressed in steradian, corresponds to the ratio between an area $A$ of the surface of a sphere of radius $r$ and the squared radius, $\Omega = A/r^2$ sr. One steradian corresponds to the solid angle for which $A = r^2$, thus 1 sr = 1.

The units rad and sr correspond to ratios of two lengths and two squared lengths, respectively. However, it shall be emphasized that rad and sr must only be used to express angles and solid angles, but not to express ratios of lengths and squared lengths in general.

When the SI was adopted by the 11th CGPM in 1960, a category of “supplementary units” was created to accommodate the radian and steradian. Decades later, The CGPM decided (1) “to interpret the supplementary units in the SI, namely the radian and the steradian, as dimensionless derived units, the names and symbols of which may, but need not, be used in expressions for other SI derived units, as is convenient”, and (2) to eliminate the separate class of supplementary units (Resolution 8 of the 20th CGPM (1995)).

# Appendix 1. Decisions of the CGPM and the CIPM

(to be completed)

# Appendix 2. Practical realization of the definitions of some important units

Appendix 2 is published in electronic form only, and is available on the BIPM website at www.bipm.org/en/publications/mises-en-pratique/.

# Appendix 3. Units for photochemical and photobiological quantities

Appendix 3 is published in electronic form only, and is available on the BIPM website at : www.bipm.org/en/measurement-units/rev-si/#communication.

# Appendix 4. Historical notes on the development of the International System of Units and its base units

## Part 1. The historical development of the realization of SI units

Experimental methods used for the realization of units and which use equations of physics are known as primary methods. The essential characteristic of a primary method is that it allows a quantity to be measured in a particular unit directly from its definition by using only quantities and constants that themselves do not contain that unit.

Traditionally, a unit for a given quantity was taken to be a particular example of that quantity, which was chosen to provide numerical values of common measurements of a convenient size. Before the rise of modern science, units were necessarily defined in terms of material artefacts, notably the metre and kilogram for length and mass, or the property of a particular object, namely the rotation of the earth for the second. Even at the origin of the metric system at the end of the 18th century it was recognized that a more desirable definition of a unit of length for example would be one based on a universal property of nature such as the length of a pendulum beating seconds. Such a definition would be independent of time and place and would in principle accessible all over the world. At the time, practical considerations resulted in the simpler, artefact definitions for the metre and the kilogram and the second remained linked to the rotation of the Earth. It was only in 1960 that the first non-material definition was adopted, namely the wavelength of a specified optical radiation for the metre.

Since then, definitions of the ampere, kelvin, mole and candela have been adopted that do not refer to material artefacts. In the case of the ampere it refers to a specified electric current required to produce a given electromagnetic force and, in the case of the kelvin, to a particular thermodynamic state, namely the triple point of water. Even the atomic definition of the second was in terms of a specified transition of the the caesium atom. The kilogram has always stood out as the one unit that had resisted the transformation from an artefact. The definition that opened the way to real universality was that of the metre in 1983.

This definition implied, although it did not state, a fixed numerical value for the speed of light. The definition was worded, however, in the traditional form and stated essentially that the metre was the distance travelled by light in a specified time. In this way it reflected the other definitions of the base units of the SI each of which has the same form, for example “the ampere is the current which…” and “the kelvin is a fraction of a specified temperature”. Such definitions can be called explicit unit definitions.

Although these definitions meet many of the requirements for universality and accessibility, and a variety of realizations are often possible, they nevertheless constrain practical realizations to experiments that are directly or indirectly linked to the particular conditions or states specified in each definition. In consequence, the accuracy of realization of such definitions can never be better than the accuracy of realization of the particular conditions or states specified in the definitions.

This is a particular problem with the present definition of the second, which is based on a microwave transition of an atom of caesium. Frequencies of optical transitions of different atoms or ions are now demonstrably more reproducible, by some orders of magnitude, than the defined frequency of caesium.

In the present definition of the SI based on the set of defining constants, instead of each definition specifying a particular condition or state, which sets a fundamental limit to the accuracy of realization, any convenient equation of physics that links the particular constant or constants to the quantity we want to measure may be used. This is a much more general way of defining the basic units of measurement. It is one that is not limited by today’s science or technology as future developments may lead to as yet unknown equations that could result in different ways of realizing units with a much higher accuracy. When defined in this way, there is, in principle, no limit to the accuracy with which a unit can be realized. The exception remains the definition of the second in which the original microwave transition of caesium remains, for the time being, the basis of the definition.

The difference between an explicit unit and an explicit constant definition can be clearly illustrated using the two previous definitions of the metre that depended upon a fixed numerical value of the speed of light and secondly the two definitions of the kelvin. The original 1983 definition of the metre states, in effect, that “the metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second”. The new definition simply states that the metre is defined by taking the constant that defines the second, the specified caesium frequency and the fixed numerical value of the speed of light expressed in units $\mathrm{m{\cdot}s^{-1}}$. We can thus use any equation of physics including, of course, that indicated by the former definition, the time taken to travel the given distance which is used for astronomical distances, but also the simple equation relating frequency and wavelength to the speed of light. The former definition of the kelvin based on a fixed numerical value for the temperature of the triple point of water requires ultimately a measurement at the triple point of water. The new definition, based on the fixed numerical value for the Boltzmann constant, is much more general in that any thermodynamic equation in which $k$ appears can in principle be used to determine a thermodynamic temperature at any point on the temperature scale. For example, by determining the total radiant exitance of a black body at temperature $T$, equal to $(2\pi^5 k^4/15c^2h^3)\,T^4$, in $\mathrm{Wm^{-2}}$ we can determine $T$ directly.

For the kilogram, the unit whose definition has undergone the most fundamental change, realization can be through any equation of physics that links mass, the Planck constant, the velocity of light and the caesium frequency. One such equation is that which describes the operation of an electro-mechanical balance, previously known as a watt balance, more recently known as a Kibble[2] balance. With this apparatus, a mechanical power, measured in terms of a mass, $m$, the local acceleration due to gravity, $g$, and a velocity, $v$, can be measured in terms of an electrical power measured in terms of an electric current and voltage measured in terms of the quantum Hall and Josephson effects respectively. The resulting equation is $mgv = \mathrm{C}h$ where C is a calibration constant that includes measured frequencies and $h$ is Planck's constant.

Another method that can be used for a primary realization of the kilogram is through the determination of the number of atoms in a silicon sphere and using the equation:

$$m = \frac{8V}{a_0^3}\frac{2R_\infty h}{c\alpha^2}\frac{m_{Si}}{m_e}$$

with the mass $m$ and volume $V$ of the sphere (about 1 kg), lattice parameter $a_0$, Rydberg constant $R_\infty$, fine structure constant $\alpha$, and the masses of a silicon atom (averaged over the three isotopes used for the sphere) $m_{\mathrm{Si}}$, and the electron $m_{\mathrm{e}}$, respectively. The first fraction corresponds to the number of atoms in the sphere, the second to the electron mass and the third fraction is the ratio of the mass of the (isotopically averaged) silicon atom to the electron mass.

Another possibility for measuring mass through the new definition, but this time at the microscopic level, is through measurements of atomic recoil using the relation that includes $h/m$.

All these provide a striking illustration of the generality of the new way of defining units. Detailed information on the current realization of the base and other units is given on the BIPM website.

## Part 2. The historical development of the International System

The 9th CGPM (1948, Resolution 6; CR 64) instructed the CIPM:

- to study the establishment of a complete set of rules for units of measurement;
- to find out for this purpose, by official enquiry, the opinion prevailing in scientific, technical and educational circles in all countries;
- to make recommendations on the establishment of a *practical system of units of measurement* suitable for adoption by all signatories to the *Metre Convention* .

The same CGPM also laid down, in Resolution 7 (CR 70), 'general principles for the writing of unit symbols' and listed some coherent derived units that were assigned special names.

The 10th CGPM (1954, Resolution 6; CR 80) adopted as base quantities and units for this practical system the following six quantities: length, mass, time, electric current, thermodynamic temperature and luminous intensity, as well as the six corresponding base units: metre, kilogram, second, ampere, kelvin and candela. After a lengthy discussion between physicists and chemists, the 14th CGPM (1971, Resolution 3, CR 78 and *Metrologia* 1972, **8**, 36) added amount of substance, unit mole, as the seventh base quantity and unit.

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[2] To recognize Bryan Kibble's invention of the watt balance

The 11th CGPM (1960, Resolution 12; CR 87) adopted the name *Système international d'unités*, with the international abbreviation *SI*, for this practical system of units and laid down rules for prefixes, derived units and the former supplementary units, as well as other matters; it thus established a comprehensive specification for units of measurement. Subsequent meetings of the CGPM and the CIPM have added to and modified the original structure of the SI to take account of advances in science and of the changing needs of users.

The historical sequence that led to these important decisions may be summarized as follows.

- The creation of the decimal metric system at the time of the French Revolution and the subsequent deposition of two platinum standards representing the metre and the kilogram, on 22 June 1799, in the *Archives de la République* in Paris, which can be seen as the first step that led to the present International System of Units.
- In 1832, Gauss strongly promoted the application of this metric system, together with the second defined in astronomy, as a coherent system of units for the physical sciences. Gauss was the first to make absolute measurements of the earth's magnetic field in terms of a decimal system based on the *three mechanical units* millimetre, gram and second for, respectively, the quantities length, mass and time. In later years Gauss and Weber extended these measurements to include other electrical phenomena.
- These applications in the field of electricity and magnetism were further extended in the 1860s under the active leadership of Maxwell and Thomson through the British Association for the Advancement of Science (BAAS). They formulated the requirement for a *coherent system of units* with *base units* and *derived units*. In 1874 the BAAS introduced the *CGS system*, a three-dimensional coherent unit system based on the three mechanical units centimetre, gram and second, using prefixes ranging from micro to mega to express decimal sub-multiples and multiples. The subsequent development of physics as an experimental science was largely based on this system.
- The sizes of the coherent CGS units in the fields of electricity and magnetism proved to be inconvenient, so in the 1880s the BAAS and the International Electrical Congress, predecessor of the International Electrotechnical Commission (IEC), approved a mutually coherent set of *practical units*. Among them were the ohm for electrical resistance, the volt for electromotive force, and the ampere for electric current.
- After the signing of the Metre Convention on 20 May 1875, which created the BIPM and established the CGPM and the CIPM, work began on establishing new international prototypes for the metre and the kilogram. In 1889 the 1st CGPM sanctioned the international prototypes for the metre and the kilogram. Together with the astronomical second as the unit of time, these units constituted a three-dimensional mechanical unit system similar to the CGS system, but with the base units metre, kilogram and second, known as the *MKS system*.
- In 1901 Giorgi showed that it is possible to combine the mechanical units of this MKS system with the practical electrical units to form a coherent four-dimensional system by adding to the three base units a fourth unit, of an electrical nature such as the ampere or the ohm, and also rewriting the equations occurring in

electromagnetism in the so-called rationalized form. Giorgi's proposal opened the path to a number of new developments.

- After the revision of the Metre Convention by the 6th CGPM (1921), which extended the scope and responsibilities of the BIPM to other fields in physics and the subsequent creation of the Consultative Committee for Electricity (CCE) by the 7th CGPM (1927), the Giorgi proposal was thoroughly discussed by the IEC, the International Union of Pure and Applied Physics (IUPAP) and other international organizations. This led the CCE to propose in 1939 the adoption of a four-dimensional system based on the metre, kilogram, second and ampere, the MKSA system, a proposal approved by the CIPM in 1946.

- Following an international enquiry by the BIPM, which began in 1948, the 10th CGPM (1954), approved the further introduction of the kelvin and the candela, as base units for thermodynamic temperature and luminous intensity, respectively. The name International System of Units, with the abbreviation SI, was given to the system by the 11th CGPM (1960). Rules for prefixes, derived units, the former supplementary units as well as other matters, were established, thus providing a comprehensive specification for all units of measurement.

- At the 14th CGPM (1971) a new base unit, the mole, symbol mol, was adopted for the quantity amount of substance. This followed a proposal from the International Organization for Standardization originating in a proposal from the Commission on Symbols, Units and Nomenclature (SUN Commission) of IUPAP, which was supported by the International Union for Pure and Applied Chemistry (IUPAC). This brought the number of base units of the SI to seven.

- Since then, extraordinary advances have been made in relating SI units to truly invariant quantities such as the fundamental constants of physics and the properties of atoms. Recognizing the importance of linking SI units to such invariant quantities, the 24th CGPM (2011), adopted the principles of a new definition of the SI based on using a set of seven such constants as references for the definitions. At the time of the 24th CGPM, experiments to determine their values in terms of the then base units were not completely consistent but by the time of the 26th CGPM (2018) this had been achieved and the new definition of the SI was adopted in Resolution 1. This is the basis of the definition presented in this brochure and it is the simplest and most fundamental way of defining the SI.

- The SI was previously defined in terms of seven base units and derived units defined as products of powers of the base units. The seven base units were chosen for historical reasons, as the metric system, later the SI, evolved and developed over the last 130 years. Their choice was not unique, but it has become established and familiar over the years, not only by providing a framework for describing the SI, but also for defining the derived units. This role for the base units continues in the present SI even though the SI itself is now defined in terms of the seven defining constants. In this brochure therefore, definitions of the seven base units can still be found but are henceforth based on the seven defining constants: the caesium hyperfine frequency $\Delta\nu_{\text{Cs}}$; the speed of light in vacuum $c$; the Planck constant $h$; elementary charge $e$; Boltzmann constant $k$; Avogadro constant $N_{\text{A}}$; and the luminous efficacy of a defined visible radiation $K_{\text{cd}}$.

The definitions of the seven base units can be related unambiguously to the numerical values of the seven defining constants. However, there is not a one-to-one relationship between the seven defining constants and the seven base units as many of the base units call upon more than one of the defining constants.

## Part 3. Historical perspective on the base units

### Unit of time, second

Before 1960, the unit of time the second, was defined as the fraction 1/86 400 of the mean solar day. The exact definition of "mean solar day" was left to astronomers. However measurements showed that irregularities in the rotation of the Earth made this an unsatisfactory definition. In order to define the unit of time more precisely, the 11th CGPM (1960, Resolution 9, CR, 86) adopted a definition given by the International Astronomical Union based on the tropical year 1900. Experimental work, however, had already shown that an atomic standard of time, based on a transition between two energy levels of an atom or a molecule, could be realized and reproduced much more accurately. Considering that a very precise definition of the unit of time is indispensable for science and technology, the 13th CGPM (1967-1968, Resolution 1, CR, 103 and *Metrologia*, 1968, **4**, 43) chose a new definition of the second referenced to the frequency of the ground state hyperfine transition in the caesium 133 atom. A revised more precise wording of this same definition now in terms of a fixed numerical value of the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, $\Delta\nu_{Cs}$, was adopted in Resolution 1 of the 26th CGPM (2018).

### Unit of length, metre

The 1889 definition of the metre, namely, the length of the international prototype of platinum-iridium, was replaced by the 11th CGPM (1960) using a definition based on the wavelength of the radiation corresponding to a particular transition in krypton 86. This change was adopted in order to improve the accuracy with which the definition of the metre could be realized, this being achieved using an interferometer with a travelling microscope to measure the optical path difference as the fringes were counted. In turn, this was replaced in 1983 by the 17th CGPM (Resolution 1, CR, 97, and *Metrologia*, 1984, **20**, 25) with a definition referenced to the distance that light travels in vacuum in a specified interval of time, as presented in 2.3.1. The original international prototype of the metre, which was sanctioned by the 1st CGPM in 1889 (CR, 34-38), is still kept at the BIPM under conditions specified in 1889. In order to make clear its dependence on the fixed numerical value of the speed of light, $c$, the wording of the definition was changed in Resolution 1 of the 26th CGPM (2018).

### Unit of mass, kilogram

The 1889 definition of the kilogram was simply the mass of the international prototype of the kilogram, an artefact made of platinum-iridium. This was, and still is, kept at the BIPM under the conditions specified by the 1st CGPM (1889, CR, 34-38) when it sanctioned the prototype and declared that "this prototype shall henceforth be considered to be the unit of mass". Forty similar prototypes were made at about the same time and these were all machined and polished to have closely the same mass as the international prototype. At the 1st CGPM (1889), after calibration against the international prototype, most of these "national prototypes" were individually assigned to Member States, and some also to the

BIPM. The 3rd CGPM (1901, CR, 70), in a declaration intended to end the ambiguity in common usage concerning the use of the word “weight”, confirmed that “the kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram”. The complete version of these declarations appears on p. 70 of the above-mentioned CGPM proceedings.

By the time of the second verification of national prototypes in 1946 it was found that on average the masses of these prototypes were diverging from that of the international prototype. This was confirmed by the third verification carried out from 1989 to 1991, the median difference being about 25 micrograms for the set of original prototypes sanctioned by the 1st CGPM (1889). In order to assure the long-term stability of the unit of mass, to take full advantage of quantum electrical standards and to be of more utility to modern science, a new definition for the kilogram based on the value of a fundamental constant, for which purpose the Planck constant $h$ was chosen, was adopted by Resolution 1 of the 26th CGPM (2018).

## Unit of electric current, ampere

Electric units, called “international units”, for current and resistance were introduced by the International Electrical Congress held in Chicago in 1893 and definitions of the “international ampere” and “international ohm” were confirmed by the International Conference in London in 1908.

By the time of the 8th CGPM (1933) there was a unanimous desire to replace the “international units” by so-called “absolute units”. However because some laboratories had not yet completed experiments needed to determine the ratios between the international and absolute units, the CGPM gave authority to the CIPM to decide at an appropriate time both these ratios and the date at which the new absolute units would come into effect. The CIPM did so in 1946 (1946, Resolution 2, PV, **20**, 129-137), when it decided that the new units would come into force on 1 January 1948. In October 1948 the 9th CGPM approved the decisions taken by the CIPM. The definition of the ampere, chosen by the CIPM, was referenced to the force between parallel wires carrying an electric current and it had the effect of fixing the numerical value of the vacuum magnetic permeability $\mu_0$ (also called the magnetic constant). The numerical value of the vacuum electric permittivity $\varepsilon_0$ (also called the electric constant) then became fixed as a consequence of the new definition of the metre adopted in 1983.

However the 1948 definition of the ampere proved difficult to realize and practical quantum standards (based on Josephson and quantum-Hall effects), which link both the volt and the ohm to particular combinations of the Planck constant $h$ and elementary charge $e$, became almost universally used as a practical realization of the ampere through Ohm’s law (18th CGPM (1987), Resolution 6, CR 100). As a consequence, it became natural not only to fix the numerical value of $h$ to redefine the kilogram, but also to fix the numerical value of $e$ to redefine the ampere in order to bring the practical quantum electrical standards into exact agreement with the SI. The present definition based on a fixed numerical value for the elementary charge, $e$, was adopted in Resolution 1 of the 26th CGPM (2018).

### Unit of thermodynamic temperature, kelvin

The definition of the unit of thermodynamic temperature was given by the 10th CGPM (1954, Resolution 3; CR 79) which selected the triple point of water, $T_{\text{TPW}}$, as a fundamental fixed point and assigned to it the temperature 273.16 K, thereby defining the kelvin. The 13th CGPM (1967-1968, Resolution 3; CR, 104 and *Metrologia*, 1968, **4**, 43) adopted the name kelvin, symbol K, instead of “degree kelvin”, symbol ºK, for the unit defined in this way. However, the practical difficulties in realizing this definition, requiring a sample of pure water of well-defined isotopic composition and the development of new primary methods of thermometry, led to the adoption of a new definition of the kelvin based on a fixed numerical value of the Boltzmann constant $k$. The present definition, which removed both of these constraints, was adopted in Resolution 1 of the 26th CGPM (2018).

### Unit of amount of substance, mole

Following the discovery of the fundamental laws of chemistry, units called, for example, “gram-atom” and “gram molecule”, were used to specify amounts of chemical elements or compounds. These units had a direct connection with “atomic weights” and “molecular weights”, which are in fact relative atomic and molecular masses. The first compilations of “Atomic weights” were originally linked to the atomic weight of oxygen, which was, by general agreement, taken as being 16. Whereas physicists separated the isotopes in a mass spectrometer and attributed the value 16 to one of the isotopes of oxygen, chemists attributed the same value to the (slightly variable) mixture of isotopes 16, 17 and 18, which for them constituted the naturally occurring element oxygen. An agreement between the International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) brought this duality to an end in 1959-1960. Physicists and chemists had agreed to assign the value 12, exactly, to the so-called atomic weight, correctly referred to as the relative atomic mass $A_r$, of the isotope of carbon with mass number 12 (carbon 12, $^{12}C$). The unified scale thus obtained gives the relative atomic and molecular masses, also known as the atomic and molecular weights, respectively. This agreement is unaffected by the redefinition of the mole.

The quantity used by chemists to specify the amount of chemical elements or compounds is called “amount of substance”. Amount of substance, symbol $n$, is defined to be proportional to the number of specified elementary entities $N$ in a sample, the proportionality constant being a universal constant which is the same for all entities. The proportionality constant is the reciprocal of the Avogadro constant $N_A$, so that $n = N/N_A$. The unit of amount of substance is called the *mole*, symbol mol. Following proposals by the IUPAP, IUPAC and ISO, the CIPM developed a definition of the mole in 1967 and confirmed it in 1969, by specifying that the molar mass of carbon 12 should be exactly 0.012 kg/mol. This allowed the amount of substance $n_S(X)$ of any pure sample S of entity $X$ to be determined directly from the mass of the sample $m_S$ and the molar mass $M(X)$ of entity $X$, the molar mass being determined from its relative atomic mass $A_r$ (atomic or molecular weight) without the need for a precise knowledge of the Avogadro constant, by using the relations

$$n_S(X) = m_S/M(X), \text{ and } M(X) = A_r(X) \text{ g/mol}$$

Thus, this definition of the mole was dependent on the artefact definition of the kilogram.

The numerical value of the Avogadro constant defined in this way was equal to the number of atoms in 12 grams of carbon 12. However, because of recent technological advances, this number is now known with such precision that a simpler and more universal definition of the mole has become possible, namely, by specifying exactly the number of entities in one mole of any substance, thus fixing the numerical value of the Avogadro constant. This has the effect that the new definition of the mole and the value of the Avogadro constant are no longer dependent on the definition of the kilogram. The distinction between the fundamentally different quantities ‘amount of substance’ and ‘mass’ is thereby emphasized. The present definition of the mole based on a fixed numerical value for the Avogadro constant, $N_A$, was adopted in Resolution 1 of the 26th CGPM (2018).

### Unit of luminous intensity, candela

The units of luminous intensity, which were based on flame or incandescent filament standards in use in various countries before 1948, were replaced initially by the “new candle” based on the luminance of a Planckian radiator (a black body) at the temperature of freezing platinum. This modification had been prepared by the International Commission on Illumination (CIE) and by the CIPM before 1937 and the decision was promulgated by the CIPM in 1946. It was then ratified in 1948 by the 9th CGPM, which adopted a new international name for this unit, the *candela*, symbol cd; in 1954 the 10th CGPM established the candela as a base unit; In 1967 the 13th CGPM (Resolution 5, CR, 104 and *Metrologia*, 1968, **4**, 43-44) amended this definition.

In 1979, because of the difficulties in realizing a Planck radiator at high temperatures, and the new possibilities offered by radiometry, i.e. the measurement of optical radiation power, the 16th CGPM (1979, Resolution 3, CR, 100 and *Metrologia*,1980, **16**, 56) adopted a new definition of the candela.

The present definition of the candela uses a fixed numerical value for the luminous efficacy of monochromatic radiation of frequency 540 $\times 10^{12}$ Hz, $K_{cd}$, adopted in Resolution 1 of the 26th CGPM (2018).