**Bureau International
des Poids et Mesures**

The International System of Units (SI)

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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 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 objectives are to:

- represent the world-wide measurement community, aiming to maximize its uptake and impact,
- be a centre for scientific and technical collaboration between Member States, providing capabilities for international measurement comparisons on a shared-cost basis,
- be the coordinator of the world-wide measurement system, ensuring it gives comparable and internationally accepted measurement results.

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 attend the General Conference, which normally 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. 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 there were fifty nine Member States: 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, Ethiopia, Georgia, Ghana, Hong Kong (China), Jamaica, Kuwait, Latvia, Luxembourg, Malta, Mauritius, Moldova (Republic of), Mongolia, Namibia, North Macedonia, Oman, Panama, Paraguay, Peru, Philippines, Qatar, Seychelles, Sri Lanka, Sudan, Syrian Arab Republic, Tanzania (United Republic of), Uzbekistan, Viet Nam, Zambia, and Zimbabwe

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 Director's report 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 (Document CIPM-D-01, *Rules of procedure for the Consultative Committees (CCs) created by the CIPM, CC working groups and CC workshops*). 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 (Document CIPM-D-01, *Rules of procedure for the Consultative Committees (CCs) created by the CIPM, CC working groups and CC workshops*). 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 γ-rays, electrons), Section II (Measurement of radionuclides), Section III (Neutron measurements), Section IV (α-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 in 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), a 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.

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.

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Preface to the 9th edition

The International System of Units, the SI, has been used around the world as the preferred system of units, the basic language for science, technology, industry and trade since it was established in 1960 by a resolution at the 11th meeting of the Conférence Générale des Poids et Mesures, the CGPM (known in English as the General Conference on Weights and Measures).

This brochure is published by the Bureau International des Poids et Mesures, the BIPM (known in English as the International Bureau of Weights and Measures) to promote and explain the SI. It lists the most significant Resolutions of the CGPM and decisions of the Comité International des Poids et Mesures, the CIPM (known in English as the International Committee on Weights and Measures) that concern the metric system going back to the 1st meeting of the CGPM in 1889.

The SI has always been a practical and dynamic system that has evolved to exploit the latest scientific and technological developments. In particular, the tremendous advances in atomic physics and quantum metrology made over the last 50 years have enabled the definitions of the second, the metre, and the practical representation of the electrical units to take advantage of atomic and quantum phenomena to achieve levels of accuracy for realizing the respective units limited only by our technical capability and not by the definitions themselves. These advances in science together with developments in measurement technology have enabled changes to the SI which have been promoted and explained in the previous editions of this brochure.

This 9th edition of the SI brochure has been prepared following the adoption by the 26th meeting of the CGPM of a set of far-reaching changes. The meeting introduced a new approach to articulating the definitions of the units in general, and of the seven base units in particular, by fixing the numerical values of seven “defining” constants. Among them are fundamental constants of nature such as the Planck constant and the speed of light, so that the definitions are based on and represent our present understanding of the laws of physics. For the first time, a complete set of definitions is available that does not make reference to any artefact standards, material properties or measurement descriptions. These changes enable the realization of all units with an accuracy that is ultimately limited only by the quantum structure of nature and our technical abilities but not by the definitions themselves. Any valid equation of physics relating the defining constants to a unit can be used to realize the unit thus creating opportunities for innovation, realization everywhere with increasing accuracy as technology proceeds. Thus, this redefinition marks a significant and historic step forward.

The changes were agreed by the CGPM in November 2018 with effect from May 20th 2019, a date chosen because it is World Metrology Day, the day when the Metre Convention was signed in 1875. Whilst the future impact of the changes will be far reaching, great attention has been paid to ensure that these definitions are consistent with those in place at the time the change was implemented.

We draw attention to the fact that since its establishment in 1960, the International System of Units has always been referred to as “the SI” in its shortened form. This principle has been maintained in the eight previous editions of this brochure and was reaffirmed in Resolution 1 adopted at the 26th meeting of the CGPM, which also confirmed that the title of this brochure is simply “The International System of Units”. This consistency of reference to the SI reflects the efforts of the CGPM and the CIPM to ensure the continuity of the values of measurements expressed in SI units through each change that has been made.

The text of this brochure has been prepared in order to provide a full description of the SI and to provide some historical background. It also has four appendices:

Appendix 1 reproduces, in chronological order, all of the decisions (Resolutions, Recommendations, Declarations) promulgated since 1889 by the CGPM and the CIPM on units of measurement and the International System of Units.

Appendix 2 is only available in an electronic version (www.bipm.org). It outlines the practical realization of the seven base units and other important units in each field. This appendix will be updated regularly to reflect improvements in the experimental techniques available for realizing the units.

Appendix 3 is only available in an electronic version (www.bipm.org). It discusses units for photochemical and photobiological quantities.

Appendix 4 provides some notes on the history of the development of the SI.

We conclude by expressing our thanks to the members of the Comité Consultatif des Unités of the CIPM, the CCU (known in English as the Consultative Committee for Units), who were responsible for drafting this brochure. Both the CCU and the CIPM have approved the final text.

March 2019

B. Inglis	J. Ullrich	M.J.T. Milton
President, CIPM	President, CCU	Director, BIPM

Note on the text

The 22nd meeting of the CGPM decided, in 2003, following a decision of the CIPM in 1997, that "the symbol for the decimal marker shall be either the point on the line or the comma on the line". Following this decision, and following custom in the two languages, in this edition the point on the line is used as a decimal marker in the English text, and a comma on the line is used in the French text. This has no implication for the translation of the decimal marker into other languages. Small spelling variations occur in the language of the English speaking countries (for instance, "metre" and "meter", "litre" and "liter"). In this respect, the English text presented here follows the ISO/IEC 80000 series *Quantities and units*. However, the symbols for SI units used in this brochure are the same in all languages.

Readers should note that the official record of the meetings of the CGPM and the sessions of the CIPM is that of the French text. This brochure provides the text in English, but when an authoritative reference is required or when there is doubt about the interpretation of the text the French should be used.

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 text "The BIPM and the Metre Convention" on page 117.

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 was 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 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 example, the speed of light in vacuum is a constant of nature, denoted by c, whose value in SI units is given by the relation c = 299 792 458 m/s where the numerical value is 299 792 458 and the unit is m/s.

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.

Quotients of SI units may be expressed using either a solidus (/) or a negative exponent (⁻)

For example,
m/s = m s^{-1}
mol/mol = mol mol^{-1}

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 quotients 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, $\Delta\nu_{Cs}$, 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_A, is 6.022 140 76 × 10^{23} mol^{-1},**
- **the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz, K_{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 Hz = s^{-1}, J = kg m^2 s^{-2}, C = A s, lm = cd m^2 m^{-2} = cd sr, and W = kg m^2 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	$\Delta\nu_{Cs}$	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_A	$6.022\ 140\ 76 \times 10^{23}$	$\mathrm{mol^{-1}}$
luminous efficacy	K_{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_{cd}, the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz refers to a special application. In principle, it 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 ε_0 is the vacuum electric permittivity or electric constant. Some theories predict a variation of α over time. The experimental limits of the maximum possible variation in α are so low, however, that any effect on foreseeable practical measurements can be excluded.

The Boltzmann constant k is a proportionality constant 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 Ω 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_{A} is a proportionality constant 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 540×10^{12} Hz, K_{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 540×10^{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 because it is useful and historically well established, noting also that the ISO/IEC 80000 series of Standards specify base and derived quantities which necessarily correspond to the SI base and derived units defined here.

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 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 1×10^{-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

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$$1\ \mathrm{A} = \frac{1}{(9\,192\,631\,770)(1.602\,176\,634 \times 10^{-19})}\ \Delta\nu_{\mathrm{Cs}}\, e \approx 6.789\,6868 \times 10^{8}\ \Delta\nu_{\mathrm{Cs}}\, e\,.$$

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 μ_0 (also known as the magnetic constant) to be exactly $4\pi \times 10^{-7}$ H m^{-1} = $4\pi \times 10^{-7}$ N 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 μ_0. As a result, μ_0 must be determined experimentally.

It also follows that since the vacuum electric permittivity ε_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 ε_0, Z_0, and Y_0 must now also be determined experimentally, and are affected by the same relative standard uncertainty as μ_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, μ_0 was equal to $4\pi \times 10^{-7}$ H/m with a relative standard uncertainty of 2.3×10^{-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 K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of *h*, *c* and $\Delta\nu_{Cs}$.

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

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

which is equal to

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

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_{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_{TPW}, the latter must now be determined experimentally. At the time of adopting the present definition T_{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:

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

The effect of this definition is that the mole is the amount of substance of a system that contains 6.022 140 76 × 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 4.5×10^{-10}.

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

$$M(\mathrm{X}) = A_r(\mathrm{X})\,[M(^{12}\mathrm{C})/12] = A_r(\mathrm{X})\,M_u$$

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

$$M(\mathrm{X}) = N_A\,m(\mathrm{X}) = N_A\,A_r(\mathrm{X})\,m_u\,.$$

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

$$M_u = N_A\,m_u\,.$$

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

This definition implies the exact relation K_{cd} = 683 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_{cd}, h and $\Delta\nu_{Cs}$:

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

which is equal to

$$1\ \mathrm{cd} = \frac{1}{(6.626\,070\,15 \times 10^{-34})\,(9\,192\,631\,770)^2\,683}\,(\Delta\nu_{\mathrm{Cs}})^2\,h\,K_{\mathrm{cd}}$$

$$\approx 2.614\,8305 \times 10^{10}\,(\Delta\nu_{\mathrm{Cs}})^2\,h\,K_{\mathrm{cd}}\,.$$

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^{-1}. 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_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 α, β, γ, δ, ε, ζ and η, 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 – necessary 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 units of flux and intensity 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	$\Omega = kg\ m^2\ s^{-3}\ A^{-2}$	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)]	$^oC = K$	
luminous flux	lumen	lm = cd sr [(g)]	cd sr
illuminance	lux	$lx = cd\ sr\ m^{-2}$	lm/m^2
activity referred to a radionuclide [(d, h)]	becquerel	$Bq = s^{-1}$	
absorbed dose, kerma	gray	$Gy = m^2\ s^{-2}$	J/kg
dose equivalent	sievert [(i)]	$Sv = m^2\ s^{-2}$	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*) In photometry the name steradian and the symbol sr are usually retained in expressions for units

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

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

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	m^2
volume	V	m^3
speed, velocity	v	$m\ s^{-1}$
acceleration	a	$m\ s^{-2}$
wavenumber	σ	m^{-1}
density, mass density	ρ	$kg\ m^{-3}$
surface density	ρ_A	$kg\ m^{-2}$
specific volume	v	$m^3\ kg^{-1}$
current density	j	$A\ m^{-2}$
magnetic field strength	H	$A\ m^{-1}$
amount of substance concentration	c	$mol\ m^{-3}$
mass concentration	ρ, γ	$kg\ m^{-3}$
luminance	L_v	$cd\ m^{-2}$

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	$kg\ m^{-1}\ s^{-1}$
moment of force	newton metre	N m	$kg\ m^2\ s^{-2}$
surface tension	newton per metre	$N\ m^{-1}$	$kg\ s^{-2}$
angular velocity, angular frequency	radian per second	$rad\ s^{-1}$	s^{-1}
angular acceleration	radian per second squared	$rad\ s^{-2}$	s^{-2}
heat flux density, irradiance	watt per square metre	$W\ m^{-2}$	$kg\ s^{-3}$
heat capacity, entropy	joule per kelvin	$J\ K^{-1}$	$kg\ m^2\ s^{-2}\ K^{-1}$
specific heat capacity, specific entropy	joule per kilogram kelvin	$J\ K^{-1}\ kg^{-1}$	$m^2\ s^{-2}\ K^{-1}$
specific energy	joule per kilogram	$J\ kg^{-1}$	$m^2\ s^{-2}$
thermal conductivity	watt per metre kelvin	$W\ m^{-1}\ K^{-1}$	$kg\ m\ s^{-3}\ K^{-1}$
energy density	joule per cubic metre	$J\ m^{-3}$	$kg\ m^{-1}\ s^{-2}$
electric field strength	volt per metre	$V\ m^{-1}$	$kg\ m\ s^{-3}\ A^{-1}$
electric charge density	coulomb per cubic metre	$C\ m^{-3}$	$A\ s\ m^{-3}$
surface charge density	coulomb per square metre	$C\ m^{-2}$	$A\ s\ m^{-2}$
electric flux density, electric displacement	coulomb per square metre	$C\ m^{-2}$	$A\ s\ m^{-2}$
permittivity	farad per metre	$F\ m^{-1}$	$kg^{-1}\ m^{-3}\ s^4\ A^2$
permeability	henry per metre	$H\ m^{-1}$	$kg\ m\ s^{-2}\ A^{-2}$
molar energy	joule per mole	$J\ mol^{-1}$	$kg\ m^2\ s^{-2}\ mol^{-1}$

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

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 2π. Ignoring this fact may cause an error of 2π. 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 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.

[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.

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.

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}

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)

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

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

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.

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	°	$1^{\circ} = (\pi/180)$ 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 = 1.660 539 066 60(50) × 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	

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}

(*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 2018 adjustment.

(*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.

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 and unambiguity of numerical results expressed in SI units.

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 mm^2 or square millimetre), cc (for either 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_{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_{max} = 1000 V
but not U = 1000 V_{max}.
The mass fraction of copper in the sample of silicon is
w(Cu) = 1.3 × 10^{-6}
but not 1.3 × 10^{-6} w/w.

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.

m = 12.3 g where m is used as a symbol for the quantity mass,
but φ = 30° 22′ 8″, where φ is used as a symbol for the quantity plane angle.

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-millimetre 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_{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_{n} referred to the last digits of the quoted value; in this case $u(m_{\mathrm{n}}) = 0.000\,000\,021 \times 10^{-27}$ 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

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

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

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.

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

Examples:

$F = ma$ for force equals mass times acceleration

(53 m/s) × 10.2 s
or (53 m/s)(10.2 s)

25 × 60.5
but not 25 · 60.5

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

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

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.

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

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.

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)).

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.

Appendix 1. Decisions of the CGPM and the CIPM

This appendix lists those decisions of the CGPM and the CIPM that bear directly upon definitions of the units of the SI, prefixes defined for use as part of the SI, and conventions for the writing of unit symbols and numbers. It is not a complete list of CGPM and CIPM decisions. For a complete list, reference must be made to successive volumes of the *Comptes Rendus des Séances de la Conférence Générale des Poids et Mesures* (CR) and *Procès-Verbaux des Séances du Comité International des Poids et Mesures* (PV) or, for recent decisions, to *Metrologia*.

Since the SI is not a static convention, but evolves following developments in the science of measurement, some decisions have been abrogated or modified; others have been clarified by additions. Decisions that have been subject to such changes are identified by an asterisk (*) and are linked by a note to the modifying decision.

The original text of each decision (or its translation) is shown in a different font (sans serif) of normal weight to distinguish it from the main text. The asterisks and notes were added by the BIPM to make the text more understandable. They do not form part of the original text.

The decisions of the CGPM and CIPM are listed in this appendix in strict chronological order, from 1889 to 2018, in order to preserve the continuity with which they were taken. However in order to make it easy to locate decisions related to particular topics a table of contents is included below, ordered by subject, with page references to the particular meetings at which decisions relating to each subject were taken.

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1st CGPM, 1889

■ Sanction of the international prototypes of the metre and the kilogram (CR, 34 - 38)*

* The definition of the metre was abrogated in 1960 by the 11th CGPM (Resolution 6, see p. 164).

The Conférence Générale des Poids et Mesures,

considering

- the "Compte rendu of the President of the Comité International des Poids et Mesures (CIPM)" and the "Report of the CIPM", which show that, by the collaboration of the French section of the International Metre Commission and of the CIPM, the fundamental measurements of the international and national prototypes of the metre and of the kilogram have been made with all the accuracy and reliability which the present state of science permits;
- that the international and national prototypes of the metre and the kilogram are made of an alloy of platinum with 10 per cent iridium, to within 0.0001;
- the equality in length of the international Metre and the equality in mass of the international Kilogram with the length of the Metre and the mass of the Kilogram kept in the Archives of France;
- that the differences between the national Metres and the international Metre lie within 0.01 millimetre and that these differences are based on a hydrogen thermometer scale which can always be reproduced thanks to the stability of hydrogen, provided identical conditions are secured;
- that the differences between the national Kilograms and the international Kilogram lie within 1 milligram;
- that the international Metre and Kilogram and the national Metres and Kilograms fulfil the requirements of the Metre Convention,

sanctions

A. As regards international prototypes:

1. The Prototype of the metre chosen by the CIPM. This prototype, at the temperature of melting ice, shall henceforth represent the metric unit of length.
2. The Prototype of the kilogram adopted by the CIPM. This prototype shall henceforth be considered as the unit of mass.
3. The hydrogen thermometer centigrade scale in terms of which the equations of the prototype Metres have been established.

B. As regards national prototypes:

…

3rd CGPM, 1901

■ Declaration concerning the definition of the litre (CR, 38-39)*

* This definition was abrogated in 1964 by the 12th CGPM (Resolution 6, see p. 167).

…

The Conference declares

1. The unit of volume, for high accuracy determinations, is the volume occupied by a mass of 1 kilogram of pure water, at its maximum density and at standard atmospheric pressure: this volume is called "litre".
2. …

■ Declaration on the unit of mass and on the definition of weight; conventional value of g_n (CR, 70)

Taking into account the decision of the Comité International des Poids et Mesures of 15 October 1887, according to which the kilogram has been defined as unit of mass;

Taking into account the decision contained in the sanction of the prototypes of the Metric System, unanimously accepted by the Conférence Générale des Poids et Mesures on 26 September 1889;

Considering the necessity to put an end to the ambiguity which in current practice still exists on the meaning of the word *weight*, used sometimes for *mass*, sometimes for *mechanical force*;

The Conference declares

1. The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram;*
2. The word "weight" denotes a quantity of the same nature as a "force": the weight of a body is the product of its mass and the acceleration due to gravity; in particular, the standard weight of a body is the product of its mass and the standard acceleration due to gravity;
3. The value adopted in the International Service of Weights and Measures for the standard acceleration due to gravity is 980.665 cm/s^2, value already stated in the laws of some countries.**

* This definition was abrogated in 2018 by the 26th CGPM (Resolution 1, see p. 197).

**This value of g_n was the conventional reference for calculating the now obsolete unit kilogram force.

7th CGPM, 1927

■ Definition of the metre by the international Prototype (CR, 49)*

The unit of length is the metre, defined by the distance, at 0°, between the axes of the two central lines marked on the bar of platinum-iridium kept at the Bureau International des Poids et Mesures and declared Prototype of the metre by the 1st Conférence Générale des Poids et Mesures, this bar being subject to standard atmospheric pressure and supported on two cylinders of at least one centimetre diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other.

* This definition was abrogated in 1960 by the 11th CGPM (Resolution 6, see p. 164).

CIPM, 1946

■ Definitions of photometric units (PV, **20**, 119-122)*

Resolution

…

4. The photometric units may be defined as follows:

New candle (unit of luminous intensity). — The value of the new candle is such that the brightness of the full radiator at the temperature of solidification of platinum is 60 new candles per square centimetre.

New lumen (unit of luminous flux). — The new lumen is the luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of 1 new candle.

5. …

* The two definitions contained in this Resolution were ratified in 1948 by the 9th CGPM, which also approved the name candela given to the "new candle" (CR, 54). For the lumen the qualifier "new" was later abandoned.

This definition was modified in 1967 by the 13th CGPM (Resolution 5, see p. 169-170).

■ **Definitions of electric units** (PV, **20**, 132-133)

The definitions contained in this Resolution were ratified in 1948 by the 9th CGPM (CR, 49), which also adopted the name newton (Resolution 7, see p. 162) for the MKS unit of force.

Resolution 2

...

4. (A) Definitions of the mechanical units which enter the definitions of electric units:

Unit of force. — The unit of force [in the MKS (metre, kilogram, second) system] is the force which gives to a mass of 1 kilogram an acceleration of 1 metre per second, per second.

Joule (unit of energy or work). — The joule is the work done when the point of application of 1 MKS unit of force [newton] moves a distance of 1 metre in the direction of the force.

Watt (unit of power). — The watt is the power which in one second gives rise to energy of 1 joule.

(B) Definitions of electric units. The Comité International des Poids et Mesures (CIPM) accepts the following propositions which define the theoretical value of the electric units:

In 1954, the 10th CGPM (Resolution 6, see p. 163) established a practical system of units of measurement for international use. The ampere was designated as a base unit of this system.

Ampere (unit of electric current). — The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} MKS unit of force [newton] per metre of length.*

Volt (unit of potential difference and of electromotive force). — The volt is the potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

* This definition of the ampere was abrogated in 2018 by the 26th CGPM (Resolution 1, see p. 197).

Ohm (unit of electric resistance). — The ohm is the electric resistance between two points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force.

Coulomb (unit of quantity of electricity). — The coulomb is the quantity of electricity carried in 1 second by a current of 1 ampere.

Farad (unit of capacitance). — The farad is the capacitance of a capacitor between the plates of which there appears a potential difference of 1 volt when it is charged by a quantity of electricity of 1 coulomb.

Henry (unit of electric inductance). — The henry is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at the rate of 1 ampere per second.

Weber (unit of magnetic flux). — The weber is the magnetic flux which, linking a circuit of one turn, would produce in it an electromotive force of 1 volt if it were reduced to zero at a uniform rate in 1 second.

9th CGPM, 1948

■ **Triple point of water; thermodynamic scale with a single fixed point; unit of quantity of heat (joule)** (CR, 55 and 63)

The kelvin was redefined by the 26th CGPM in 2018 (Resolution 1, see p. 197).

Resolution 3

1. With present-day techniques, the triple point of water is capable of providing a thermometric reference point with an accuracy higher than can be obtained from the melting point of ice.

   In consequence the Comité Consultatif de Thermométrie et Calorimétrie (CCTC) considers that the zero of the centesimal thermodynamic scale must be defined as the temperature 0.0100 degree below that of the triple point of water.

2. The CCTC accepts the principle of an absolute thermodynamic scale with a single fundamental fixed point, at present provided by the triple point of pure water, the absolute temperature of which will be fixed at a later date.

   The introduction of this new scale does not affect in any way the use of the International Scale, which remains the recommended practical scale.

3. The unit of quantity of heat is the joule.

Note: It is requested that the results of calorimetric experiments be as far as possible expressed in joules. If the experiments are made by comparison with the rise of temperature of water (and that, for some reason, it is not possible to avoid using the calorie), the information necessary for conversion to joules must be provided. The CIPM, advised by the CCTC, should prepare a table giving, in joules per degree, the most accurate values that can be obtained from experiments on the specific heat of water.

A table, prepared in response to this request, was approved and published by the CIPM in 1950 (PV, **22**, 92).

■ Adoption of "degree Celsius" [CIPM, 1948 (PV, 21, 88) and 9th CGPM, 1948 (CR, 64)]

From three names ("degree centigrade", "centesimal degree", "degree Celsius") proposed to denote the degree of temperature, the CIPM has chosen "degree Celsius" (PV, **21**, 88).

This name is also adopted by the 9th CGPM (CR, 64).

■ Proposal for establishing a practical system of units of measurement (CR, 64)

Resolution 6

The Conférence Générale des Poids et Mesures (CGPM),

considering

- that the Comité International des Poids et Mesures (CIPM) has been requested by the International Union of Physics to adopt for international use a practical Système International d'Unités; that the International Union of Physics recommends the MKS system and one electric unit of the absolute practical system, but does not recommend that the CGS system be abandoned by physicists;
- that the CGPM has itself received from the French Government a similar request, accompanied by a draft to be used as basis of discussion for the establishment of a complete specification of units of measurement;

instructs the CIPM:

- to seek by an energetic, active, official enquiry the opinion of scientific, technical and educational circles of all countries (offering them, in fact, the French document as basis);
- to gather and study the answers;
- to make recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Metre Convention.

■ **Writing and printing of unit symbols and of numbers** (CR, 70)*

* The CGPM abrogated certain decisions on units and terminology, in particular: micron, degree absolute, and the terms “degree”, and “deg”, 13th CGPM, 1967/68 (Resolutions 7 and 3, see pp. 170 and 169, respectively), and the litre; 16th CGPM, 1979 (Resolution 6, see p. 174).

Resolution 7

Principles

Roman (upright) type, in general lower-case, is used for symbols of units; if, however, the symbols are derived from proper names, capital roman type is used. These symbols are not followed by a full stop.

In numbers, the comma (French practice) or the dot (British practice) is used only to separate the integral part of numbers from the decimal part. Numbers may be divided in groups of three in order to facilitate reading; neither dots nor commas are ever inserted in the spaces between groups.

Unit	Symbol	Unit	Symbol
• metre	m	ampere	A
• square metre	m^2	volt	V
• cubic metre	m^3	watt	W
• micron	μ	ohm	Ω
• litre	l	coulomb	C
• gram	g	farad	F
• tonne	t	henry	H
second	s	hertz	Hz
erg	erg	poise	P
dyne	dyn	newton	N
degree Celsius	°C	• candela (new candle)	cd
• degree absolute	°K	lux	lx
calorie	cal	lumen	lm
bar	bar	stilb	sb
hour	h		

Notes

1. The symbols whose unit names are preceded by dots are those which had already been adopted by a decision of the CIPM.
2. The symbol for the stere, the unit of volume for firewood, shall be “st” and not “s”, which had been previously assigned to it by the CIPM.
3. To indicate a temperature interval or difference, rather than a temperature, the word “degree” in full, or the abbreviation “deg”, must be used.

10th CGPM, 1954

■ **Definition of the thermodynamic temperature scale** (CR, 79)*

* The 13th CGPM in 1967 explicitly defined the kelvin (Resolution 4, see p. 169).

* The kelvin was redefined by the 26th CGPM in 2018 (Resolution 1, see p. 197).

Resolution 3

The 10th Conférence Générale des Poids et Mesures decides to define the thermodynamic temperature scale by choosing the triple point of water as the fundamental fixed point, and assigning to it the temperature 273.16 degrees Kelvin, exactly.

■ **Definition of the standard atmosphere** (CR, 79)

Resolution 4

The 10th Conférence Générale des Poids et Mesures (CGPM), having noted that the definition of the standard atmosphere given by the 9th CGPM when defining the International Temperature Scale led some physicists to believe that this definition of the standard atmosphere was valid only for accurate work in thermometry,

declares that it adopts, for general use, the definition:

1 standard atmosphere = 1 013 250 dynes per square centimetre,

i.e., 101 325 newtons per square metre.

■ **Practical system of units** (CR, 80)*

* The unit name "degree kelvin" was changed to "kelvin" in 1967 by the 13th CGPM (Resolution 3, see p. 169).

Resolution 6

In accordance with the wish expressed by the 9th Conférence Générale des Poids et Mesures (CGPM) in its Resolution 6 concerning the establishment of a practical system of units of measurement for international use, the 10th CGPM

decides to adopt as base units of the system, the following units:

length	metre
mass	kilogram
time	second
electric current	ampere
thermodynamic temperature	degree Kelvin
luminous intensity	candela

CIPM, 1956

■ **Definition of the unit of time (second)** (PV, **25**, 77)*

* This definition was abrogated in 1967 by the 13th CGPM (Resolution 1, see p. 168).

Resolution 1

In virtue of the powers invested in it by Resolution 5 of the 10th Conférence Générale des Poids et Mesures, the Comité International des Poids et Mesures,

considering

1. that the 9th General Assembly of the International Astronomical Union (Dublin, 1955) declared itself in favour of linking the second to the tropical year,
2. that, according to the decisions of the 8th General Assembly of the International Astronomical Union (Rome, 1952), the second of ephemeris time (ET) is the fraction

$$\frac{12\,960\,276\,813}{408\,986\,496} \times 10^{-9} \text{ of the tropical year for 1900 January 0 at 12 h ET,}$$

decides

"The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

■ **Système International d'Unités** (PV, **25**, 83)

Resolution 3

The Comité International des Poids et Mesures,

considering

- the task entrusted to it by Resolution 6 of the 9th Conférence Générale des Poids et Mesures (CGPM) concerning the establishment of a practical system of units of measurement suitable for adoption by all countries adhering to the Metre Convention,
- the documents received from twenty-one countries in reply to the enquiry requested by the 9th CGPM,
- Resolution 6 of the 10th CGPM, fixing the base units of the system to be established,

recommends

1. that the name "Système International d'Unités" be given to the system founded on the base units adopted by the 10th CGPM, viz.:

   [This is followed by the list of the six base units with their symbols, reproduced in Resolution 12 of the 11th CGPM (1960)].

2. that the units listed in the table below be used, without excluding others which might be added later:

   [This is followed by the table of units reproduced in paragraph 4 of Resolution 12 of the 11th CGPM (1960)].

11th CGPM, 1960

■ **Definition of the metre** (CR, 85)*

* This definition was abrogated in 1983 by the 17th CGPM (Resolution 1, see p. 175).

Resolution 6

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the international Prototype does not define the metre with an accuracy adequate for the present needs of metrology,
- that it is moreover desirable to adopt a natural and indestructible standard,

decides

1. The metre is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton 86 atom.
2. The definition of the metre in force since 1889, based on the international Prototype of platinum-iridium, is abrogated.
3. The international Prototype of the metre sanctioned by the 1st CGPM in 1889 shall be kept at the BIPM under the conditions specified in 1889.

■ **Definition of the unit of time (second)** (CR, 86)*

* This definition was abrogated in 1967 by the 13th CGPM (Resolution 1, see p. 168).

Resolution 9

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- the powers given to the Comité International des Poids et Mesures (CIPM) by the 10th CGPM to define the fundamental unit of time,
- the decision taken by the CIPM in 1956,

ratifies the following definition:

"The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

■ **Système International d'Unités** (CR, 87)*

* The CGPM later abrogated certain of its decisions and extended the list of prefixes, see notes below.

Resolution 12

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- Resolution 6 of the 10th CGPM, by which it adopted six base units on which to establish a practical system of measurement for international use:

length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	degree Kelvin	°K
luminous intensity	candela	cd

The name and symbol for the unit of thermodynamic temperature was modified by the 13th CGPM in 1967 (Resolution 3, see p. 169).

- Resolution 3 adopted by the Comité International des Poids et Mesures (CIPM) in 1956,
- the recommendations adopted by the CIPM in 1958 concerning an abbreviation for the name of the system, and prefixes to form multiples and submultiples of the units,

decides

1. the system founded on the six base units above is called the "Système International d'Unités";
2. the international abbreviation of the name of the system is: SI;
3. names of multiples and submultiples of the units are formed by means of the following prefixes:

A seventh base unit, the mole, was adopted by the 14th CGPM in 1971 (Resolution 3, see p. 172).

Multiplying factor	Prefix	Symbol	Multiplying factor	Prefix	Symbol
$1\,000\,000\,000\,000 = 10^{12}$	tera	T	$0.1 = 10^{-1}$	deci	d
$1\,000\,000\,000 = 10^{9}$	giga	G	$0.01 = 10^{-2}$	centi	c
$1\,000\,000 = 10^{6}$	mega	M	$0.001 = 10^{-3}$	milli	m
$1\,000 = 10^{3}$	kilo	k	$0.000\,001 = 10^{-6}$	micro	μ
$100 = 10^{2}$	hecto	h	$0.000\,000\,001 = 10^{-9}$	nano	n
$10 = 10^{1}$	deca	da	$0.000\,000\,000\,001 = 10^{-12}$	pico	p

Further prefixes were adopted by the 12th CGPM in 1964 (Resolution 8, see p. 168), the 15th CGPM in 1975 (Resolution 10, see p. 173) and the 19th CGPM in 1991 (Resolution 4, see p. 179).

4. the units listed below are used in the system, without excluding others which might be added later.

Supplementary units

plane angle	radian	rad
solid angle	steradian	sr

The 20th CGPM in 1995 abrogated the class of supplementary units in the SI (Resolution 8, see p. 179). These are now considered as derived units.

Derived units

area	square metre	m^2	
volume	cubic metre	m^3	
frequency	hertz	Hz	1/s
mass density (density)	kilogram per cubic metre	kg/m^3	
speed, velocity	metre per second	m/s	
angular velocity	radian per second	rad/s	
acceleration	metre per second squared	m/s^2	
angular acceleration	radian per second squared	rad/s^2	
force	newton	N	$kg \cdot m/s^2$
pressure (mechanical stress)	newton per square metre	N/m^2	
kinematic viscosity	square metre per second	m^2/s	
dynamic viscosity	newton-second per square metre	$N \cdot s/m^2$	
work, energy, quantity of heat	joule	J	$N \cdot m$
power	watt	W	J/s
quantity of electricity (side bar)	coulomb	C	$A \cdot s$
tension (voltage), potential difference, electromotive force	volt	V	W/A
electric field strength	volt per metre	V/m	
electric resistance	ohm	Ω	V/A
capacitance	farad	F	$A \cdot s/V$
magnetic flux	weber	Wb	$V \cdot s$
inductance	henry	H	$V \cdot s/A$
magnetic flux density	tesla	T	Wb/m^2
magnetic field strength	ampere per metre	A/m	
magnetomotive force	ampere	A	
luminous flux	lumen	lm	$cd \cdot sr$
luminance	candela per square metre	cd/m^2	
illuminance	lux	lx	lm/m^2

The 13th CGPM in 1967 (Resolution 6, see p. 170) specified other units which should be added to the list. In principle, this list of derived units is without limit.

Modern practice is to use the phrase "amount of heat" rather than "quantity of heat", because the word quantity has a different meaning in metrology.

Modern practice is to use the phrase "amount of electricity" rather than "quantity of electricity" (see note above).

■ **Cubic decimetre and litre** (CR, 88)

Resolution 13

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the cubic decimetre and the litre are unequal and differ by about 28 parts in 10^6,
- that determinations of physical quantities which involve measurements of volume are being made more and more accurately, thus increasing the risk of confusion between the cubic decimetre and the litre,

requests the Comité International des Poids et Mesures to study the problem and submit its conclusions to the 12th CGPM.

CIPM, 1961

■ **Cubic decimetre and litre** (PV, **29**, 34)

Recommendation

The Comité International des Poids et Mesures recommends that the results of accurate measurements of volume be expressed in units of the International System and not in litres.

CIPM, 1964

■ **Atomic and molecular frequency standards** (PV, **32**, 26)

Declaration

The Comité International des Poids et Mesures,

empowered by Resolution 5 of the 12th Conférence Générale des Poids et Mesures to name atomic or molecular frequency standards for temporary use for time measurements in physics,

declares that the standard to be employed is the transition between the hyperfine levels $F = 4$, $M = 0$ and $F = 3$, $M = 0$ of the ground state $^2S_{1/2}$ of the caesium 133 atom, unperturbed by external fields, and that the frequency of this transition is assigned the value 9 192 631 770 hertz.

12th CGPM, 1964

■ **Atomic standard of frequency** (CR, 93)

Resolution 5

The 12th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the 11th CGPM noted in its Resolution 10 the urgency, in the interests of accurate metrology, of adopting an atomic or molecular standard of time interval,
- that, in spite of the results already obtained with caesium atomic frequency standards, the time has not yet come for the CGPM to adopt a new definition of the second, base unit of the Système International d'Unités, because of the new and considerable improvements likely to be obtained from work now in progress,

considering also that it is not desirable to wait any longer before time measurements in physics are based on atomic or molecular frequency standards,

empowers the Comité International des Poids et Mesures to name the atomic or molecular frequency standards to be employed for the time being,

requests the organizations and laboratories knowledgeable in this field to pursue work connected with a new definition of the second.

■ **Litre** (CR, 93)

Resolution 6

The 12th Conférence Générale des Poids et Mesures (CGPM),

considering Resolution 13 adopted by the 11th CGPM in 1960 and the Recommendation adopted by the Comité International des Poids et Mesures in 1961,

1. **abrogates** the definition of the litre given in 1901 by the 3rd CGPM,
2. **declares** that the word "litre" may be employed as a special name for the cubic decimetre,
3. **recommends** that the name litre should not be employed to give the results of high-accuracy volume measurements.

■ **Curie** (CR, 94)*

* The name "becquerel" (Bq) was adopted by the 15th CGPM in 1975 (Resolution 8, see p. 172) for the SI unit of activity: 1 Ci = 3.7×10^{10} Bq.

Resolution 7

The 12th Conférence Générale des Poids et Mesures,

considering that the curie has been used for a long time in many countries as unit of activity for radionuclides,

recognizing that in the Système International d'Unités (SI), the unit of this activity is the second to the power of minus one (s^{-1}),

accepts that the curie be still retained, outside SI, as unit of activity, with the value 3.7×10^{10} s^{-1}. The symbol for this unit is Ci.

■ **SI prefixes femto and atto** (CR, 94)*

* New prefixes were added by the 15th CGPM in 1975 (Resolution 10, see p. 173).

Resolution 8

The 12th Conférence Générale des Poids et Mesures (CGPM)

decides to add to the list of prefixes for the formation of names of multiples and submultiples of units, adopted by the 11th CGPM, Resolution 12, paragraph 3, the following two new prefixes:

Multiplying factor	Prefix	Symbol
10^{-15}	femto	f
10^{-18}	atto	a

CIPM, 1967

■ **Decimal multiples and submultiples of the unit of mass** (PV, **35,** 29 and *Metrologia*, 1968, **4**, 45)

Recommendation 2

The Comité International des Poids et Mesures,

considering that the rule for forming names of decimal multiples and submultiples of the units of paragraph 3 of Resolution 12 of the 11th Conférence Générale des Poids et Mesures (CGPM) (1960) might be interpreted in different ways when applied to the unit of mass,

declares that the rules of Resolution 12 of the 11th CGPM apply to the kilogram in the following manner: the names of decimal multiples and submultiples of the unit of mass are formed by attaching prefixes to the word "gram".

13th CGPM, 1967/68

■ **SI unit of time (second)** (CR, 103 and *Metrologia*, 1968, **4**, 43)

Resolution 1

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the definition of the second adopted by the Comité International des Poids et Mesures (CIPM) in 1956 (Resolution 1) and ratified by Resolution 9 of the 11th CGPM (1960), later upheld by Resolution 5 of the 12th CGPM (1964), is inadequate for the present needs of metrology,
- that at its meeting of 1964 the CIPM, empowered by Resolution 5 of the 12th CGPM (1964), recommended, in order to fulfil these requirements, a caesium atomic frequency standard for temporary use,
- that this frequency standard has now been sufficiently tested and found sufficiently accurate to provide a definition of the second fulfilling present requirements,
- that the time has now come to replace the definition now in force of the unit of time of the Système International d'Unités by an atomic definition based on that standard,

decides

1. The SI unit of time is the second defined as follows:

   "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom";

2. Resolution 1 adopted by the CIPM at its meeting of 1956 and Resolution 9 of the 11th CGPM are now abrogated.

At its 1997 meeting, the CIPM affirmed that this definition refers to a caesium atom at rest at a thermodynamic temperature of 0 K. The wording of the definition of the second was modified by the 26th CGPM in 2018 (Resolution 1, see p. 197).

■ SI unit of thermodynamic temperature (kelvin) (CR, 104 and *Metrologia*, 1968, **4**, 43)*

Resolution 3

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- the names "degree Kelvin" and "degree", the symbols "°K" and "deg" and the rules for their use given in Resolution 7 of the 9th CGPM (1948), in Resolution 12 of the 11th CGPM (1960), and the decision taken by the Comité International des Poids et Mesures in 1962 (PV, **30**, 27),
- that the unit of thermodynamic temperature and the unit of temperature interval are one and the same unit, which ought to be denoted by a single name and a single symbol,

decides

1. the unit of thermodynamic temperature is denoted by the name "kelvin" and its symbol is "K";**
2. the same name and the same symbol are used to express a temperature interval;
3. a temperature interval may also be expressed in degrees Celsius;
4. the decisions mentioned in the opening paragraph concerning the name of the unit of thermodynamic temperature, its symbol and the designation of the unit to express an interval or a difference of temperatures are abrogated, but the usages which derive from these decisions remain permissible for the time being.

* At its 1980 meeting, the CIPM approved the report of the 7th meeting of the CCU, which requested that the use of the symbols "°K" and "deg" no longer be permitted.

** See Recommendation 2 (CI-2005) of the CIPM on the isotopic composition of water entering in the definition of the kelvin, p. 184.

■ Definition of the SI unit of thermodynamic temperature (kelvin) (CR, 104 and *Metrologia*, 1968, **4**, 43)*

Resolution 4

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering that it is useful to formulate more explicitly the definition of the unit of thermodynamic temperature contained in Resolution 3 of the 10th CGPM (1954),

decides to express this definition as follows:

"The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water."

* See Recommendation 5 (CI-1989) of the CIPM on the International Temperature Scale of 1990, p. 178.

* The kelvin was redefined by the 26th CGPM in 2018 (Resolution 1, see p. 197).

■ SI unit of luminous intensity (candela) (CR, 104 and *Metrologia*, 1968, **4**, 43-44)*

Resolution 5

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- the definition of the unit of luminous intensity ratified by the 9th CGPM (1948) and contained in the "Resolution concerning the change of photometric units" adopted by the Comité International des Poids et Mesures in 1946 (PV, **20**, 119) in virtue of the powers conferred by the 8th CGPM (1933),
- that this definition fixes satisfactorily the unit of luminous intensity, but that its wording may be open to criticism,

* This definition was abrogated by the 16th CGPM in 1979 (Resolution 3, see p. 173).

decides to express the definition of the candela as follows:

"The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre."

■ **SI derived units** (CR, 105 and *Metrologia*, 1968, **4**, 44)*****

* The unit of activity was given a special name and symbol by the 15th CGPM in 1975 (Resolution 8, see p. 172).

Resolution 6

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering that it is useful to add some derived units to the list of paragraph 4 of Resolution 12 of the 11th CGPM (1960),

decides to add:

wave number	1 per metre	m^{-1}
entropy	joule per kelvin	J/K
specific heat capacity	joule per kilogram kelvin	J/(kg · K)
thermal conductivity	watt per metre kelvin	W/(m · K)
radiant intensity	watt per steradian	W/sr
activity (of a radioactive source)	1 per second	s^{-1}

■ **Abrogation of earlier decisions (micron and new candle)** (CR, 105 and *Metrologia*, 1968, **4**, 44)

Resolution 7

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering that subsequent decisions of the General Conference concerning the Système International d'Unités are incompatible with parts of Resolution 7 of the 9th CGPM (1948),

decides accordingly to remove from Resolution 7 of the 9th Conference:

1. the unit name "micron", and the symbol "μ" which had been given to that unit but which has now become a prefix;
2. the unit name "new candle".

CIPM, 1969

■ **Système International d'Unités, Rules for application of Resolution 12 of the 11th CGPM (1960)** (PV, **37**, 30 and *Metrologia*, 1970, **6**, 66)*****

* The 20th CGPM in 1995 decided to abrogate the class of supplementary units in the SI (Resolution 8, see p. 179).

Recommendation 1

The Comité International des Poids et Mesures,

considering that Resolution 12 of the 11th Conférence Générale des Poids et Mesures (CGPM) (1960), concerning the Système International d'Unités, has provoked discussions on certain of its aspects,

declares

1. the base units, the supplementary units and the derived units of the Système International d'Unités, which form a coherent set, are denoted by the name "SI units";**
2. the prefixes adopted by the CGPM for the formation of decimal multiples and submultiples of SI units are called "SI prefixes";

** The CIPM approved in 2001 a proposal of the CCU to clarify the definition of "SI units" and "units of the SI", see p. 180.

and **recommends**

3. the use of SI units and of their decimal multiples and submultiples whose names are formed by means of SI prefixes.

Note: The name "supplementary units", appearing in Resolution 12 of the 11th CGPM (and in the present Recommendation) is given to SI units for which the General Conference declines to state whether they are base units or derived units.

CCDS, 1970 (*In* CIPM, 1970)

■ **Definition of TAI** (PV, **38**, 110-111 and *Metrologia*, 1971, **7**, 43)

Recommendation S 2

International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units.

In 1980, the definition of TAI was completed as follows (declaration of the CCDS, *BIPM Com. Cons. Déf. Seconde*, 1980, **9**, S 15 and *Metrologia*, 1981, **17**, 70):

TAI is a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit.

This definition was further amplified by the International Astronomical Union in 1991, Resolution A4:

"TAI is a realized time scale whose ideal form, neglecting a constant offset of 32.184 s, is Terrestrial Time (TT), itself related to the time coordinate of the geocentric reference frame, Geocentric Coordinate Time (TCG), by a constant rate."

(see Proc. 21st General Assembly of the IAU, *IAU Trans.*, 1991, vol. **XXIB,** Kluwer.)

14th CGPM, 1971

■ **Pascal and siemens** (CR, 78)

The 14th Conférence Générale des Poids et Mesures adopted the special names "pascal" (symbol Pa), for the SI unit newton per square metre, and "siemens" (symbol S), for the SI unit of electric conductance [reciprocal ohm].

■ **International Atomic Time, function of CIPM** (CR, 77-78 and *Metrologia*, 1972, **8**, 35)

Resolution 1

The 14th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the second, unit of time of the Système International d'Unités, has since 1967 been defined in terms of a natural atomic frequency, and no longer in terms of the time scales provided by astronomical motions,
- that the need for an International Atomic Time (TAI) scale is a consequence of the atomic definition of the second,
- that several international organizations have ensured and are still successfully ensuring the establishment of the time scales based on astronomical motions, particularly thanks to the permanent services of the Bureau International de l'Heure (BIH),
- that the BIH has started to establish an atomic time scale of recognized quality and proven usefulness,
- that the atomic frequency standards for realizing the second have been considered and must continue to be considered by the Comité International des Poids et Mesures (CIPM) helped by a Consultative Committee, and that the unit interval of the International Atomic Time scale must be the second realized according to its atomic definition,
- that all the competent international scientific organizations and the national laboratories active in this field have expressed the wish that the CIPM and the CGPM should give a definition of International Atomic Time, and should contribute to the establishment of the International Atomic Time scale,
- that the usefulness of International Atomic Time entails close coordination with the time scales based on astronomical motions,

requests the CIPM

1. to give a definition of International Atomic Time,
2. to take the necessary steps, in agreement with the international organizations concerned, to ensure that available scientific competence and existing facilities are used in the best possible way to realize the International Atomic Time scale and to satisfy the requirements of users of International Atomic Time.

The definition of TAI was given by the CCDS in 1970 (now the CCTF), see CCDS report p. 22.

■ **SI unit of amount of substance (mole)** (CR, 78 and *Metrologia*, 1972, **8**, 36)*****

Resolution 3

The 14th Conférence Générale des Poids et Mesures (CGPM),

considering the advice of the International Union of Pure and Applied Physics, of the International Union of Pure and Applied Chemistry, and of the International Organization for Standardization, concerning the need to define a unit of amount of substance,

decides

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is "mol".**
2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
3. The mole is a base unit of the Système International d'Unités.

* At its 1980 meeting, the CIPM approved the report of the 7th meeting of the CCU (1980) specifying that, in this definition, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

** The mole was redefined by the 26th CGPM in 2018 (Resolution 1, see p. 197).

15th CGPM, 1975

■ **Recommended value for the speed of light** (CR, 103 and *Metrologia*, 1975, **11**, 179-180)

Resolution 2

The 15th Conférence Générale des Poids et Mesures,

considering the excellent agreement among the results of wavelength measurements on the radiations of lasers locked on a molecular absorption line in the visible or infrared region, with an uncertainty estimated at $\pm 4 \times 10^{-9}$ which corresponds to the uncertainty of the realization of the metre,

considering also the concordant measurements of the frequencies of several of these radiations,

recommends the use of the resulting value for the speed of propagation of electromagnetic waves in vacuum c = 299 792 458 metres per second.

The relative uncertainty given here corresponds to three standard deviations in the data considered.

■ **Coordinated Universal Time (UTC)** (CR, 104 and *Metrologia*, 1975, **11**, 180)

Resolution 5

The 15th Conférence Générale des Poids et Mesures,

considering that the system called "Coordinated Universal Time" (UTC) is widely used, that it is broadcast in most radio transmissions of time signals, that this wide diffusion makes available to the users not only frequency standards but also International Atomic Time and an approximation to Universal Time (or, if one prefers, mean solar time),

notes that this Coordinated Universal Time provides the basis of civil time, the use of which is legal in most countries,

judges that this usage can be strongly endorsed.

■ **SI units for ionizing radiation (becquerel and gray)** (CR, 105 and *Metrologia*, 1975, **11**, 180)*****

Resolutions 8 and 9

The 15th Conférence Générale des Poids et Mesures,

by reason of the pressing requirement, expressed by the International Commission on Radiation Units and Measurements (ICRU), to extend the use of the Système International d'Unités to radiological research and applications,

by reason of the need to make as easy as possible the use of the units for nonspecialists,

taking into consideration also the grave risks of errors in therapeutic work,

adopts the following special name for the SI unit of activity:

* At its 1976 meeting, the CIPM approved the report of the 5th meeting of the CCU (1976), specifying that, following the advice of the ICRU, the gray may also be used to express specific energy imparted, kerma and absorbed dose index.

becquerel, symbol Bq, equal to one reciprocal second (Resolution 8),

adopts the following special name for the SI unit of ionizing radiation:

gray, symbol Gy, equal to one joule per kilogram (Resolution 9).

Note: The gray is the SI unit of absorbed dose. In the field of ionizing radiation, the gray may be used with other physical quantities also expressed in joules per kilogram: the Comité Consultatif des Unités has responsibility for studying this matter in collaboration with the competent international organizations.

■ **SI prefixes peta and exa** (CR, 106 and *Metrologia*, 1975, **11**, 180-181)*****

* New prefixes were added by the 19th CGPM in 1991 (Resolution 4, see p. 179).

Resolution 10

The 15th Conférence Générale des Poids et Mesures (CGPM)

decides to add to the list of SI prefixes to be used for multiples, which was adopted by the 11th CGPM, Resolution 12, paragraph 3, the two following prefixes:

Multiplying factor	Prefix	Symbol
10^{15}	peta	P
10^{18}	exa	E

16th CGPM, 1979

■ **SI unit of luminous intensity (candela)** (CR, 100 and *Metrologia*, 1980, **16**, 56)

The wording of the definition of the candela was modified by the 26th CGPM in 2018 (Resolution 1, see p. 197).

Resolution 3

The 16th Conférence Générale des Poids et Mesures (CGPM),

considering

- that despite the notable efforts of some laboratories there remain excessive divergences between the results of realizations of the candela based upon the present black body primary standard,
- that radiometric techniques are developing rapidly, allowing precisions that are already equivalent to those of photometry and that these techniques are already in use in national laboratories to realize the candela without having to construct a black body,
- that the relation between luminous quantities of photometry and radiometric quantities, namely the value of 683 lumens per watt for the spectral luminous efficacy of monochromatic radiation of frequency 540×10^{12} hertz, has been adopted by the Comité International des Poids et Mesures (CIPM) in 1977,
- that this value has been accepted as being sufficiently accurate for the system of luminous photopic quantities, that it implies a change of only about 3 % for the system of luminous scotopic quantities, and that it therefore ensures satisfactory continuity,
- that the time has come to give the candela a definition that will allow an improvement in both the ease of realization and the precision of photometric standards, and that applies to both photopic and scotopic photometric quantities and to quantities yet to be defined in the mesopic field,

Photopic vision is detected by the cones on the retina of the eye, which are sensitive to a high level of luminance ($L >$ ca. 10 cd/m^2) and are used in daytime vision.

Scotopic vision is detected by the rods of the retina, which are sensitive to low level luminance ($L <$ ca. 10^{-3} cd/m^2), used in night vision.

In the domain between these levels of luminance both cones and rods are used, and this is described as mesopic vision.

decides

1. The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.
2. The definition of the candela (at the time called new candle) adopted by the CIPM in 1946 by reason of the powers conferred by the 8th CGPM in 1933, ratified by the 9th CGPM in 1948, then amended by the 13th CGPM in 1967, is abrogated.

■ **Special name for the SI unit of dose equivalent (sievert)** (CR, 100 and *Metrologia*, 1980, **16**, 56)*****

* The CIPM, in 1984, decided to accompany this Resolution with an explanation (Recommendation 1, see p. 176).

Resolution 5

The 16th Conférence Générale des Poids et Mesures,

considering

- the effort made to introduce SI units into the field of ionizing radiations,
- the risk to human beings of an underestimated radiation dose, a risk that could result from a confusion between absorbed dose and dose equivalent,
- that the proliferation of special names represents a danger for the Système International d'Unités and must be avoided in every possible way, but that this rule can be broken when it is a matter of safeguarding human health,

adopts the special name ***sievert,*** symbol Sv, for the SI unit of dose equivalent in the field of radioprotection. The sievert is equal to the joule per kilogram.

■ **Symbols for the litre** (CR, 101 and *Metrologia*, 1980, **16**, 56-57)

Resolution 6

The 16th Conférence Générale des Poids et Mesures (CGPM),

recognizing the general principles adopted for writing the unit symbols in Resolution 7 of the 9th CGPM (1948),

considering that the symbol l for the unit litre was adopted by the Comité International des Poids et Mesures (CIPM) in 1879 and confirmed in the same Resolution of 1948,

considering also that, in order to avoid the risk of confusion between the letter l and the number 1, several countries have adopted the symbol L instead of l for the unit litre,

considering that the name litre, although not included in the Système International d'Unités, must be admitted for general use with the System,

decides, as an exception, to adopt the two symbols l and L as symbols to be used for the unit litre,

The CIPM, in 1990, considered that it was still too early to choose a single symbol for the litre.

considering further that in the future only one of these two symbols should be retained,

invites the CIPM to follow the development of the use of these two symbols and to give the 18th CGPM its opinion as to the possibility of suppressing one of them.

CIPM, 1980

■ **SI supplementary units (radian and steradian)** (PV, **48**, 24 and *Metrologia*, 1981, **17**, 72)*****

* The class of SI supplementary units was abrogated by decision of the 20th CGPM in 1995 (Resolution 8, see p. 179).

Recommendation 1

The Comité International des Poids et Mesures (CIPM),

taking into consideration Resolution 3 adopted by ISO/TC 12 in 1978 and Recommendation U 1 (1980) adopted by the Comité Consultatif des Unités at its 7th meeting,

considering

- that the units radian and steradian are usually introduced into expressions for units when there is need for clarification, especially in photometry where the steradian plays an important role in distinguishing between units corresponding to different quantities,
- that in the equations used one generally expresses plane angle as the ratio of two lengths and solid angle as the ratio between an area and the square of a length, and consequently that these quantities are treated as dimensionless quantities,
- that the study of the formalisms in use in the scientific field shows that none exists which is at the same time coherent and convenient and in which the quantities plane angle and solid angle might be considered as base quantities,

considering also

- that the interpretation given by the CIPM in 1969 for the class of supplementary units introduced in Resolution 12 of the 11th Conférence Générale des Poids et Mesures (CGPM) in 1960 allows the freedom of treating the radian and the steradian as SI base units,
- that such a possibility compromises the internal coherence of the SI based on only seven base units,

decides to interpret the class of supplementary units in the International System as a class of dimensionless derived units for which the CGPM allows the freedom of using or not using them in expressions for SI derived units.

17th CGPM, 1983

■ **Definition of the metre** (CR, 97 and *Metrologia*, 1984, **20**, 25)

The wording of the definition of the metre was modified by the 26th CGPM in 2018 (Resolution 1, see p. 197).

Resolution 1

The 17th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the present definition does not allow a sufficiently precise realization of the metre for all requirements,
- that progress made in the stabilization of lasers allows radiations to be obtained that are more reproducible and easier to use than the standard radiation emitted by a krypton 86 lamp,
- that progress made in the measurement of the frequency and wavelength of these radiations has resulted in concordant determinations of the speed of light whose accuracy is limited principally by the realization of the present definition of the metre,
- that wavelengths determined from frequency measurements and a given value for the speed of light have a reproducibility superior to that which can be obtained by comparison with the wavelength of the standard radiation of krypton 86,
- that there is an advantage, notably for astronomy and geodesy, in maintaining unchanged the value of the speed of light recommended in 1975 by the 15th CGPM in its Resolution 2 (c = 299 792 458 m/s),
- that a new definition of the metre has been envisaged in various forms all of which have the effect of giving the speed of light an exact value, equal to the recommended value, and that this introduces no appreciable discontinuity into the unit of length, taking into account the relative uncertainty of $\pm 4 \times 10^{-9}$ of the best realizations of the present definition of the metre,

The relative uncertainty given here corresponds to three standard deviations in the data considered.

- that these various forms, making reference either to the path travelled by light in a specified time interval or to the wavelength of a radiation of measured or specified frequency, have been the object of consultations and deep discussions, have been recognized as being equivalent and that a consensus has emerged in favour of the first form,
- that the Comité Consultatif pour la Définition du Mètre (CCDM) is now in a position to give instructions for the practical realization of such a definition, instructions which could include the use of the orange radiation of krypton 86 used as standard up to now, and which may in due course be extended or revised,

decides

1. 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,
2. The definition of the metre in force since 1960, based upon the transition between the levels $2p_{10}$ and $5d_5$ of the atom of krypton 86, is abrogated.

■ **On the realization of the definition of the metre** (CR, 98 and *Metrologia*, 1984, **20**, 25-26)

See Recommendation 1 (CI-2002) of the CIPM on the revision of the practical realization of the definition of the metre, p. 181.

Resolution 2

The 17th Conférence Générale des Poids et Mesures,

invites the Comité International des Poids et Mesures

- to draw up instructions for the practical realization of the new definition of the metre,
- to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and to draw up instructions for their use,
- to pursue studies undertaken to improve these standards.

CIPM, 1984

■ **Concerning the sievert** (PV*,* **52***,* 31 and *Metrologia*, 1985, **21**, 90)*****

* The CIPM, in 2002, decided to change the explanation of the quantity dose equivalent in the SI Brochure (Recommendation 2, see p. 182).

Recommendation 1

The Comité International des Poids et Mesures,

considering the confusion which continues to exist on the subject of Resolution 5, approved by the 16th Conférence Générale des Poids et Mesures (1979),

decides to introduce the following explanation in the brochure “Le Système International d'Unités (SI)”:

The quantity dose equivalent H is the product of the absorbed dose D of ionizing radiation and the dimensionless factors Q (quality factor) and N (product of any other multiplying factors) stipulated by the International Commission on Radiological Protection:

$$H = Q \cdot N \cdot D.$$

Thus, for a given radiation, the numerical value of H in joules per kilogram may differ from that of D in joules per kilogram depending upon the values of Q and N. In order to avoid any risk of confusion between the absorbed dose D and the dose equivalent H, the special names for the respective units should be used, that is, the name gray should be used instead of joules per kilogram for the unit of absorbed dose D and the name sievert instead of joules per kilogram for the unit of dose equivalent H.

18th CGPM, 1987

■ **Forthcoming adjustment to the representations of the volt and of the ohm** (CR, 100 and *Metrologia*, 1988, **25**, 115)

Resolution 6

The 18th Conférence Générale des Poids et Mesures,

considering

- that worldwide uniformity and long-term stability of national representations of the electrical units are of major importance for science, commerce and industry from both the technical and economic points of view,
- that many national laboratories use the Josephson effect and are beginning to use the quantum Hall effect to maintain, respectively, representations of the volt and of the ohm, as these offer the best guarantees of long-term stability,
- that because of the importance of coherence among the units of measurement of the various physical quantities the values adopted for these representations must be as closely as possible in agreement with the SI,
- that the results of recent and current experiment will permit the establishment of an acceptable value, sufficiently compatible with the SI, for the coefficient which relates each of these effects to the corresponding electrical unit,

invites the laboratories whose work can contribute to the establishment of the quotient voltage/frequency in the case of the Josephson effect and of the quotient voltage/current for the quantum Hall effect to vigorously pursue these efforts and to communicate their results without delay to the Comité International des Poids et Mesures, and

instructs the Comité International des Poids et Mesures to recommend, as soon as it considers it possible, a value for each of these quotients together with a date for them to be put into practice simultaneously in all countries; these values should be announced at least one year in advance and would be adopted on 1 January 1990.

CIPM, 1988

■ Representation of the volt by means of the Josephson effect (PV, **56**, 44 and *Metrologia*, 1989, **26**, 69)*

* The 26th CGPM in 2018 (Resolution 1, see p. 197) abrogated the adoption of a conventional value for K_J.

Recommendation 1

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

- that a detailed study of the results of the most recent determinations leads to a value of 483 597.9 GHz/V for the Josephson constant, K_J, that is to say, for the quotient of frequency divided by the potential difference corresponding to the $n = 1$ step in the Josephson effect,
- that the Josephson effect, together with this value of K_J, can be used to establish a reference standard of electromotive force having a one-standard-deviation uncertainty with respect to the volt estimated to be 4 parts in 10^7, and a reproducibility which is significantly better,

recommends

- that 483 597.9 GHz/V exactly be adopted as a conventional value, denoted by $K_{J\text{-}90}$ for the Josephson constant, K_J,
- that this new value be used from 1 January 1990, and not before, to replace the values currently in use,
- that this new value be used from this same date by all laboratories which base their measurements of electromotive force on the Josephson effect, and
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with the new adopted value,

is of the opinion that no change in this recommended value of the Josephson constant will be necessary in the foreseeable future, and

draws the attention of laboratories to the fact that the new value is greater by 3.9 GHz/V, or about 8 parts in 10^6, than the value given in 1972 by the Comité Consultatif d'Électricité in its Declaration E-72.

■ Representation of the ohm by means of the quantum Hall effect (PV, **56**, 45 and *Metrologia*, 1989, **26**, 70)*

At its 89th meeting in 2000, the CIPM approved the declaration of the 22nd meeting of the CCEM on the use of the value of the von Klitzing constant.

Recommendation 2

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

*The 26th CGPM in 2018 (Resolution 1, see p. 197) abrogated the adoption of a conventional value for R_K.

considering

- that most existing laboratory reference standards of resistance change significantly with time,
- that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,
- that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau i = 1 in the quantum Hall effect,
- that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

- that 25 812.807 Ω exactly be adopted as a conventional value, denoted by $R_{K\text{-}90}$, for the von Klitzing constant, R_K,
- that this value be used from 1 January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with $R_{K\text{-}90}$,
- that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the technical guidelines for reliable measurements of the quantized Hall resistance drawn up by the Comité Consultatif d'Électricité and published by the Bureau International des Poids et Mesures, and

is of the opinion that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

CIPM, 1989

■ The International Temperature Scale of 1990 (PV, **57**, 115 and *Metrologia*, 1990, **27**, 13)

The kelvin was redefined by the 26th CGPM in 2018 (Resolution 1, see p. 197).

Recommendation 5

The Comité International des Poids et Mesures (CIPM) acting in accordance with Resolution 7 of the 18th Conférence Générale des Poids et Mesures (1987) has adopted the International Temperature Scale of 1990 (ITS-90) to supersede the International Practical Temperature Scale of 1968 (IPTS-68).

The CIPM **notes** that, by comparison with the IPTS-68, the ITS-90

- extends to lower temperatures, down to 0.65 K, and hence also supersedes the EPT-76,
- is in substantially better agreement with corresponding thermodynamic temperatures,
- has much improved continuity, precision and reproducibility throughout its range and
- has subranges and alternative definitions in certain ranges which greatly facilitate its use.

The CIPM also **notes** that, to accompany the text of the ITS-90 there will be two further documents, the *Supplementary Information for the ITS-90* and *Techniques for Approximating the ITS-90*. These documents will be published by the BIPM and periodically updated.

The CIPM **recommends**

- that on 1 January 1990 the ITS-90 come into force and
- that from this same date the IPTS-68 and the EPT-76 be abrogated.

19th CGPM, 1991

■ **SI prefixes zetta, zepto, yotta and yocto** (CR, 185 and *Metrologia*, 1992, **29**, 3)

The names zepto and zetta are derived from septo suggesting the number seven (the seventh power of 10^3) and the letter "z" is substituted for the letter "s" to avoid the duplicate use of the letter "s" as a symbol. The names yocto and yotta are derived from octo, suggesting the number eight (the eighth power of 10^3); the letter "y" is added to avoid the use of the letter "o" as a symbol because it may be confused with the number zero.

Resolution 4

The 19th Conférence Générale des Poids et Mesures (CGPM)

decides to add to the list of SI prefixes to be used for multiples and submultiples of units, adopted by the 11th CGPM, Resolution 12, paragraph 3, the 12th CGPM, Resolution 8 and the 15th CGPM, Resolution 10, the following prefixes:

Multiplying factor	Prefix	Symbol
10^{21}	zetta	Z
10^{-21}	zepto	z
10^{24}	yotta	Y
10^{-24}	yocto	y

20th CGPM, 1995

■ **Elimination of the class of supplementary units in the SI** (CR, 223 and *Metrologia*, 1996, **33**, 83)

Resolution 8

The 20th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the 11th Conférence Générale in 1960 in its Resolution 12, establishing the Système International d'Unités, SI, distinguished between three classes of SI units: the base units, the derived units, and the supplementary units, the last of these comprising the radian and the steradian,
- that the status of the supplementary units in relation to the base units and the derived units gave rise to debate,
- that the Comité International des Poids et Mesures, in 1980, having observed that the ambiguous status of the supplementary units compromises the internal coherence of the SI, has in its Recommendation 1 (CI-1980) interpreted the supplementary units, in the SI, as dimensionless derived units,

approving the interpretation given by the Comité International in 1980,

decides

- 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, consequently, to eliminate the class of supplementary units as a separate class in the SI.

21st CGPM, 1999

■ **The definition of the kilogram** (CR, 331 and *Metrologia*, 2000, **37**, 94)

Resolution 7

The 21st Conférence Générale des Poids et Mesures,

considering

- the need to assure the long-term stability of the International System of Units (SI),
- the intrinsic uncertainty in the long-term stability of the artefact defining the unit of mass, one of the base units of the SI,
- the consequent uncertainty in the long-term stability of the other three base units of the SI that depend on the kilogram, namely, the ampere, the mole and the candela,

- the progress already made in a number of different experiments designed to link the unit of mass to fundamental or atomic constants,
- the desirability of having more than one method of making such a link,

recommends that national laboratories continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram.

■ Special name for the SI derived unit mole per second, the katal, for the expression of catalytic activity (CR, 334-335 and *Metrologia*, 2000, **37**, 95)

Resolution 12

The 21st Conférence Générale des Poids et Mesures,

considering

- the importance for human health and safety of facilitating the use of SI units in the fields of medicine and biochemistry,
- that a non-SI unit called "unit", symbol U, equal to 1 $\mu\text{mol} \cdot \text{min}^{-1}$, which is not coherent with the International System of Units (SI), has been in widespread use in medicine and biochemistry since 1964 for expressing catalytic activity,
- that the absence of a special name for the SI coherent derived unit mole per second has led to results of clinical measurements being given in various local units,
- that the use of SI units in medicine and clinical chemistry is strongly recommended by the international unions in these fields,
- that the International Federation of Clinical Chemistry and Laboratory Medicine has asked the Consultative Committee for Units to recommend the special name katal, symbol kat, for the SI unit mole per second,
- that while the proliferation of special names represents a danger for the SI, exceptions are made in matters related to human health and safety (15th General Conference, 1975, Resolutions 8 and 9, 16th General Conference, 1979, Resolution 5),

noting that the name katal, symbol kat, has been used for the SI unit mole per second for over thirty years to express catalytic activity,

decides to adopt the special name katal, symbol kat, for the SI unit mole per second to express catalytic activity, especially in the fields of medicine and biochemistry,

and **recommends** that when the katal is used, the measurand be specified by reference to the measurement procedure; the measurement procedure must identify the indicator reaction.

CIPM, 2001

■ "SI units" and "units of the SI" (PV, **69**, 120)

The CIPM approved in 2001 the following proposal of the CCU regarding "SI units" and "units of the SI":

"We suggest that "SI units" and "units of the SI" should be regarded as names that include both the base units and the coherent derived units, and also all units obtained by combining these with the recommended multiple and sub-multiple prefixes.

We suggest that the name "coherent SI units" should be used when it is desired to restrict the meaning to only the base units and the coherent derived units."

CIPM, 2002

■ **Revision of the practical realization of the definition of the metre** (PV, **70**, 194-204 and *Metrologia*, **40**, 103-133)

Recommendation 1

The International Committee for Weights and Measures,

recalling

- that in 1983 the 17th General Conference (CGPM) adopted a new definition of the metre;
- that in the same year the CGPM invited the International Committee (CIPM)
  - to draw up instructions for the practical realization of the metre,
  - to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use,
  - to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;
- that in response to this invitation the CIPM adopted Recommendation 1 (CI-1983) (*mise en pratique* of the definition of the metre) to the effect
  - that the metre should be realized by one of the following methods:

    (a) by means of the length l of the path travelled in vacuum by a plane electromagnetic wave in a time t; this length is obtained from the measured time t, using the relation $l = c_0 \cdot t$ and the value of the speed of light in vacuum c_0 = 299 792 458 m/s,

    (b) by means of the wavelength in vacuum λ of a plane electromagnetic wave of frequency f; this wavelength is obtained from the measured frequency f using the relation $\lambda = c_0 / f$ and the value of the speed of light in vacuum c_0 = 299 792 458 m/s,

    (c) by means of one of the radiations from the list below, whose stated wavelength in vacuum or whose stated frequency can be used with the uncertainty shown, provided that the given specifications and accepted good practice are followed;
  - that in all cases any necessary corrections be applied to take account of actual conditions such as diffraction, gravitation or imperfection in the vacuum;
  - that in the context of general relativity, the metre is considered a unit of proper length. Its definition, therefore, applies only within a spatial extent sufficiently small that the effects of the non-uniformity of the gravitational field can be ignored (note that, at the surface of the Earth, this effect in the vertical direction is about 1 part in 10^{16} per metre). In this case, the effects to be taken into account are those of special relativity only. The local methods for the realization of the metre recommended in (b) and (c) provide the proper metre but not necessarily that given in (a). Method (a) should therefore be restricted to lengths l which are sufficiently short for the effects predicted by general relativity to be negligible with respect to the uncertainties of realization. For advice on the interpretation of measurements in which this is not the case, see the report of the Consultative Committee for Time and Frequency (CCTF) Working Group on the Application of General Relativity to Metrology (Application of general relativity to metrology, *Metrologia*, 1997, **34**, 261-290);
- that the CIPM had already recommended a list of radiations for this purpose;

recalling also that in 1992 and in 1997 the CIPM revised the practical realization of the definition of the metre;

considering

- that science and technology continue to demand improved accuracy in the realization of the metre;
- that since 1997 work in national laboratories, in the BIPM and elsewhere has identified new radiations and methods for their realization which lead to lower uncertainties;

- that there is an increasing move towards optical frequencies for time-related activities, and that there continues to be a general widening of the scope of application of the recommended radiations of the *mise en pratique* to cover not only dimensional metrology and the realization of the metre, but also high-resolution spectroscopy, atomic and molecular physics, fundamental constants and telecommunication;
- that a number of new frequency values with reduced uncertainties for radiations of high-stability cold atom and ion standards already listed in the recommended radiations list are now available, that the frequencies of radiations of several new cold atom and ion species have also recently been measured, and that new improved values with substantially reduced uncertainties for a number of optical frequency standards based on gas cells have been determined, including the wavelength region of interest to optical telecommunications;
- that new femtosecond comb techniques have clear significance for relating the frequency of high-stability optical frequency standards to that of the frequency standard realizing the SI second, that these techniques represent a convenient measurement technique for providing traceability to the International System of Units (SI) and that comb technology also can provide frequency sources as well as a measurement technique;

recognizes comb techniques as timely and appropriate, and recommends further research to fully investigate the capability of the techniques;

welcomes validations now being made of comb techniques by comparison with other frequency chain techniques;

urges national metrology institutes and other laboratories to pursue the comb technique to the highest level of accuracy achievable and also to seek simplicity so as to encourage widespread application;

recommends

- that the list of recommended radiations given by the CIPM in 1997 (Recommendation 1 (CI-1997)) be replaced by the list of radiations given below*, including
  - updated frequency values for cold Ca atom, H atom and the trapped Sr^+ ion,
  - frequency values for new cold ion species including trapped Hg^+ ion, trapped In^+ ion and trapped Yb^+ ion,
  - updated frequency values for Rb-stabilized lasers, I_2-stabilized Nd:YAG and He-Ne lasers, CH_4-stabilized He-Ne lasers and OsO_4-stabilized CO_2 lasers at 10 μm,
  - frequency values for standards relevant to the optical communications bands, including Rb- and C_2H_2-stabilized lasers.

* The list of recommended radiations, Recommendation 1 (CI-2002), is given in PV, **70**, 197-204 and *Metrologia*, 2003, **40**, 104-115.

. . .

■ **Dose equivalent** (PV, **70**, 205)

See also *J. Radiol. Prot.*, 2005, **25**, 97-100.

Recommendation 2

The International Committee for Weights and Measures,

considering that

- the current definition of the SI unit of dose equivalent (sievert) includes a factor "*N*" (product of any other multiplying factors) stipulated by the International Commission on Radiological Protection (ICRP), and
- both the ICRP and the International Commission on Radiation Units and Measurements (ICRU) have decided to delete this factor *N* as it is no longer deemed to be necessary, and
- the current SI definition of *H* including the factor *N* is causing some confusion,

decides to change the explanation in the brochure "Le Système International d'Unités (SI)" to the following:

The quantity dose equivalent *H* is the product of the absorbed dose *D* of ionizing radiation and the dimensionless factor *Q* (quality factor) defined as a function of linear energy transfer by the ICRU:

$$H = Q \cdot D.$$

Thus, for a given radiation, the numerical value of *H* in joules per kilogram may differ from that of *D* in joules per kilogram depending on the value of *Q.*

The Committee further **decides** to maintain the final sentence in the explanation as follows:

In order to avoid any risk of confusion between the absorbed dose *D* and the dose equivalent *H*, the special names for the respective units should be used, that is, the name gray should be used instead of joules per kilogram for the unit of absorbed dose *D* and the name sievert instead of joules per kilogram for the unit of dose equivalent *H.*

CIPM, 2003

■ Revision of the *Mise en Pratique* list of recommended radiations (PV*,* **71***,* 146 and *Metrologia*, 2004, **41**, 99-100)

Recommendation 1

The International Committee for Weights and Measures,

considering that

- improved frequency values for radiations of some high-stability cold ion standards already documented in the recommended radiations list have recently become available;
- improved frequency values for the infra-red gas-cell-based optical frequency standard in the optical telecommunications region, already documented in the recommended radiations list, have been determined;
- femtosecond comb-based frequency measurements for certain iodine gas-cell standards on the subsidiary recommended source list have recently been made for the first time, leading to significantly reduced uncertainty;

proposes that the *recommended radiation* list be revised to include the following:

- updated frequency values for the single trapped $^{88}Sr^{+}$ ion quadrupole transition and the single trapped $^{171}Yb^{+}$ octupole transition;
- an updated frequency value for the C_2H_2-stabilized standard at 1.54 μm;
- updated frequency values for the I_2-stabilized standards at 543 nm and 515 nm.

22nd CGPM, 2003

■ Symbol for the decimal marker (CR, 381 and *Metrologia*, 2004, **41**, 104)

Resolution 10

The 22nd General Conference,

considering that

- a principal purpose of the International System of Units (SI) is to enable values of quantities to be expressed in a manner that can be readily understood throughout the world,
- the value of a quantity is normally expressed as a number times a unit,
- often the number in the expression of the value of a quantity contains multiple digits with an integral part and a decimal part,
- in Resolution 7 of the 9th General Conference, 1948, it is stated that “In numbers, the comma (French practice) or the dot (British practice) is used only to separate the integral part of numbers from the decimal part”,
- following a decision of the International Committee made at its 86th meeting (1997), the International Bureau of Weights and Measures now uses the dot (point on the line) as the decimal marker in all the English language versions of its publications, including the English text of the SI Brochure (the definitive international reference on the SI), with the comma (on the line) remaining the decimal marker in all of its French language publications,
- however, some international bodies use the comma on the line as the decimal marker in their English language documents,

- furthermore, some international bodies, including some international standards organizations, specify the decimal marker to be the comma on the line in all languages,
- the prescription of the comma on the line as the decimal marker is in many languages in conflict with the customary usage of the point on the line as the decimal marker in those languages,
- in some languages that are native to more than one country, either the point on the line or the comma on the line is used as the decimal marker depending on the country, while in some countries with more than one native language, either the point on the line or comma on the line is used depending on the language,

declares that the symbol for the decimal marker shall be either the point on the line or the comma on the line,

reaffirms that "Numbers may be divided in groups of three in order to facilitate reading; neither dots nor commas are ever inserted in the spaces between groups", as stated in Resolution 7 of the 9th CGPM, 1948.

CIPM, 2005

■ Clarification of the definition of the kelvin, unit of thermodynamic temperature (PV, **73**, 235 and *Metrologia*, 2006, **43**, 177-178)*

* The kelvin was redefined by the 26th CGPM in 2018 (Resolution 1, see p. 197).

Recommendation 2

The International Committee for Weights and Measures (CIPM),

considering

- that the kelvin, unit of thermodynamic temperature, is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water,
- that the temperature of the triple point depends on the relative amount of isotopes of hydrogen and oxygen present in the sample of water used,
- that this effect is now one of the major sources of the observed variability between different realizations of the water triple point,

decides

- that the definition of the kelvin refer to water of a specified isotopic composition,
- that this composition be:

  0.000 155 76 mole of ^{2}H per mole of ^{1}H,

  0.000 379 9 mole of ^{17}O per mole of ^{16}O, and

  0.002 005 2 mole of ^{18}O per mole of ^{16}O,

which is the composition of the International Atomic Energy Agency reference material Vienna Standard Mean Ocean Water (VSMOW), as recommended by IUPAC in "Atomic Weights of the Elements: Review 2000".

- that this composition be stated in a note attached to the definition of the kelvin in the SI brochure as follows:

  "This definition refers to water having the isotopic composition defined exactly by the following amount of substance ratios: 0.000 155 76 mole of ^{2}H per mole of ^{1}H, 0.000 379 9 mole of ^{17}O per mole of ^{16}O and 0.002 005 2 mole of ^{18}O per mole of ^{16}O".

■ **Revision of the *Mise en pratique* list of recommended radiations** (PV*,* **73,** 236 and *Metrologia*, 2006, **43**, 178)

Recommendation 3

The International Committee for Weights and Measures (CIPM),

considering that:

- improved frequency values for radiations of some high-stability cold ion and cold atom standards already documented in the recommended radiations list have recently become available;
- improved frequency values for the infra-red gas-cell-based optical frequency standard in the optical telecommunications region, already documented in the recommended radiations list, have been determined;
- improved frequency values for certain iodine gas-cell standard, already documented in the subsidiary recommended source list, have been determined;
- frequencies of new cold atoms, of atoms in the near-infrared region and of molecules in the optical telecommunications region have been determined by femtosecond comb-based frequency measurements for the first time;

decides that the list of *recommended radiations* be revised to include the following:

- updated frequency values for the single trapped $^{88}Sr^{+}$ ion quadrupole transition, the single trapped $^{199}Hg^{+}$ quadrupole transition and the single trapped $^{171}Yb^{+}$ quadrupole transition;
- an updated frequency value for the Ca atom transition;
- an updated frequency value for the C_2H_2-stabilized standard at 1.54 μm;
- an updated frequency value for the I_2-stabilized standard at 515 nm;
- the addition of the ^{87}Sr atom transition at 698 nm;
- the addition of the ^{87}Rb atom two-photon transitions at 760 nm;
- the addition of the $^{12}C_2H_2$ ($\nu1 + \nu3$) band and the $^{13}C_2H_2$ ($\nu1 + \nu3$) and ($\nu1 + \nu3 + \nu4 + \nu5$) bands at 1.54 μm.

CIPM, 2006

■ **Concerning secondary representations of the second** (PV*,* **74,** 249 and *Metrologia*, 2007, **44**, 97)

Recommendation 1

The International Committee for Weights and Measures (CIPM),

considering that

- a common list of “Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second” shall be established,
- the CCL/CCTF Joint Working Group (JWG) on the *Mise en Pratique* of the Definition of the Metre and the Secondary Representations of the Second in its meeting at the International Bureau of Weights and Measures (BIPM) in September 2005 discussed possible candidates to be included in this list for secondary representations of the second,
- the CCL/CCTF JWG reviewed and updated the values for the Hg ion, Sr ion, Yb ion, and the Sr neutral atom transition frequencies in its session in September 2006,
- the CCTF in its Recommendation CCTF 1 (2004) already recommended the unperturbed ground-state hyperfine quantum transition frequency of 87Rb as a secondary representation of the second;

recommends that the following transition frequencies shall be used as secondary representations of the second and be included into the new list of “Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second”

- the unperturbed ground-state hyperfine quantum transition of ^{87}Rb with a frequency of f^{87}_{Rb} = 6 834 682 610.904 324 Hz and an estimated relative standard uncertainty of 3×10^{-15},
- the unperturbed optical 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ transition of the $^{88}Sr^+$ ion with a frequency of $f^{88}Sr^+$ = 444 779 044 095 484 Hz and a relative uncertainty of 7×10^{-15},
- the unperturbed optical 5d^{10} 6s $^2S_{1/2}$ (F = 0) – 5d^9 6s^2 $^2D_{5/2}$ (F = 2) transition of the $^{199}Hg^+$ ion with a frequency of $f^{199}Hg^+$ = 1 064 721 609 899 145 Hz and a relative standard uncertainty of 3×10^{-15},
- the unperturbed optical 6s $^2S_{1/2}$ (F = 0) – 5d $^2D_{3/2}$ (F = 2) transition of the $^{171}Yb^+$ ion with a frequency of $f^{171}Yb^+$ = 688 358 979 309 308 Hz and a relative standard uncertainty of 9×10^{-15},
- the unperturbed optical transition 5s^2 $^1S_0$ – 5s 5p $^3P_0$ of the ^{87}Sr neutral atom with a frequency of f^{87}_{Sr} = 429 228 004 229 877 Hz and a relative standard uncertainty of 1.5×10^{-14}.

CIPM, 2007

■ Revision of the Mise en pratique list of recommended radiations (PV, **75,** 185)

Recommendation 1

The International Committee for Weights and Measures,

considering that:

- improved frequency values of molecules in the optical telecommunications region, already documented in the list of standard frequencies, have been determined by femtosecond comb-based frequency measurements;
- frequencies of molecules in the optical telecommunications region have been determined by femtosecond comb-based frequency measurements for the first time;
- frequencies of certain iodine gas-cell absorptions close to the 532 nm optical frequency standard have been determined by femtosecond comb-based frequency measurements for the first time;

proposes that the list of standard frequencies be revised to include the following:

- an updated list of frequency values for the $^{12}C_2H_2$ ($\nu 1 + \nu 3$) band at 1.54 µm;
- the addition of frequency values for the $^{12}C_2HD$ ($2\nu_1$) band at 1.54 µm;
- the addition of frequency values for the hyperfine components of the P(142) 37-0, R(121) 35-0 and R(85) 33-0 iodine transitions at 532 nm.

23rd CGPM, 2007

■ On the revision of the mise en pratique of the definition of the metre and the development of new optical frequency standards (CR, 431)

Resolution 9

The 23rd General Conference,

considering that:

- there have been rapid and important improvements in the performance of optical frequency standards,
- femtosecond comb techniques are now used routinely for relating optical and microwave radiations at a single location,
- National Metrology Institutes (NMIs) are working on comparison techniques for optical frequency standards over short distances,
- remote comparison techniques need to be developed at an international level so that optical frequency standards can be compared,

welcomes

- the activities of the Joint Working Group of the Consultative Committee for Length and the Consultative Committee for Time and Frequency to review the frequencies of optically-based representations of the second,
- the additions to the *mise en pratique* of the definition of the metre and to the list of recommended radiations made by the International Committee in 2002, 2003, 2005, 2006, and 2007,
- the initiative taken by the International Bureau of Weights and Measures (BIPM) to raise the issue of how to compare optical frequency standards,

recommends that:

- NMIs commit resources to the development of optical frequency standards and their comparison,
- the BIPM works toward the coordination of an international project with the participation of NMIs, oriented to the study of the techniques which could serve to compare optical frequency standards.

■ Clarification of the definition of the kelvin, unit of thermodynamic temperature (CR, 432)

The kelvin was redefined by the 26th CGPM in 2018 (Resolution 1, see p. 197).

Resolution 10

The 23rd General Conference,

considering

- that the kelvin, unit of thermodynamic temperature, is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water,
- that the temperature of the triple point depends on the relative amount of isotopes of hydrogen and oxygen present in the sample of water used,
- that this effect is now one of the major sources of the observed variability between different realizations of the water triple point,

notes and welcomes the decision by the International Committee for Weights and Measures in October 2005, on the advice of the Consultative Committee for Thermometry, that

- the definition of the kelvin refers to water of a specified isotopic composition,
- this composition be:

  0.000 155 76 mole of ^{2}H per mole of ^{1}H,

  0.000 379 9 mole of ^{17}O per mole of ^{16}O, and

  0.002 005 2 mole of ^{18}O per mole of ^{16}O,

which is the composition of the International Atomic Energy Agency reference material Vienna Standard Mean Ocean Water (VSMOW), as recommended by the International Union of Pure and Applied Chemistry in "Atomic Weights of the Elements: Review 2000",

- this composition be stated in a note attached to the definition of the kelvin in the SI Brochure as follows:

  "This definition refers to water having the isotopic composition defined by the following amount-of-substance ratios: 0.000 155 76 mole of ^{2}H per mole of ^{1}H, 0.000 379 9 mole of ^{17}O per mole of ^{16}O and 0.002 005 2 mole of ^{18}O per mole of ^{16}O".

■ On the possible redefinition of certain base units of the International System of Units (SI) (CR, 434)

The 26th CGPM in 2018 (Resolution 1, see p. 197) finally approved the revision of the SI.

Resolution 12

The 23rd General Conference,

considering

- that, for many years, National Metrology Institutes (NMIs) as well as the International Bureau of Weights and Measures (BIPM) have made considerable efforts to advance and improve the International System of Units (SI) by extending the frontiers of metrology so that the SI base units could be defined in terms of the invariants of nature - the fundamental physical constants,
- that, of the seven base units of the SI, only the kilogram is still defined in terms of a material artefact - the international prototype of the kilogram (2nd CGPM, 1889, 3rd CGPM, 1901) and that the definitions of the ampere, mole and candela depend on the kilogram,
- Resolution 7 of the 21st General Conference (1999) which recommended that "national laboratories continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram",
- the many advances, made in recent years, in experiments which relate the mass of the international prototype to the Planck constant h or the Avogadro constant N_A,
- initiatives to determine the value of a number of relevant fundamental constants, including work to redetermine the Boltzmann constant k_B,
- that as a result of recent advances, there are significant implications for, and potential benefits from, redefinitions of the kilogram, the ampere, the kelvin and the mole,
- Recommendation 1 of the International Committee (C1-2005) at its meeting in October 2005, and various Recommendations of Consultative Committees on the subject of a redefinition of one or more of the base units of the SI,

noting

- that any changes in definitions of units of the SI must be constrained by self-consistency,
- that it is desirable that definitions of the base units should be easily understood,
- the work of the International Committee and the Consultative Committees,
- the need to monitor the results of relevant experiments,
- the importance of soliciting comments and contributions from the wider scientific and user communities, and
- the decision of the International Committee in 2005 to approve, in principle, the preparation of new definitions of the kilogram, ampere, kelvin and the possibility of redefining the mole,

recommends that National Metrology Institutes and the BIPM

- pursue the relevant experiments so that the International Committee can come to a view on whether it may be possible to redefine the kilogram, the ampere, the kelvin, and the mole using fixed values of the fundamental constants at the time of the 24th General Conference (2011),
- should, together with the International Committee, its Consultative Committees, and appropriate working groups, work on practical ways of realizing any new definitions based on fixed values of the fundamental constants, prepare a mise en pratique for each of them, and consider the most appropriate way of explaining the new definitions to users,
- initiate awareness campaigns to alert user communities to the possibility of redefinitions and that the technical and legislative implications of such redefinitions and their practical realizations be carefully discussed and considered,

and requests the International Committee to report on these issues to the 24th General Conference in 2011 and to undertake whatever preparations are considered necessary so that, if the results of experiments are found to be satisfactory and the needs of users met, formal proposals for changes in the definitions of the kilogram, ampere, the kelvin and mole can be put to the 24th General Conference.

CIPM, 2009

■ **Updates to the list of standard frequencies** (PV, **77,** 235)

Recommendation 2

The International Committee for Weights and Measures (CIPM),

considering that

- a common list of "Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second" has been established;
- the CCL-CCTF Frequency Standards Working Group (FSWG) has reviewed several promising candidates for inclusion in the list;

recommends

that the following transition frequencies shall be included or updated in the list of recommended standard frequencies:

- the unperturbed optical transition $5s^2\ {}^1S_0 – 5s\ 5p\ {}^3P_0$ of the ^{87}Sr neutral atom with a frequency of f = 429 228 004 229 873.7 Hz and a relative standard uncertainty of 1×10^{-15} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $5s^2\ {}^1S_0 – 5s\ 5p\ {}^3P_0$ of the ^{88}Sr neutral atom with a frequency of f = 429 228 066 418 012 Hz and a relative standard uncertainty of 1×10^{-14};
- the unperturbed optical transition $4s\ {}^2S_{1/2} – 3d\ {}^2D_{5/2}$ of the $^{40}Ca^+$ ion with a frequency of f = 411 042 129 776 393 Hz and a relative standard uncertainty of 4×10^{-14};
- the unperturbed optical transition ${}^2S_{1/2}$ (F = 0) – ${}^2F_{7/2}$ (F = 3, m_F = 0) of the $^{171}Yb^+$ ion with a frequency of f = 642 121 496 772 657 Hz and a relative standard uncertainty of 6×10^{-14};
- the unperturbed optical transition $6s^2\ {}^1S_0$ (F = 1/2) – $6s\ 6p\ {}^3P_0$ (F = 1/2) of the ^{171}Yb neutral atom with a frequency of f = 518 295 836 590 864 Hz and a relative standard uncertainty of 1.6×10^{-13}.

24th CGPM, 2011

■ **On the possible future revision of the International System of Units, the SI** (CR, 532)

The 26th CGPM in 2018 (Resolution 1, see p. 197) finally approved the revision of the SI.

Resolution 1

The General Conference on Weights and Measures (CGPM), at its 24th meeting,

considering

- the international consensus on the importance, value, and potential benefits of a redefinition of a number of units of the International System of Units (SI),
- that the national metrology institutes (NMIs) as well as the International Bureau of Weights and Measures (BIPM) have rightfully expended significant effort during the last several decades to advance the International System of Units (SI) by extending the frontiers of metrology so that SI base units can be defined in terms of the invariants of nature - the fundamental physical constants or properties of atoms,
- that a prominent example of the success of such efforts is the current definition of the SI unit of length, the metre (17th meeting of the CGPM, 1983, Resolution 1), which links it to an exact value of the speed of light in vacuum c, namely, 299 792 458 metre per second,
- that of the seven base units of the SI, only the kilogram is still defined in terms of a material artefact, namely, the international prototype of the kilogram (1st meeting of the CGPM, 1889, 3rd meeting of the CGPM, 1901), and that the definitions of the ampere, mole and candela depend on the kilogram,
- that although the international prototype has served science and technology well since it was sanctioned by the CGPM at its 1st meeting in 1889, it has a number of important limitations, one of the most significant being that its mass is not explicitly linked to an invariant of nature and in consequence its long-term stability is not assured,

- that the CGPM at its 21st meeting in 1999 adopted Resolution 7 in which it recommended that "national laboratories continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram",
- that many advances have been made in recent years in relating the mass of the international prototype to the Planck constant h, by methods which include watt balances and measurements of the mass of a silicon atom,
- that the uncertainties of all SI electrical units realized directly or indirectly by means of the Josephson and quantum Hall effects together with the SI values of the Josephson and von Klitzing constants K_J and R_K could be significantly reduced if the kilogram were redefined so as to be linked to an exact numerical value of h, and if the ampere were to be redefined so as to be linked to an exact numerical value of the elementary charge e,
- that the kelvin is currently defined in terms of an intrinsic property of water that, while being an invariant of nature, in practice depends on the purity and isotopic composition of the water used,
- that it is possible to redefine the kelvin so that it is linked to an exact numerical value of the Boltzmann constant k,
- that it is also possible to redefine the mole so that it is linked to an exact numerical value of the Avogadro constant N_A, and is thus no longer dependent on the definition of the kilogram even when the kilogram is defined so that it is linked to an exact numerical value of h, thereby emphasizing the distinction between amount of substance and mass,
- that the uncertainties of the values of many other important fundamental constants and energy conversion factors would be eliminated or greatly reduced if h, e, k and N_A had exact numerical values when expressed in SI units,
- that the General Conference, at its 23rd meeting in 2007, adopted Resolution 12 in which it outlined the work that should be carried out by the NMIs, the BIPM and the International Committee for Weights and Measures (CIPM) together with its Consultative Committees (CCs) so that new definitions of the kilogram, ampere, kelvin, and mole in terms of fundamental constants could be adopted,
- that, although this work has progressed well, not all the requirements set out in Resolution 12 adopted by the General Conference at its 23rd meeting in 2007 have been satisfied and so the International Committee for Weights and Measures is not yet ready to make a final proposal,
- that, nevertheless, a clear and detailed explanation of what is likely to be proposed can now be presented,

takes note of the intention of the International Committee for Weights and Measures to propose a revision of the SI as follows:

- the International System of Units, the SI, will be the system of units in which:
  - the ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$ is exactly 9 192 631 770 hertz,
  - the speed of light in vacuum c is exactly 299 792 458 metre per second,
  - the Planck constant h is exactly 6.626 06X $\times 10^{-34}$ joule second*,
  - the elementary charge e is exactly 1.602 17X $\times 10^{-19}$ coulomb,
  - the Boltzmann constant k is exactly 1.380 6X $\times 10^{-23}$ joule per kelvin,
  - the Avogadro constant N_A is exactly 6.022 14X $\times 10^{23}$ reciprocal mole,
  - the luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} Hz is exactly 683 lumen per watt,

* The X digit appearing in the expression of the constants indicates that this digit was unknown at the time of the resolution.

where

(i) 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 Hz = s^{-1}, J = m^2 kg s^{-2}, C = s A, lm = cd m^2 m^{-2} = cd sr, and W = m^2 kg s^{-3},

(ii) the symbol X in this Draft Resolution represents one or more additional digits to be added to the numerical values of h, e, k, and N_A, using values based on the most recent CODATA adjustment,

from which it follows that the SI will continue to have the present set of seven base units, in particular

- the kilogram will continue to be the unit of mass, but its magnitude will be set by fixing the numerical value of the Planck constant to be equal to exactly $6.626\ 06X \times 10^{-34}$ when it is expressed in the SI unit $m^2\ kg\ s^{-1}$, which is equal to J s,
- the ampere will continue to be the unit of electric current, but its magnitude will be set by fixing the numerical value of the elementary charge to be equal to exactly $1.602\ 17X \times 10^{-19}$ when it is expressed in the SI unit s A, which is equal to C,
- the kelvin will continue to be the unit of thermodynamic temperature, but its magnitude will be set by fixing the numerical value of the Boltzmann constant to be equal to exactly $1.380\ 6X \times 10^{-23}$ when it is expressed in the SI unit $m^2\ kg\ s^{-2}\ K^{-1}$, which is equal to $J\ K^{-1}$,
- the mole will continue to be the unit of amount of substance of a specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles, but its magnitude will be set by fixing the numerical value of the Avogadro constant to be equal to exactly $6.022\ 14X \times 10^{23}$ when it is expressed in the SI unit mol^{-1}.

The General Conference on Weights and Measures

further notes that since

- the new definitions of the kilogram, ampere, kelvin and mole are intended to be of the explicit-constant type, that is, a definition in which the unit is defined indirectly by specifying explicitly an exact value for a well-recognized fundamental constant,
- the existing definition of the metre is linked to an exact value of the speed of light in vacuum, which is also a well-recognized fundamental constant,
- the existing definition of the second is linked to an exact value of a well-defined property of the caesium atom, which is also an invariant of nature,
- although the existing definition of the candela is not linked to a fundamental constant, it may be viewed as being linked to an exact value of an invariant of nature,
- it would enhance the understandability of the International System if all of its base units were of similar wording,

the International Committee for Weights and Measures will also propose

the reformulation of the existing definitions of the second, metre and candela in completely equivalent forms, which might be the following:

- the second, symbol s, is the unit of time; its magnitude is set by fixing the numerical value of the ground state hyperfine splitting frequency of the caesium 133 atom, at rest and at a temperature of 0 K, to be equal to exactly 9 192 631 770 when it is expressed in the SI unit s^{-1}, which is equal to Hz,
- the metre, symbol m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299 792 458 when it is expressed in the SI unit $m\ s^{-1}$,
- the candela, symbol cd, is the unit of luminous intensity in a given direction; its magnitude is set by fixing the numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz to be equal to exactly 683 when it is expressed in the SI unit $m^{-2}\ kg^{-1}\ s^3$ cd sr, or cd sr W^{-1}, which is equal to lm W^{-1}.

In this way, the definitions of all seven base units will be seen to follow naturally from the set of seven constants given above.

In consequence, on the date chosen for the implementation of the revision of the SI:

- the definition of the kilogram in force since 1889 based upon the mass of the international prototype of the kilogram (1st meeting of the CGPM, 1889, 3rd meeting of the CGPM, 1901) will be abrogated,
- the definition of the ampere in force since 1948 (9th meeting of the CGPM, 1948) based upon the definition proposed by the International Committee (CIPM, 1946, Resolution 2) will be abrogated,
- the conventional values of the Josephson constant $K_{J\text{-}90}$ and of the von Klitzing constant $R_{K\text{-}90}$ adopted by the International Committee (CIPM, 1988, Recommendations 1 and 2) at the request of the General Conference (18th meeting of the CGPM, 1987, Resolution 6) for the establishment of representations of the volt and the ohm using the Josephson and quantum Hall effects, respectively, will be abrogated,
- the definition of the kelvin in force since 1967/68 (13th meeting of the CGPM, 1967/68, Resolution 4) based upon a less explicit, earlier definition (10th meeting of the CGPM, 1954, Resolution 3) will be abrogated,
- the definition of the mole in force since 1971 (14th meeting of the CGPM, 1971, Resolution 3) based upon a definition whereby the molar mass of carbon 12 had the exact value 0.012 kg mol^{-1} will be abrogated,
- the existing definitions of the metre, second and candela in force since they were adopted by the CGPM at its 17th (1983, Resolution 1), 13th (1967/68, Resolution 1) and 16th (1979, Resolution 3) meetings, respectively, will be abrogated.

The General Conference on Weights and Measures

further notes that on the same date

- the mass of the international prototype of the kilogram $m(K)$ will be 1 kg but with a relative uncertainty equal to that of the recommended value of h just before redefinition and that subsequently its value will be determined experimentally,
- that the magnetic constant (permeability of vacuum) μ_0 will be $4\pi \times 10^{-7}$ H m^{-1} but with a relative uncertainty equal to that of the recommended value of the fine-structure constant alpha and that subsequently its value will be determined experimentally,
- that the thermodynamic temperature of the triple point of water T_{TPW} will be 273.16 K but with a relative uncertainty equal to that of the recommended value of k just before redefinition and that subsequently its value will be determined experimentally,
- that the molar mass of carbon 12 $M(^{12}C)$ will be 0.012 kg mol^{-1} but with a relative uncertainty equal to that of the recommended value of $N_A h$ just before redefinition and that subsequently its value will be determined experimentally.

The General Conference on Weights and Measures

encourages

- researchers in national metrology institutes, the BIPM and academic institutions to continue their efforts and make known to the scientific community in general and to CODATA in particular, the outcome of their work relevant to the determination of the constants h, e, k, and N_A, and
- the BIPM to continue its work on relating the traceability of the prototypes it maintains to the international prototype of the kilogram, and in developing a pool of reference standards to facilitate the dissemination of the unit of mass when redefined,

invites

- CODATA to continue to provide adjusted values of the fundamental physical constants based on all relevant information available and to make the results known to the International Committee through its Consultative Committee for Units since these CODATA values and uncertainties will be those used for the revised SI,

- the CIPM to make a proposal for the revision of the SI as soon as the recommendations of Resolution 12 of the 23rd meeting of the General Conference are fulfilled, in particular the preparation of *mises en pratique* for the new definitions of the kilogram, ampere, kelvin and mole,
- the CIPM to continue its work towards improved formulations for the definitions of the SI base units in terms of fundamental constants, having as far as possible a more easily understandable description for users in general, consistent with scientific rigour and clarity,
- the CIPM, the Consultative Committees, the BIPM, the OIML and National Metrology Institutes significantly to increase their efforts to initiate awareness campaigns aimed at alerting user communities and the general public to the intention to redefine various units of the SI and to encourage consideration of the practical, technical, and legislative implications of such redefinitions, so that comments and contributions can be solicited from the wider scientific and user communities.

■ On the revision of the mise en pratique of the metre and the development of new optical frequency standards (CR, 546)

Resolution 8

The General Conference on Weight and Measures (CGPM), at its 24th meeting,

considering that

- there have been rapid and important improvements in the performance of optical frequency standards,
- national metrology institutes are working on comparison techniques for optical frequency standards over short distances,
- remote comparison techniques need to be developed at an international level so that optical frequency standards can be compared,

welcomes

- the activities of the joint working group of the CCTF and the CCL to review the frequencies of optically-based representations of the second,
- the additions made by the CIPM in 2009 to the common list of "Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second",
- the establishment of a CCTF working group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques,

recommends that

- NMIs commit resources to the development of optical frequency standards and their comparison,
- the BIPM supports the coordination of an international project with the participation of NMIs, oriented to the study of the techniques which could serve to compare optical frequency standards**.**

CIPM, 2013

■ Updates to the list of standard frequencies (PV, **81,** 144)

Recommendation 1

The International Committee for Weights and Measures (CIPM),

considering that

- a common list of “Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second” has been established,
- the CCL-CCTF Frequency Standards Working Group (FSWG) has reviewed several candidates for inclusion into the list,

recommends the following changes to the list of "Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second":

- that the following transition frequency be added to the list:
  - the unperturbed optical transition $6s^2\ {}^1S_0$ – 6s 6p ${}^3P_0$ of the ${}^{199}Hg$ neutral atom with a frequency of 1 128 575 290 808 162 Hz and an estimated relative standard uncertainty of 1.7×10^{-14};
- that the following transition frequencies be updated in the list:
  - the unperturbed optical transition 4s ${}^2S_{1/2}$ – 3d ${}^2D_{5/2}$ of the ${}^{40}Ca^+$ ion with a frequency of 411 042 129 776 395 Hz and an estimated relative standard uncertainty of 1.5×10^{-14};
  - the unperturbed optical transition 1S – 2S of the ${}^1H$ neutral atom with a frequency of 1 233 030 706 593 518 Hz and an estimated relative standard uncertainty of 1.2×10^{-14};

Note: This frequency corresponds to half of the energy difference between the 1S and 2S states;

- that the following transition frequencies be updated in the list and endorsed as secondary representations of the second:
  - the unperturbed optical transition 6s ${}^2S_{1/2}$ – 4f ${}^{13}6s^2\ {}^2F_{7/2}$ of the ${}^{171}Yb^+$ ion (octupole) with a frequency of 642 121 496 772 645.6 Hz and an estimated relative standard uncertainty of 1.3×10^{-15};
  - the unperturbed optical transition $6s^2\ {}^1S_0$ – 6s 6p ${}^3P0$ of the ${}^{171}Yb$ neutral atom with a frequency of 518 295 836 590 865.0 Hz and an estimated relative standard uncertainty of 2.7×10^{-15};
- that the following transition frequency be added to the list and as a secondary representation of the second:
  - the unperturbed optical transition $3s^2\ {}^1S_0$ – 3s 3p ${}^3P_0$ of the ${}^{27}Al^+$ ion with a frequency of 1 121 015 393 207 857.3 Hz and an estimated relative standard uncertainty of 1.9×10^{-15};
- that the following transition frequencies be updated in the list and as secondary representations of the second:
  - the unperturbed optical transition 5d ${}^{10}6s$ ${}^2S_{1/2}$ – 5d ${}^9 6s^2\ {}^2D_{5/2}$ of the ${}^{199}Hg^+$ ion with a frequency of 1 064 721 609 899 145.3 Hz and an estimated relative standard uncertainty of 1.9×10^{-15};
  - the unperturbed optical transition 6s ${}^2S_{1/2}$ ($F = 0$, $m_F = 0$) – 5d ${}^2D_{3/2}$ ($F = 2$, $m_F = 0$) of the 171Yb+ ion (quadrupole) with a frequency of 688 358 979 309 307.1 Hz and an estimated relative standard uncertainty of 3×10^{-15};
  - the unperturbed optical transition 5s ${}^2S_{1/2}$ – 4d ${}^2D_{5/2}$ of the ${}^{88}Sr^+$ ion with a frequency of 444 779 044 095 485.3 Hz and an estimated relative standard uncertainty of 4.0×10^{-15};
  - the unperturbed optical transition $5s^2\ {}^1S_0$ – 5s5p ${}^3P_0$ of the ${}^{87}Sr$ neutral atom with a frequency of 429 228 004 229 873.4 Hz and an estimated relative standard uncertainty of 1×10^{-15};
- that the following transition frequency be updated as a secondary representation of the second:
  - the unperturbed ground - state hyperfine transition of ${}^{87}Rb$ with a frequency of 6 834 682 610.904 312 Hz and an estimated relative standard uncertainty of 1.3×10^{-15}.

Note: The value of the estimated standard uncertainty is assumed to correspond to a confidence level of 68 %. However, given the very limited number of available data there is a possibility that in hindsight this might not prove to be exact.

25th CGPM, 2014

■ **On the future revision of the International System of Units, the SI** (CR, 416 and *Metrologia*, 2015, **52**, 155)

The 26th CGPM in 2018 (Resolution 1, see p. 197) finally approved the revision of the SI.

Resolution 1

The General Conference on Weights and Measures (CGPM), at its 25th meeting,

recalling

- Resolution 1 adopted by the CGPM at its 24th meeting (2011), which takes note of the intention of the International Committee for Weights and Measures (CIPM) to propose a revision of the SI that links the definitions of the kilogram, ampere, kelvin, and mole to exact numerical values of the Planck constant h, elementary charge e, Boltzmann constant k, and Avogadro constant N_A, respectively, and which revises the way the SI is defined including the wording of the definitions of the SI units for time, length, mass, electric current, thermodynamic temperature, amount of substance, and luminous intensity so that the reference constants on which the SI is based are clearly apparent,
- the many benefits summarized in Resolution 1 that will accrue to science, technology, industry, and commerce from such a revision, especially from linking the kilogram to an invariant of nature rather than to the mass of a material artefact, thereby ensuring its long-term stability,
- Resolution 7 adopted by the CGPM at its 21st meeting (1999), which encourages work at the National Metrology Institutes (NMIs) that can lead to such a redefinition of the kilogram,
- Resolution 12 adopted by the CGPM at its 23rd meeting (2007), which outlines the work that should be carried out by the NMIs, the International Bureau of Weights and Measures (BIPM), and the CIPM together with its Consultative Committees (CCs) that could enable the planned revision of the SI to be adopted by the CGPM,

considering that there has been significant progress in completing the necessary work, including

- the acquisition of relevant data and their analysis by the Committee on Data for Science and Technology (CODATA) to obtain the required values of h, e, k, and N_A,
- establishment by the BIPM of an ensemble of reference standards of mass to facilitate the dissemination of the unit of mass in the revised SI,
- the preparation of mises-en-pratique for the new definitions of the kilogram, ampere, kelvin, and mole,

noting that further work by the Consultative Committee for Units (CCU), the CIPM, the BIPM, the NMIs and the CCs should focus on

- awareness campaigns to alert user communities as well as the general public to the proposed revision of the SI,
- the preparation of the 9th edition of the SI Brochure that presents the revised SI in a way that can be understood by a diverse readership without compromising scientific rigour,

that despite this progress the data do not yet appear to be sufficiently robust for the CGPM to adopt the revised SI at its 25th meeting,

encourages

- continued effort in the NMIs, the BIPM, and academic institutions to obtain data relevant to the determination of h, e, k, and N_A with the requisite uncertainties,
- the NMIs to continue acting through the CCs to discuss and review this data,
- the CIPM to continue developing a plan to provide the path via the Consultative Committees and the CCU for implementing Resolution 1 adopted by the CGPM at its 24th meeting (2011), and
- continued effort by the CIPM, together with its Consultative Committees, the NMIs, the BIPM, and other organizations such as the International Organization of Legal Metrology (OIML), to complete all work necessary for the CGPM at its 26th meeting to adopt a resolution that would replace the current SI with the revised SI, provided the amount of data, their uncertainties, and level of consistency are deemed satisfactory.

CIPM, 2015

■ **Updates to the list of standard frequencies** (PV, **83,** 207)

Further updates are available on the BIPM website.

Recommendation 2

The International Committee for Weights and Measures (CIPM),

considering

- a common list of "Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second" has been established,
- the CCL-CCTF Frequency Standards Working Group (WGFS) has reviewed several candidates for updating the list,

recommends

that the following transition frequencies shall be updated in the list of recommended values of standard frequencies:

- the unperturbed optical transition $6s^2\ {}^1S_0$ – $6s6p\ {}^3P_0$ of the ^{199}Hg neutral atom with a frequency of f_{199Hg} = 1 128 575 290 808 154.8 Hz and an estimated relative standard uncertainty of 6×10^{-16};
- the unperturbed optical transition $6s\ {}^2S_{1/2}$ – $4f^{13}\ 6s^2\ {}^2F_{7/2}$ of the $^{171}Yb^+$ ion with a frequency of f_{171Yb+} (octupole) = 642 121 496 772 645.0 Hz and an estimated relative standard uncertainty of 6×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $6s\ {}^2S_{1/2}$ (F = 0, m_F = 0) – $5d\ {}^2D_{3/2}$ (F = 2, m_F = 0) of the $^{171}Yb^+$ ion with a frequency of f_{171Yb+} (quadrupole) = 688 358 979 309 308.3 Hz and an estimated relative standard uncertainty of 6×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $5s\ {}^2S_{1/2}$ – $4d\ {}^2D_{5/2}$ of the $^{88}Sr^+$ ion with a frequency of f_{88Sr+} = 444 779 044 095 486.6 Hz and an estimated relative standard uncertainty of 1.6×10^{-15} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $4s\ {}^2S_{1/2}$ – $3d\ {}^2D_{5/2}$ of the $^{40}Ca^+$ ion with a frequency of f_{40Ca+} = 411 042 129 776 398.4 Hz and an estimated relative standard uncertainty of 1.2×10^{-14};
- the unperturbed optical transition 1S – 2S of the 1H neutral atom with a frequency of f_{1H} = 1 233 030 706 593 514 Hz and an estimated relative standard uncertainty of 9×10^{-15}.

Note: This frequency corresponds to half of the energy difference between the 1S and 2S states;

- the unperturbed optical transition $5s^2\ {}^1S_0$ – $5s5p\ {}^3P_0$ of the ^{87}Sr neutral atom with a frequency of f_{87Sr} = 429 228 004 229 873.2 Hz and an estimated relative standard uncertainty of 5×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed optical transition $6s^2\ {}^1S_0$ – $6s6p\ {}^3P_0$ of the ^{171}Yb neutral atom with a frequency of f_{171Yb} = 518 295 836 590 864.0 Hz and an estimated relative standard uncertainty of 2×10^{-15} (this radiation is already endorsed by the CIPM as a secondary representation of the second);
- the unperturbed ground-state hyperfine transition of ^{87}Rb with a frequency of f_{87Rb} = 6 834 682 610.904 310 Hz and an estimated relative standard uncertainty of 7×10^{-16} (this radiation is already endorsed by the CIPM as a secondary representation of the second).

and also **recommends**

that the following transition frequencies shall be included in the list of recommended values of standard frequencies:

- Absorbing molecule $^{127}I_2$, saturated absorption a_1 component, R(36) 32-0 transition.

The values f_{a1} = 564 074 632.42 MHz

λ_{a1} = 531 476 582.65 fm

with an estimated relative standard uncertainty of 1×10^{-10} apply to the radiation of a frequency-doubled diode DFB laser, stabilized with an iodine cell external to the laser.

- Absorbing atom ^{87}Rb $5S_{1/2}$ - $5P_{3/2}$ crossover between the d and f hyperfine components of the saturated absorption at 780 nm (D2 transition)

The values $f_{\text{d/f crossover}}$ = 384 227 981.9 MHz

$\lambda_{\text{d/f crossover}}$ = 780 246 291.6 fm

with an estimated relative standard uncertainty of 5×10^{-10} apply to the radiation of a tunable External Cavity Diode Laser, stabilized to the d/f crossover in a rubidium cell external to the laser.

Note: The value of the standard uncertainty is assumed to correspond to a confidence level of 68 %. However, given the limited availability of data there is a possibility that in hindsight this might not prove to be exact

CIPM, 2017

■ **On progress towards the possible redefinition of the SI** (PV*,* **85,** 101)

Decision 10

The International Committee for Weights and Measures (CIPM) welcomed recommendations regarding the redefinition of the SI from its Consultative Committees.

The CIPM noted that the agreed conditions for the redefinition are now met and decided to submit draft Resolution A to the 26th meeting of the General Conference on Weights and Measures (CGPM) and to undertake all other necessary steps to proceed with the planned redefinition of the kilogram, ampere, kelvin and mole.

26th CGPM, 2018

■ **On the revision of the International System of Units, the SI** (CR*,* in press and *Metrologia*, 2019, **56**, 022001)

Resolution 1

The General Conference on Weights and Measures (CGPM), at its 26th meeting,

considering

- the essential requirement for an International System of Units (SI) that is uniform and accessible world-wide for international trade, high-technology manufacturing, human health and safety, protection of the environment, global climate studies and the basic science that underpins all these,
- that the SI units must be stable in the long term, internally self-consistent and practically realizable being based on the present theoretical description of nature at the highest level,
- that a revision of the SI to meet these requirements was described in Resolution 1 of the 24th General Conference in 2011, adopted unanimously, that laid out in detail a new way of defining the SI based on a set of seven defining constants, drawn from the fundamental constants of physics and other constants of nature, from which the definitions of the seven base units are deduced,
- that the conditions set by the 24th General Conference, confirmed by the 25th General Conference, before such a revised SI could be adopted have now been met,

decides

that, effective from 20 May 2019, 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 $\Delta\nu_{\text{Cs}}$ is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ C,

- the Boltzmann constant k is $1.380\,649 \times 10^{-23}$ J/K,
- the Avogadro constant N_A is $6.022\,140\,76 \times 10^{23}$ mol^{-1},
- the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{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 Hz = s^{-1}, J = kg m^2 s^{-2}, C = A s, lm = cd m^2 m^{-2} = cd sr, and W = kg m^2 s^{-3}.

In making this decision, the General Conference notes the consequences as set out in Resolution 1 of the 24th General Conference in respect to the base units of the SI and confirms these in the following Appendices to this Resolution, which have the same force as the Resolution itself.

The General Conference invites the International Committee to produce a new edition of its Brochure *The International System of Units, SI* in which a full description of the SI is given.

Appendix 1. Abrogation of former definitions of the base units:

It follows from the new definition of the SI adopted above that

- the definition of the second in force since 1967/68 (13th meeting of the CGPM, Resolution 1) is abrogated,
- the definition of the metre in force since 1983 (17th meeting of the CGPM, Resolution 1), is abrogated,
- the definition of the kilogram in force since 1889 (1st meeting of the CGPM, 1889, 3rd meeting of the CGPM, 1901) based upon the mass of the international prototype of the kilogram is abrogated,
- the definition of the ampere in force since 1948 (9th meeting of the CGPM) based upon the definition proposed by the International Committee (CIPM, 1946, Resolution 2) is abrogated,
- the definition of the kelvin in force since 1967/68 (13th meeting of the CGPM, Resolution 4) is abrogated,
- the definition of the mole in force since 1971 (14th meeting of the CGPM, Resolution 3) is abrogated,
- the definition of the candela in force since 1979 (16th meeting of the CGPM, Resolution 3) is abrogated,
- the decision to adopt the conventional values of the Josephson constant K_{J-90} and of the von Klitzing constant R_{K-90} taken by the International Committee (CIPM, 1988, Recommendations 1 and 2) at the request of the General Conference (18th meeting of the CGPM, 1987, Resolution 6) for the establishment of representations of the volt and the ohm using the Josephson and quantum Hall effects, respectively, is abrogated.

Appendix 2. Status of constants previously used in the former definitions:

It follows from the new definition of the SI adopted above, and from the recommended values of the 2017 special CODATA adjustment on which the values of the defining constants are based, that at the time this Resolution was adopted

- the mass of the international prototype of the kilogram $m(K)$ is equal to 1 kg within a relative standard uncertainty equal to that of the recommended value of h at the time this Resolution was adopted, namely 1.0×10^{-8} and that in the future its value will be determined experimentally,
- the vacuum magnetic permeability μ_0 is equal to $4\pi \times 10^{-7}$ H m^{-1} within a relative standard uncertainty equal to that of the recommended value of the fine-structure constant α at the time this Resolution was adopted, namely 2.3×10^{-10} and that in the future its value will be determined experimentally,

- the thermodynamic temperature of the triple point of water T_{TPW} is equal to 273.16 K within a relative standard uncertainty closely equal to that of the recommended value of k at the time this Resolution was adopted, namely 3.7×10^{-7}, and that in the future its value will be determined experimentally,
- the molar mass of carbon 12, $M(^{12}C)$, is equal to 0.012 kg mol^{-1} within a relative standard uncertainty equal to that of the recommended value of $N_A h$ at the time this Resolution was adopted, namely 4.5×10^{-10}, and that in the future its value will be determined experimentally.

Appendix 3. The base units of the SI

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

- The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.
- 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, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.
- The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\ 070\ 15 \times 10^{-34}$ when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.
- The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602\ 176\ 634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.
- The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\ 649 \times 10^{-23}$ when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.
- The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.022\ 140\ 76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.

  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.
- The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr kg^{-1} m^{-2} s^3, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

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 (www.bipm.org).

Appendix 3. Units for photochemical and photobiological quantities

Appendix 3 is published in electronic form only, and is available on the BIPM website (www.bipm.org).

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 m 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 $(2\pi^5k^4/15c^2h^3)\,T^4$, in W m^{-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[1] 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 $mgv = Ch$ 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:

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

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

with the mass m and volume V of the sphere (about 1 kg), lattice parameter a_0, Rydberg constant R_∞, fine structure constant α, and the masses of a silicon atom (averaged over the three isotopes used for the sphere) m_{Si}, and the electron m_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.

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 $\Delta\nu_{\mathrm{Cs}}$; the speed of light in vacuum c; the Planck constant h; elementary charge e; Boltzmann constant k; Avogadro constant N_{A}; and the luminous efficacy of a defined visible radiation K_{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, $\Delta\nu_{\mathrm{Cs}}$, 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. 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 of the Meter Convention, 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 μ_0 (also called the magnetic constant). The numerical value of the vacuum electric permittivity ε_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_{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 540×10^{12} Hz, K_{cd}, adopted in Resolution 1 of the 26th CGPM (2018).

List of acronyms used in the present volume

1 Acronyms for laboratories, committees and conferences

BAAS	British Association for the Advancement of Science
BIPM	Bureau international des poids et mesures/ International Bureau of Weights and Measures
CARICOM	Caribbean Community
CCAUV	Comité consultatif de l'acoustique, des ultrasons et des vibrations/ Consultative Committee for Acoustics, Ultrasound and Vibration
CCDS	Comité consultatif pour la définition de la seconde/ Consultative Committee for the Definition of the Second, see CCTF
CCE	Comité consultatif d'électricité/ Consultative Committee for Electricity, see CCEM
CCEM	(formerly the CCE) Comité consultatif d'électricité et magnétisme/ Consultative Committee for Electricity and Magnetism
CCL	Comité consultatif des longueurs/Consultative Committee for Length
CCM	Comité consultatif pour la masse et les grandeurs apparentées/ Consultative Committee for Mass and Related Quantities
CCPR	Comité consultatif de photométrie et radiométrie/ Consultative Committee for Photometry and Radiometry
CCQM	Comité consultatif pour la quantité de matière : métrologie en chimie et biologie/Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology
CCRI	Comité consultatif des rayonnements ionisants/ Consultative Committee for Ionizing Radiation
CCT	Comité consultatif de thermométrie/ Consultative Committee for Thermometry
CCTF	(formerly the CCDS) Comité consultatif du temps et des fréquences/ Consultative Committee for Time and Frequency
CCU	Comité consultatif des unités/Consultative Committee for Units
CGPM	Conférence générale des poids et mesures/ General Conference on Weights and Measures
CIPM	Comité international des poids et mesures/ International Committee for Weights and Measures
CODATA	Committee on Data for Science and Technology
CR	*Comptes Rendus* of the Conférence générale des poids et mesures, CGPM
IAU	International Astronomical Union
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IEC	International Electrotechnical Commission
IERS	International Earth Rotation and Reference Systems Service
ISO	International Organization for Standardization
IUPAC	International Union of Pure and Applied Chemistry

IUPAP	International Union of Pure and Applied Physics
OIML	Organisation internationale de métrologie légale/International Organization of Legal Metrology
PV	*Procès-Verbaux* of the Comité international des poids et mesures, CIPM
SUNAMCO	Commission for Symbols, Units, Nomenclature, Atomic Masses and Fundamental Constants, IUPAP
WHO	World Health Organization

2 Acronyms for scientific terms

CGS	Three-dimensional coherent system of units based on the three mechanical units centimetre, gram and second
EPT-76	Échelle provisoire de température de 1976/Provisional Low Temperature Scale of 1976
GUM	Guide pour l'expression de l'incertitude de mesure/Guide to the Expression of Uncertainty in Measurement
IPTS-68	International Practical Temperature Scale of 1968
ITS-90	International Temperature Scale of 1990
MKS	System of units based on the three mechanical units metre, kilogram, and second
MKSA	Four-dimensional system of units based on the metre, kilogram, second, and the ampere
SI	Système international d'unités/International System of Units
TAI	Temps atomique international/International Atomic Time
TCG	Temps-coordonnée géocentrique/Geocentric Coordinated Time
TT	Terrestrial Time
UTC	Coordinated Universal Time
VSMOW	Vienna Standard Mean Ocean Water

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