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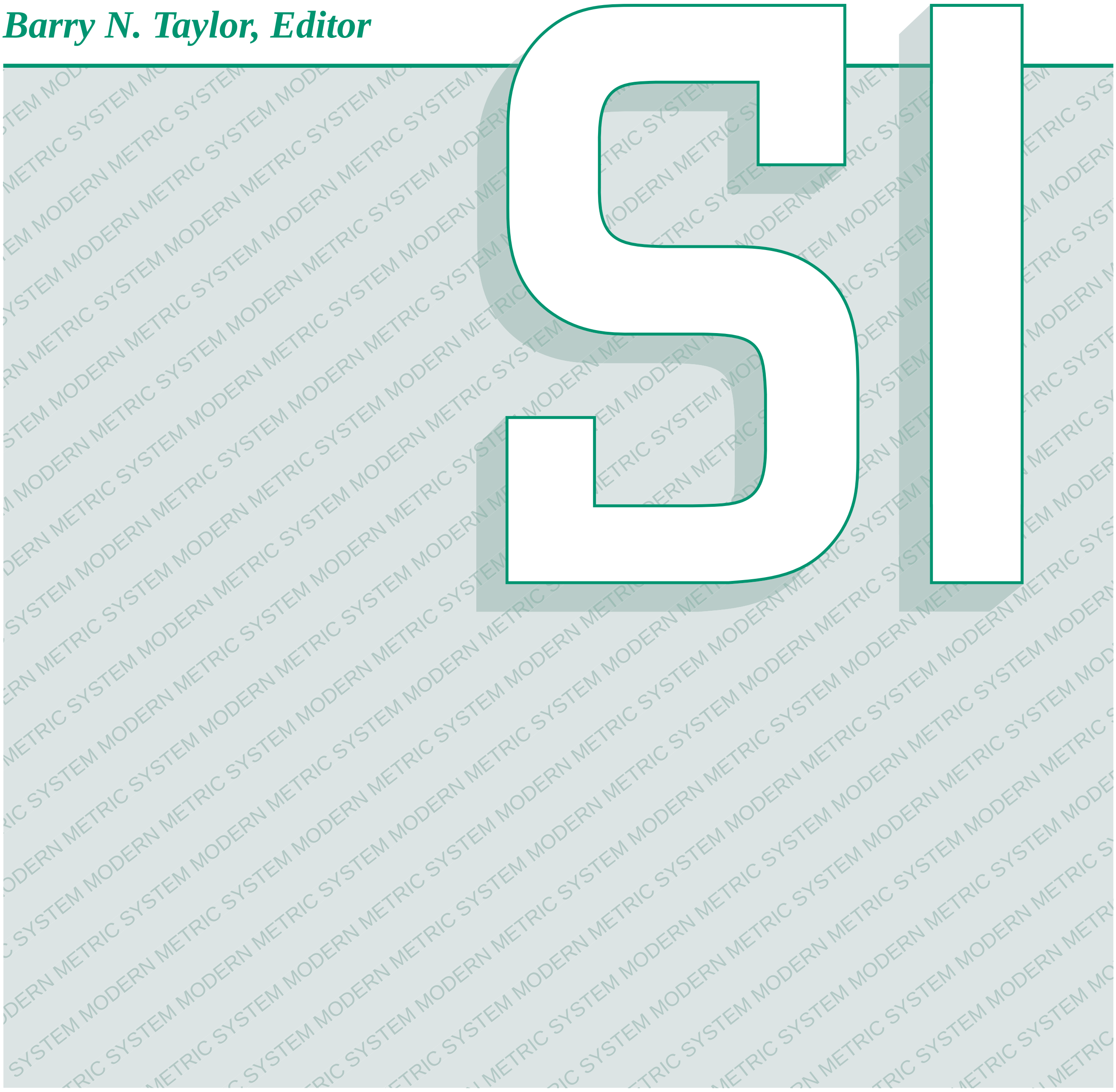
The International System of Units (SI)

Barry N. Taylor, Editor



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2001 EDITION

THE INTERNATIONAL SYSTEM OF UNITS (SI)

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Foreword

The International System of Units, universally abbreviated SI (from the French *Le Système International d'Unités*), is the modern metric system of measurement. Long the dominant system used in science, the SI is rapidly becoming the dominant measurement system used in international commerce. In recognition of this fact and the increasing global nature of the marketplace, the Omnibus Trade and Competitiveness Act of 1988, which changed the name of the National Bureau of Standards (NBS) to the National Institute of Standards and Technology (NIST) and gave to NIST the added task of helping U.S. industry increase its competitiveness, designates "the metric system of measurement as the preferred system of weights and measures for United States trade and commerce."

The definitive international reference on the SI is a booklet published by the International Bureau of Weights and Measures (BIPM, *Bureau International des Poids et Mesures*) and often referred to as the BIPM SI Brochure. Entitled *Le Système International d'Unités (SI)*, the booklet is in French followed by a text in English. This 2001 edition of NIST Special Publication (SP) 330 is the United States version of the English text of the seventh edition of the Brochure (the most current). However, it also incorporates the contents of *Supplement 2000: addenda and corrigenda to the 7th edition (1998)* [*Supplément 2000: additions et corrections à la 7^e édition (1998)*] published by the BIPM in June 2000. The 2001 edition of NIST SP 330 replaces its immediate predecessor, the 1991 edition, which was based on the sixth edition of the BIPM SI Brochure published in 1991.

Like its 1991 predecessor, this edition of NIST SP 330 conforms with the English text in the BIPM SI Brochure but contains a few minor differences to reflect the most recent interpretation of the SI for the United States by the Secretary of Commerce, as published in the Federal Register of July 28, 1998, 63 FR 40334-40340. (The Metric Conversion Act of 1975 gives the Secretary of Commerce the responsibility of interpreting or modifying the SI for use in the United States.) These differences are as follows: (i) The spelling of English words is in accordance with the *United States Government Printing Office Style Manual,* which follows Webster's *Third New International Dictionary* rather than the *Oxford Dictionary.* Thus the spellings "meter," "liter," and "deca" are used rather than "metre," "litre," and "deka" as in the original BIPM English text; (ii) the name of the unit with symbol t and defined according to $1\ \mathrm{t} = 10^3\ \mathrm{kg}$ is called "metric ton" rather than "tonne"; (iii) the four units curie, roentgen, rad, and rem are included in Table 8; (iv) a number of "Editor's notes" are added in order to indicate such differences (except spelling differences) and to clarify the text; and (v) a few very minor editorial changes are made in order to "Americanize" some phrases.

Because of the importance of the SI to science, technology, and commerce, and because (i) NIST coordinates the Federal Government policy on the conversion to the SI by Federal agencies and on the use of the SI by U.S. industry, (ii) NIST provides official U.S. representation in the various international bodies established by the Meter Convention (see Appendix 3), and (iii) the Secretary of Commerce has delegated his authority to interpret or modify the SI for use in the United States to the NIST Director, NIST provides a number of other sources of information on the SI in addition to NIST SP 330. These include NIST Special Publication 811, *Guide for the Use of the International System of Units (SI),* by Barry N. Taylor; and NIST Special Publication 814, *Interpretation of the SI for the United States and Metric Conversion Policy for Federal Agencies,* Barry N. Taylor, Editor. Further, NIST SP 330, NIST SP 811, the aforementioned 1998 Federal Register notice, the "essentials" of the SI together with useful background information, and links to other organizations involved with the SI, for example, the NIST Metric Program and the BIPM itself, are all available on the Web site entitled "NIST Reference on Constants, Units, and Uncertainty" at physics.nist.gov/cuu. Users of this NIST publication are encouraged to take advantage of these other sources of information.

I should like to thank James B. McCracken of the NIST Metric Program, NIST Guest Researcher Ralph P. Hudson, and Ilse E. Putman of the NIST Electronic Typesetting Group for their highly capable assistance in the preparation of this publication.

July, 2001

Barry N. Taylor

Preface to the 7th edition

Since 1970, the Bureau International des Poids et Mesures (BIPM) has now published seven editions of this document. It lists all Resolutions and Recommendations of the Conférence Générale des Poids et Mesures (CGPM) and the Comité International des Poids et Mesures (CIPM) relating to the International System of Units. Formal reference to CIPM and CGPM decisions are to be found in successive volumes of the *Comptes Rendus* of the CGPM (CR) and *Procès-Verbaux* of the CIPM (PV); the most recent are also listed in *Metrologia*. To simplify practical use of the SI, the text provides explanations of these decisions and accompanies them with relevant extracts from the international standards of the International Organization for Standardization (ISO).

The Comité Consultatif des Unités (CCU) of the CIPM helped to draft the document and approved the final text. This 7th edition is a revision of the 6th edition (1991); it takes into consideration decisions made by the CGPM and the CIPM since 1991. It also incorporates amendments made by the CCU.

Appendix 1 reproduces 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 outlines the measurements, consistent with the theoretical definitions given in the principal text, which metrological laboratories can make to realize physical units and to calibrate material standards of the highest quality. In this edition, for the first time, the definition and hence the practical realizations of both the meter and the second are considered in the context of general relativity. Except where specified, uncertainties are quoted in the form of combined standard uncertainties or as relative combined standard uncertainties.

For more than twenty-five years this document has been used as a work of reference in many countries, organizations and scientific unions. To make its contents accessible to a greater number of readers, the CIPM decided, in 1985, to include an English version of the text in the 5th edition; this double presentation is continued in this 7th edition. For the first English version the BIPM endeavoured to produce a faithful translation of the French original by close collaboration with the National Physical Laboratory (Teddington, United Kingdom) and the National Institute of Standards and Technology (Gaithersburg, United States), at that time the National Bureau of Standards. For the present edition the French and English versions were prepared by the BIPM in close collaboration with the CCU. The CIPM decided in 1997 that in the English text the decimal marker would be the dot on the line, treating this as a translation of the comma, the French decimal marker. This has no implication for the translation of the decimal marker into other languages. A point to note is that slight 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 International Standard ISO 31 (1992), *Quantities and units*. Readers should note that the official record is always that of the French text. This must be used when an authoritative reference is required or when there is doubt about the interpretation of the text.

November 1997

T. J. QUINN *Director, BIPM*	I. M. MILLS *President, CCU*

Note on the use of the English text

To make its work more widely accessible, the Comité International des Poids et Mesures has decided to publish an English version of its reports. Readers should note that the official record is always that of the French text. This must be used when an authoritative reference is required or when there is doubt about the interpretation of the text.

Translations, complete or partial, of this brochure (or of its earlier editions) have been published in various languages, notably in Bulgarian, Chinese, Czech, English, German, Japanese, Korean, Portuguese, Romanian and Spanish. The ISO and numerous countries have also published standards and guides to the use of SI units.

The International System of Units

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1 Introduction

1.1 Historical note

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 inquiry, 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 Meter Convention.

Decisions of the CGPM are recorded in the *Comptes Rendus des Séances de la Conferénce Générale des Poids et Mesures* and are here identified by the letters CR.

It also laid down, in Resolution 7 (CR, 70), general principles for the writing of unit symbols and listed units which have been assigned special names.

The 10th CGPM (1954, Resolution 6; CR, 80), and the 14th CGPM (1971, Resolution 3; CR, 78 and *Metrologia*, 1972, **8**, 36), adopted as base units of this practical system of units, the units of the following seven quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity.

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

The main historical steps which led to these important CGPM 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 meter and the kilogram, on 22 June 1799, in the Archives de la République in Paris can be seen as the first step in the development of 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* millimeter, gram and second for, respectively, the quantities length, mass and time. In later years Gauss and Weber extended these measurements to include electrical phenomena.

[†] Editor's note: Throughout, CGPM means General Conference on Weights and Measures (*Conférence Générale des Poids et Mesures*), CIPM means International Committee for Weights and Measures (*Comité International des Poids et Mesures*), and BIPM means International Bureau of Weights and Measures (*Bureau International des Poids et Mesures*). See Appendix 3, p. 63, for a discussion of the Meter Convention (*Convention du Mètre*), often called the Treaty of the Meter in the United States, and of the CGPM, CIPM, and BIPM which were established by the Convention.

- These applications in the field of electricity and magnetism were further developed 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 centimeter, gram, and second, using prefixes ranging from micro to mega to express decimal submultiples and multiples. The following 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 establishment of the Meter Convention on 20 May 1875 the CIPM concentrated on the construction of new prototypes taking the meter and kilogram as the base units of length and mass. In 1889 the 1st CGPM sanctioned the international prototypes for the meter and the kilogram. Together with the astronomical second as unit of time, these units constituted a three-dimensional mechanical unit system similar to the CGS system, but with the base units meter, kilogram, and second, the MKS system.
- In 1901 Giorgi showed that it is possible to combine the mechanical units of this meter-kilogram-second system with the practical electric units to form a single 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 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 Meter Convention by the 6th CGPM in 1921, which extended the scope and responsibilities of the BIPM to other fields in physics, and the subsequent creation of the CCE[†] by the 7th CGPM in 1927, the Giorgi proposal was thoroughly discussed by the IEC, the IUPAP[‡] and other international organizations. This led the CCE to propose, in 1939, the adoption of a four-dimensional system based on the meter, kilogram, second, and ampere, the MKSA system, a proposal approved by the CIPM in 1946.
- Following an international inquiry by the BIPM, which began in 1948, the 10th CGPM, in 1954, approved the introduction of the *ampere,* the *kelvin* and the *candela* as base units, respectively, for electric current, thermodynamic temperature and luminous intensity. The name *Système International d'Unités (SI)* was given to the system by the 11th CGPM in 1960. At the 14th CGPM in 1971 the current version of the SI was completed by adding the *mole* as the base unit for amount of substance, bringing the total number of base units to seven.

[†] Editor's note: CCE—Consultative Committee for Electricity; see Appendix 3.

[‡] Editor's note: IUPAP—International Union of Pure and Applied Physics.

1.2 Two classes of SI units

SI units are divided into two classes:

- *base* units;
- *derived* units.

From the scientific point of view, the division of SI units into these two classes is to a certain extent arbitrary, because it is not essential to the physics of the subject. Nevertheless, the CGPM, considering the advantages of a single, practical, world-wide system of units for international relations, for teaching, and for scientific work, decided to base the International System on a choice of seven well-defined units which by convention are regarded as dimensionally independent: the meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela (see 2.1, p. 5). These SI units are called *base units*.

The radian and steradian, units of plane and solid angle, were admitted to the SI as a separate class of units, called supplementary units, by the 11th CGPM (1960, Resolution 12; CR, 87). The 20th CGPM (1995, Resolution 8; CR, 223 and *Metrologia,* 1996, **33**, 83) eliminated the supplementary units as a separate class within the SI and included the radian and steradian in the class of derived units.

The second class of SI units is that of *derived units*. These are units that are formed as products of powers of the base units according to the algebraic relations linking the quantities concerned. The names and symbols of some units thus formed in terms of base units may be replaced by special names and symbols which can themselves be used to form expressions and symbols for other derived units (see 2.2, p. 9).

The SI units of these two classes form a *coherent* set of units, where coherent is used in the specialist sense of a system whose units are mutually related by rules of multiplication and division with no numerical factor other than 1. Following CIPM Recommendation 1 (1969; PV, **37**, 30-31 and *Metrologia*, 1970, **6**, 66), the units of this coherent set of units are designated by the name *SI units.*

Recommendations of the CIPM are recorded in the *Procès-Verbaux des Séances du Comité International des Poids et Mesures* and are here identified by the letters PV.

It is important to emphasize that each physical quantity has only one SI unit, even if this unit can be expressed in different forms. The inverse, however, is not true; in some cases the same SI unit can be used to express the values of several different quantities (see p. 12).

1.3 The SI prefixes

The CGPM adopted a series of prefixes for use in forming the decimal multiples and submultiples of SI units (see 3.1 and 3.2, p. 14). Following CIPM Recommendation 1 (1969) mentioned above, these are designated by the name *SI prefixes.*

The SI units, that is to say the base and derived units of the SI, form a coherent set, *the set of SI units.* The multiples and submultiples of the SI units formed by using the SI units combined with SI prefixes are designated by their complete name, *decimal multiples and submultiples of SI units.* These decimal multiples and submultiples of SI units are not coherent with the SI units themselves.

As an exception, the multiples and submultiples of the kilogram are formed by attaching prefix names to the unit name “gram,” and prefix symbols to the unit symbol “g.”

1.4 System of quantities

The system of quantities used with the SI units is dealt with by Technical Committee 12 of the International Organization for Standardization (ISO/TC 12) and is not treated here. Since 1955, the ISO/TC 12 has published a series of International Standards on quantities and their units which strongly recommends the use of the International System of Units.

In these International Standards, the ISO has adopted a system of physical quantities based on the seven base quantities corresponding to the seven base units of the SI, namely: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity. Other quantities, called derived quantities, are defined in terms of these seven base quantities; the relationships between derived quantities and base quantities are expressed by a system of equations. It is this system of quantities and equations that is properly used with the SI units.

For a detailed exposition of the system of quantities used with the SI units see ISO 31, *Quantities and units* (ISO Standards Handbook, 3rd edition, ISO, Geneva, 1993).

1.5 SI units in the framework of general relativity

The definitions of the base units of the SI were agreed to in a context which takes no account of relativistic effects. When such account is taken, it is clear that the definitions apply only in a small spatial domain which shares the motion of the standards that realize them. These units are therefore *proper units*; they are realized from local experiments in which the relativistic effects that need to be taken into account are those of special relativity. The constants of physics are local quantities with their values expressed in proper units.

Realizations of a unit using different standards are usually compared locally. For frequency standards, however, it is possible to make such comparisons at a distance by means of electromagnetic signals. To interpret the results, the theory of general relativity is required since it predicts, among other things, a frequency shift between standards of about 1 part in 10^{16} per meter of altitude difference at the surface of the Earth. Effects of this magnitude can be comparable with the uncertainty of realization of the meter or the second based on a periodic signal of given frequency (*see* Appendix 2, p. 45).

The question of proper units is addressed in Resolution A4 adopted by the XXIst General Assembly of the International Astronomical Union (IAU) in 1991 and by the report of the CCDS working group on the application of general relativity to metrology (*Metrologia*, 1997, **34**, 261-290).

1.6 Legislation on units

By legislation, individual countries have established rules concerning the use of units on a national basis, 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 use of the International System of Units.

The International Organization of Legal Metrology (OIML, *Organisation Internationale de Métrologie Légale*), founded in 1955, is charged with the international harmonization of this legislation.

2 SI units

2.1 SI base units

Formal definitions of all SI base units are approved by the CGPM. The first such definition was approved in 1889 and the most recent in 1983. These definitions are modified from time to time as techniques of measurement evolve in order to allow more accurate realizations of the base units.

2.1.1 Definitions

Current definitions of the base units, as taken from the *Comptes Rendus* (CR) of the corresponding CGPM, are here shown indented and in a heavy font. Related decisions which clarify these definitions but are not formally part of them, as taken from the *Comptes Rendus* (CR) of the corresponding CGPM or the *Procès-Verbaux* (PV) of the CIPM, are also shown indented but in a font of normal weight. For recent decisions, the appropriate article in *Metrologia* is also cited. The associated text provides historical notes and explanations but is not part of the definitions themselves.

2.1.1.1 Unit of length (meter)

The 1889 definition of the meter, based upon the international prototype of platinum-iridium, was replaced by the 11th CGPM (1960) using a definition based upon a wavelength of krypton 86 radiation. This definition was adopted in order to improve the accuracy with which the meter may be realized. This was replaced in 1983 by the 17th CGPM (Resolution 1; CR, 97 and *Metrologia,* 1984, **20**, 25):

> **The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.**

Note that the effect of this definition is to fix the speed of light at exactly[†] 299 792 458 $\mathrm{m \cdot s^{-1}}$. The original international prototype of the meter, which was sanctioned by the 1st CGPM in 1889 (CR, 34-38), is still kept at the BIPM under conditions specified in 1889.

2.1.1.2 Unit of mass (kilogram)

The international prototype of the kilogram, made of platinum-iridium, is kept at the BIPM under conditions specified by the 1st CGPM in 1889 (CR, 34-38) when it sanctioned the prototype and declared:

> This prototype shall henceforth be considered to be the unit of mass.

[†] Editor's note: Hence formally we have $c_0 = 299\ 792\ 458\ \mathrm{m \cdot s^{-1}}$ exactly, where c_0 is the quantity symbol for the speed of light in vacuum.

The 3rd CGPM (1901; CR, 70), in a declaration intended to end the ambiguity in popular usage concerning 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 declaration appears on page 29.

2.1.1.3 Unit of time (second)

The unit of time, the second, was at one time considered to be the fraction 1/86 400 of the mean solar day. The exact definition of “mean solar day” was based on astronomical theories. However, measurement showed that irregularities in the rotation of the Earth could not be taken into account by the theory and have the effect that this definition does not allow the required accuracy to be achieved. In order to define the unit of time more precisely, the 11th CGPM (1960; CR, 86) adopted a definition given by the International Astronomical Union which was based on the tropical year. Experimental work, however, had already shown that an atomic standard of time interval, based on a transition between two energy levels of an atom or a molecule, could be realized and reproduced much more precisely. Considering that a very precise definition of the unit of time is indispensable for the International System, the 13th CGPM (1967-1968, Resolution 1; CR, 103 and *Metrologia,* 1968, **4**, 43) replaced the definition of the second with the following:

> **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 cesium 133 atom.**

At its 1997 meeting, the CIPM affirmed that:

> This definition refers to a cesium atom at rest at a temperature of 0 K.[†]

This note was intended to make it clear that the definition of the SI second is based on a Cs atom unperturbed by black-body radiation, that is, in an environment whose temperature is 0 K, and that the frequencies of primary frequency standards should therefore be corrected for the shift due to ambient radiation, as stated at the meeting of the CCTF in 1999.

2.1.1.4 Unit of electric current (ampere)

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

[†] Editor’s note: This wording of the CIPM affirmation and the subsequent paragraph are given in *Supplement 2000: addenda and corrigenda to the 7th edition (1998)*; June 2000. For the meaning of CCTF see Appendix 3, p. 65.

Although it was already obvious on the occasion of the 8th CGPM (1933) that there was a unanimous desire to replace those "international" units by so-called "absolute" units, the official decision to abolish them was only taken by the 9th CGPM (1948), which adopted the ampere for the unit of electric current, following a definition proposed by the CIPM (1946, Resolution 2; PV, **20**, 129-137):

> **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 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.**

The expression "MKS unit of force" which occurs in the original text of 1946 has been replaced here by "newton," a name adopted for this unit by the 9th CGPM (1948, Resolution 7; CR, 70). Note that the effect of this definition is to fix the permeability of vacuum at exactly[†] $4\pi\times10^{-7}\ \mathrm{H\cdot m^{-1}}$.

2.1.1.5 Unit of thermodynamic temperature (kelvin)

The definition of the unit of thermodynamic temperature was given in substance by the 10th CGPM (1954, Resolution 3; CR, 79) which selected the triple point of water as the fundamental fixed point and assigned to it the temperature 273.16 K so defining the unit. 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 °K) and defined the unit of thermodynamic temperature as follows (Resolution 4; CR, 104 and *Metrologia,* 1968, **4**, 43):

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

Because 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, the ice point. This temperature difference is called the Celsius temperature, symbol t, and 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 kelvin. A difference or interval of temperature may be expressed in kelvins or in degrees Celsius (13th CGPM, 1967-1968, Resolution 3, mentioned above). The numerical value of a Celsius temperature t expressed in degrees Celsius is given by

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

The kelvin and the degree Celsius are also the units of the International Temperature Scale of 1990 (ITS-90) adopted by the CIPM in 1989 in its Recommendation 5 (CI-1989) (PV, **57**, 115 and *Metrologia,* 1990, **27**, 13).

[†] Editor's note: Hence formally we have $\mu_0 = 4\pi\times10^{-7}\ \mathrm{H\cdot m^{-1}}$ exactly, where μ_0 is the quantity symbol for the magnetic constant, which is also called the permeability of vacuum.

2.1.1.6 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 masses. "Atomic weights" were originally referred to the atomic weight of oxygen, by general agreement taken as 16. But whereas physicists separated isotopes in the mass spectrometer and attributed the value 16 to one of the isotopes of oxygen, chemists attributed that same value to the (slightly variable) mixture of isotopes 16, 17 and 18, which was for them the naturally occurring element oxygen. Finally, 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 1959/60. Physicists and chemists have ever since agreed to assign the value 12, exactly, to the "atomic weight," correctly the relative atomic mass, of the isotope of carbon with mass number 12 (carbon 12, ^{12}C). The unified scale thus obtained gives values of relative atomic mass.

It remained to define the unit of amount of substance by fixing the corresponding mass of carbon 12; by international agreement this mass was fixed at 0.012 kg, and the unit of the quantity "amount of substance" was given the name *mole* (symbol mol).

Following proposals by the IUPAP, the IUPAC and the ISO, the CIPM gave a definition of the mole in 1967 and confirmed it in 1969: this was adopted by the 14th CGPM[†] (1971, Resolution 3; CR, 78 and *Metrologia,* 1972, **8**, 36):

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.**

In 1980 the CIPM approved the report of the CCU (1980) which specified that

> In this definition, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

When the definition of the mole is quoted, it is conventional also to include this remark.

2.1.1.7 Unit of luminous intensity (candela)

The units of luminous intensity 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, *Commission Internationale de l'Éclairage*) 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

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[†] Editor's note: The effect of this definition is to fix the molar mass of the carbon-12 atom, quantity symbol $M(^{12}C)$, to be exactly 12×10^{-3} kg · mol^{-1}, or formally $M(^{12}C) = 12 \times 10^{-3}$ kg · mol^{-1} exactly.

adopted a new international name for this unit, the *candela* (symbol cd); in 1967 the 13th CGPM (Resolution 5; CR, 104 and *Metrologia,* 1968, **4**, 43-44) gave an amended version of the 1946 definition.

In 1979, because of the experimental 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 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.**

2.1.2 Symbols for base units

The base units of the International System are listed in Table 1 which relates the base quantity to the unit name and unit symbol [10th CGPM (1954, Resolution 6; CR, 80); 11th CGPM (1960, Resolution 12; CR, 87); 13th CGPM (1967-1968, Resolution 3; CR, 104 and *Metrologia,* 1968, **4**, 43); 14th CGPM (1971, Resolution 3; CR, 78 and *Metrologia,* 1972, **8**, 36)].

Table 1. SI base units

	SI base unit	
Base quantity	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

2.2 SI derived units

Derived units are units which may be expressed in terms of base units by means of the mathematical symbols of multiplication and division. Certain derived units have been given special names and symbols, and these special names and symbols may themselves be used in combination with those for base and other derived units to express the units of other quantities.

2.2.1 Units expressed in terms of base units

Table 2 lists some examples of derived units expressed directly in terms of base units. The derived units are obtained by multiplication and division of base units.

Table 2. Examples of SI derived units expressed in terms of base units

	SI derived unit	
Derived quantity	Name	Symbol
area	square meter	m^2
volume	cubic meter	m^3
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s^2
wave number	reciprocal meter	m^{-1}
density, mass density	kilogram per cubic meter	kg/m^3
specific volume	cubic meter per kilogram	m^3/kg
current density	ampere per square meter	A/m^2
magnetic field strength	ampere per meter	A/m
concentration (of amount of substance)	mole per cubic meter	mol/m^3
luminance	candela per square meter	cd/m^2
refractive index	(the number) one	1(*a*)

(*a*) The symbol "1" is generally omitted in combination with a numerical value.

2.2.2 Units with special names and symbols; units which incorporate units with special names and symbols

For convenience, certain derived units, which are listed in Table 3, have been given special names and symbols. These names and symbols may themselves be used to express other derived units: Table 4 shows some examples. The special names and symbols are a compact form for the expression of units which are used frequently.

Among these names and symbols, the last four entries in Table 3 are of particular note since they were accepted by the 15th CGPM (1975, Resolutions 8 and 9; CR, 105 and *Metrologia,* 1975, **11**, 180), the 16th CGPM (1979, Resolution 5; CR, 100 and *Metrologia,* 1980, **16**, 56), and the 21st CGPM (1999, Resolution 12; CR, 444)[†] specifically with a view to safeguarding human health.

In Tables 3 and 4, the final column shows how the SI units concerned may be expressed in terms of SI base units. In this column, factors such as m^0, kg^0 ..., which are all equal to 1, are not shown explicitly.

[†] Editor's note: This last phrase is given in *Supplement 2000: addenda and corrigenda to the 7th edition (1998)*; June 2000.

Table 3. SI derived units with special names and symbols

	SI derived unit			
Derived quantity	Name	Symbol	Expressed in terms of other SI units	Expressed in terms of SI base units
plane angle	radian(a)	rad		$\mathrm{m} \cdot \mathrm{m}^{-1} = 1$(b)
solid angle	steradian(a)	sr(c)		$\mathrm{m}^2 \cdot \mathrm{m}^{-2} = 1$(b)
frequency	hertz	Hz		s^{-1}
force	newton	N		$\mathrm{m} \cdot \mathrm{kg} \cdot \mathrm{s}^{-2}$
pressure, stress	pascal	Pa	$\mathrm{N/m}^2$	$\mathrm{m}^{-1} \cdot \mathrm{kg} \cdot \mathrm{s}^{-2}$
energy, work, quantity of heat	joule	J	$\mathrm{N} \cdot \mathrm{m}$	$\mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-2}$
power, radiant flux	watt	W	J/s	$\mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-3}$
electric charge, quantity of electricity	coulomb	C		$\mathrm{s} \cdot \mathrm{A}$
electric potential difference,† electromotive force	volt	V	W/A	$\mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-3} \cdot \mathrm{A}^{-1}$
capacitance	farad	F	C/V	$\mathrm{m}^{-2} \cdot \mathrm{kg}^{-1} \cdot \mathrm{s}^4 \cdot \mathrm{A}^2$
electric resistance	ohm	Ω	V/A	$\mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-3} \cdot \mathrm{A}^{-2}$
electric conductance	siemens	S	A/V	$\mathrm{m}^{-2} \cdot \mathrm{kg}^{-1} \cdot \mathrm{s}^3 \cdot \mathrm{A}^2$
magnetic flux	weber	Wb	$\mathrm{V} \cdot \mathrm{s}$	$\mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-2} \cdot \mathrm{A}^{-1}$
magnetic flux density	tesla	T	$\mathrm{Wb/m}^2$	$\mathrm{kg} \cdot \mathrm{s}^{-2} \cdot \mathrm{A}^{-1}$
inductance	henry	H	Wb/A	$\mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-2} \cdot \mathrm{A}^{-2}$
Celsius temperature	degree Celsius(d)	°C		K
luminous flux	lumen	lm	$\mathrm{cd} \cdot \mathrm{sr}$(c)	$\mathrm{m}^2 \cdot \mathrm{m}^{-2} \cdot \mathrm{cd} = \mathrm{cd}$
illuminance	lux	lx	$\mathrm{lm/m}^2$	$\mathrm{m}^2 \cdot \mathrm{m}^{-4} \cdot \mathrm{cd} = \mathrm{m}^{-2} \cdot \mathrm{cd}$
activity (referred to a radionuclide)	becquerel	Bq		s^{-1}
absorbed dose, specific energy (imparted), kerma	gray	Gy	J/kg	$\mathrm{m}^2 \cdot \mathrm{s}^{-2}$
dose equivalent, ambient dose equivalent, directional dose equivalent, personal dose equivalent, organ equivalent dose	sievert	Sv	J/kg	$\mathrm{m}^2 \cdot \mathrm{s}^{-2}$
catalytic activity‡	katal	kat		$\mathrm{s}^{-1} \cdot \mathrm{mol}$

(*a*) The radian and steradian may be used with advantage in expressions for derived units to distinguish between quantities of different nature but the same dimension. Some examples of their use in forming derived units are given in Table 4.

(*b*) In practice, the symbols rad and sr are used where appropriate, but the derived unit "1" is generally omitted in combination with a numerical value.

(*c*) In photometry, the name steradian and the symbol sr are usually retained in expressions for units.

(*d*) This unit may be used in combination with SI prefixes, e.g., millidegree Celsius, m°C.

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† Editor's note: electric potential difference is also called "voltage" in the United States and in many other countries, as well as "electric tension" or simply "tension" in some countries.

‡ Editor's note: This derived quantity and its unit are given in *Supplement 2000: addenda and corrigenda to the 7th edition (1998)*; June 2000.

Table 4. Examples of SI derived units whose names and symbols include SI derived units with special names and symbols

	SI derived unit		
Derived quantity	Name	Symbol	Expressed in terms of SI base units
dynamic viscosity	pascal second	$\mathrm{Pa \cdot s}$	$\mathrm{m^{-1} \cdot kg \cdot s^{-1}}$
moment of force	newton meter	$\mathrm{N \cdot m}$	$\mathrm{m^{2} \cdot kg \cdot s^{-2}}$
surface tension	newton per meter	$\mathrm{N/m}$	$\mathrm{kg \cdot s^{-2}}$
angular velocity	radian per second	$\mathrm{rad/s}$	$\mathrm{m \cdot m^{-1} \cdot s^{-1} = s^{-1}}$
angular acceleration	radian per second squared	$\mathrm{rad/s^{2}}$	$\mathrm{m \cdot m^{-1} \cdot s^{-2} = s^{-2}}$
heat flux density, irradiance	watt per square meter	$\mathrm{W/m^{2}}$	$\mathrm{kg \cdot s^{-3}}$
heat capacity, entropy	joule per kelvin	$\mathrm{J/K}$	$\mathrm{m^{2} \cdot kg \cdot s^{-2} \cdot K^{-1}}$
specific heat capacity, specific entropy	joule per kilogram kelvin	$\mathrm{J/(kg \cdot K)}$	$\mathrm{m^{2} \cdot s^{-2} \cdot K^{-1}}$
specific energy	joule per kilogram	$\mathrm{J/kg}$	$\mathrm{m^{2} \cdot s^{-2}}$
thermal conductivity	watt per meter kelvin	$\mathrm{W/(m \cdot K)}$	$\mathrm{m \cdot kg \cdot s^{-3} \cdot K^{-1}}$
energy density	joule per cubic meter	$\mathrm{J/m^{3}}$	$\mathrm{m^{-1} \cdot kg \cdot s^{-2}}$
electric field strength	volt per meter	$\mathrm{V/m}$	$\mathrm{m \cdot kg \cdot s^{-3} \cdot A^{-1}}$
electric charge density	coulomb per cubic meter	$\mathrm{C/m^{3}}$	$\mathrm{m^{-3} \cdot s \cdot A}$
electric flux density	coulomb per square meter	$\mathrm{C/m^{2}}$	$\mathrm{m^{-2} \cdot s \cdot A}$
permittivity	farad per meter	$\mathrm{F/m}$	$\mathrm{m^{-3} \cdot kg^{-1} \cdot s^{4} \cdot A^{2}}$
permeability	henry per meter	$\mathrm{H/m}$	$\mathrm{m \cdot kg \cdot s^{-2} \cdot A^{-2}}$
molar energy	joule per mole	$\mathrm{J/mol}$	$\mathrm{m^{2} \cdot kg \cdot s^{-2} \cdot mol^{-1}}$
molar entropy, molar heat capacity	joule per mole kelvin	$\mathrm{J/(mol \cdot K)}$	$\mathrm{m^{2} \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}}$
exposure (x and γ rays)	coulomb per kilogram	$\mathrm{C/kg}$	$\mathrm{kg^{-1} \cdot s \cdot A}$
absorbed dose rate	gray per second	$\mathrm{Gy/s}$	$\mathrm{m^{2} \cdot s^{-3}}$
radiant intensity	watt per steradian	$\mathrm{W/sr}$	$\mathrm{m^{4} \cdot m^{-2} \cdot kg \cdot s^{-3}}$ $\mathrm{= m^{2} \cdot kg \cdot s^{-3}}$
radiance	watt per square meter steradian	$\mathrm{W/(m^{2} \cdot sr)}$	$\mathrm{m^{2} \cdot m^{-2}\, kg \cdot s^{-3}}$ $\mathrm{= kg \cdot s^{-3}}$
catalytic (activity) concentration[†]	katal per cubic meter	$\mathrm{kat/m^{3}}$	$\mathrm{m^{-3} \cdot s^{-1} \cdot mol}$

A single SI unit may correspond to several different quantities, as noted in paragraph 1.2 (p. 3). In the above table, which is not exhaustive, there are several examples. Thus the joule per kelvin (J/K) is the SI unit for the quantity heat capacity as well as for the quantity entropy; also the ampere (A) is the SI unit for the base quantity electric current as well as for the derived quantity magnetomotive force. It is therefore important not to use the unit alone to specify the quantity. This rule applies not only to scientific and technical texts but also, for example, to measuring instruments (i.e., an instrument should indicate both the unit and the quantity measured).

[†] Editor's note: This derived quantity and its unit are given in *Supplement 2000: addenda and corrigenda to the 7th edition (1998)*; June 2000.

A derived unit can often be expressed in different ways by combining the names of base units with special names for derived units. This, however, is an algebraic freedom to be governed by common-sense physical considerations. Joule, for example, may formally be written newton meter, or even kilogram meter squared per second squared, but in a given situation some forms may be more helpful than others.

In practice, with certain quantities preference is given to the use of certain special unit names, or combinations of unit names, in order to facilitate the distinction between different quantities having the same dimension. For example, the SI unit of frequency is designated the hertz, rather than the reciprocal second, and the SI unit of angular velocity is designated the radian per second rather than the reciprocal second (in this case retaining the word radian emphasizes that angular velocity is equal to 2π times the rotational frequency). Similarly the SI unit of moment of force is designated the newton meter rather than the joule.

In the field of ionizing radiation, the SI unit of activity is designated the becquerel rather than the reciprocal second, and the SI units of absorbed dose and dose equivalent the gray and sievert, respectively, rather than the joule per kilogram. In the field of catalysis, the SI unit of catalytic activity is designated the katal rather than the mole per second.[†] The special names becquerel, gray, sievert and katal were specifically introduced because of the dangers to human health which might arise from mistakes involving the units reciprocal second, joule per kilogram and mole per second.

The CIPM, recognizing the particular importance of the health-related units, approved a detailed text on the sievert for the 5th edition of the BIPM SI Brochure. That text is given in Recommendation 1 (CI-1984) adopted by the CIPM (PV, 1984, **52**, 31 and *Metrologia,* 1985, **21**, 90); see p. 38.

2.2.3 Units for dimensionless quantities, quantities of dimension one

Certain quantities are defined as the ratios of two quantities of the same kind, and thus have a dimension which may be expressed by the number one. The unit of such quantities is necessarily a derived unit coherent with the other units of the SI and, since it is formed as the ratio of two identical SI units, the unit also may be expressed by the number one. Thus the SI unit of all quantities having the dimensional product one is the number one. Examples of such quantities are refractive index, relative permeability, and friction factor. Other quantities having the unit 1 include "characteristic numbers" like the Prandtl number $\eta c_p/\lambda$ and numbers which represent a count, such as a number of molecules, degeneracy (number of energy levels) and partition function in statistical thermodynamics. All of these quantities are described as being dimensionless, or of dimension one, and have the coherent SI unit 1. Their values are simply expressed as numbers and, in general, the unit 1 is not explicitly shown. In a few cases, however, a special name is given to this unit, mainly to avoid confusion between some compound derived units. This is the case for the radian, steradian and neper.

[†] Editor's note: This sentence and portions of the subsequent sentence are given in *Supplement 2000: addenda and corrigenda to the 7th edition (1998)*; June 2000.

3 Decimal multiples and submultiples of SI units

3.1 SI prefixes

The 11th CGPM (1960, Resolution 12; CR, 87) adopted a series of prefixes and prefix symbols to form the names and symbols of the decimal multiples and submultiples of SI units ranging from 10^{12} to 10^{-12}. Prefixes for 10^{-15} and 10^{-18} were added by the 12th CGPM (1964, Resolution 8; CR, 94), for 10^{15} and 10^{18} by the 15th CGPM (1975, Resolution 10; CR, 106 and *Metrologia,* 1975, **11**, 180-181), and for 10^{21}, 10^{24}, 10^{-21} and 10^{-24} by the 19th CGPM (1991, Resolution 4; CR, 185 and *Metrologia,* 1992, **29**, 3). Table 5 lists all approved prefixes and symbols.

These 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).

Table 5. SI prefixes

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

Editor's note: The IEC has adopted prefixes for binary multiples in International Standard IEC 60027-2, Second edition, 2000-11, *Letter symbols to be used in electrical technology—Part 2: Telecommunications and electronics.* The names and symbols for the prefixes corresponding to 2^{10}, 2^{20}, 2^{30}, 2^{40}, 2^{50}, and 2^{60} are, respectively: kibi, Ki; mebi, Mi; gibi, Gi; tebi, Ti; pebi, Pi; and exbi, Ei. Thus, for example, one kibibyte would be written $1\ \text{KiB} = 2^{10}\ \text{B} = 1024\ \text{B}$. Although these prefixes are not part of the SI, they should be used in the field of information technology to avoid the incorrect usage of the SI prefixes.

3.2 The kilogram

Among the base units of the International System, the unit of mass is the only one whose name, for historical reasons, contains a prefix. Names and symbols for decimal multiples and submultiples of the unit of mass are formed by attaching prefix names to the unit name “gram” and prefix symbols to the unit symbol “g” (CIPM, 1967, Recommendation 2; PV, **35,** 29 and *Metrologia,* 1968, **4**, 45),

Example: 10^{-6} kg = 1 mg (1 milligram)
but not 1 µkg (1 microkilogram).

4 Units outside the SI

SI units are recommended for use throughout science, technology, and commerce. They are adopted internationally by the CGPM, and provide the reference in terms of which all other units are now defined. The SI base units and SI derived units, including those with special names, have the important advantage of forming a coherent set with the effect that unit conversions are not required when inserting particular values for quantities in quantity equations.

Nonetheless it is recognized that some non-SI units still appear widely in the scientific, technical and commercial literature, and some will probably continue to be used for many years. Other non-SI units, such as the units of time, are so widely used in everyday life, and are so deeply embedded in the history and culture of the human race, that they will continue to be used for the foreseeable future. For these reasons some of the more important non-SI units are listed in the tables below.

The inclusion of tables of non-SI units in this text does not imply that the use of non-SI units is to be encouraged. With a few exceptions discussed below, SI units are always to be preferred to non-SI units. It is desirable to avoid combining non-SI units with units of the SI; in particular the combination of such units with SI units to form compound units should be restricted to special cases so as to retain the advantage of coherence conferred by the use of SI units.

4.1 Units used with the SI

The CIPM (1969), recognizing that users would wish to employ the SI with units which are not part of it but are important and widely used, listed three categories of non-SI units: units to be maintained; to be tolerated temporarily; and to be avoided. In reviewing this categorization the CIPM (1996) adopted a new classification of non-SI units: units accepted for use with the SI, Table 6; units accepted for use with the SI whose values are obtained experimentally, Table 7; and other units currently accepted for use with the SI to satisfy the needs of special interests, Table 8.

Table 6 lists non-SI units which are accepted for use with the SI. It includes units which are in continuous everyday use, in particular the traditional units of time and of angle, together with a few other units which have assumed increasing technical importance.

Table 6. Non-SI units accepted for use with the International System

Name	Symbol	Value in SI units
minute	min	1 min = 60 s
hour(*a*)	h	1 h = 60 min = 3600 s
day	d	1 d = 24 h = 86 400 s
degree(*b*)	°	$1° = (\pi/180)$ rad
minute	′	$1' = (1/60)° = (\pi/10\,800)$ rad
second	″	$1'' = (1/60)' = (\pi/648\,000)$ rad
liter(*c*)	l, L	$1\ \mathrm{L} = 1\ \mathrm{dm}^3 = 10^{-3}\ \mathrm{m}^3$
metric ton(*d, e*)	t	$1\ \mathrm{t} = 10^3$ kg
neper(*f, h*)	Np	1 Np = 1
bel(*g, h*)	B	1 B = (1/2) ln 10 (Np)(*i*)

(*a*) The symbol of this unit is included in Resolution 7 of the 9th CGPM (1948; CR, 70).

(*b*) ISO 31 recommends that the degree be subdivided decimally rather than using the minute and second.

(*c*) This unit and the symbol l were adopted by CIPM in 1879 (PV, 1879, 41). The alternative symbol, 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 and the number 1. The present definition of the liter is given in Resolution 6 of the 12th CGPM (1964; CR, 93).
Editor's note: The preferred symbol for liter in the United States is L; see the Federal Register notice of July 28, 1998, "Metric System of Measurement: Interpretation of the International System of Units for the United States" (63 FR 40334 –40340).

(*d*) This unit and its symbol were adopted by the CIPM in 1879 (PV, 1879, 41).

(*e*) **Editor's note:** This is the name to be used for this unit in the United States (see the above-mentioned Federal Register notice). The original BIPM English text uses the CGPM adopted name "tonne" and footnote (*e*) reads as follows: In some English-speaking countries this unit is called "metric ton."

(*f*) The neper is used to express values of such logarithmic quantities as field level, power level, sound pressure level, and logarithmic decrement. Natural logarithms are used to obtain the numerical values of quantities expressed in nepers. The neper is coherent with the SI, but is not yet adopted by the CGPM as an SI unit. For further information see International Standard ISO 31.

(*g*) The bel is used to express values of such logarithmic quantities as field level, power level, sound-pressure level, and attenuation. Logarithms to base ten are used to obtain the numerical values of quantities expressed in bels. The submultiple decibel, dB, is commonly used. For further information see International Standard ISO 31.

(*h*) In using these units it is particularly important that the quantity be specified. The unit must not be used to imply the quantity.

(*i*) Np is enclosed in parentheses because, although the neper is coherent with the SI, it has not yet been adopted by the CGPM.

Table 7 lists three non-SI units which are also accepted for use with the SI, whose values expressed in SI units must be obtained by experiment and are therefore not known exactly. Their values are given with their combined standard uncertainties (coverage factor $k = 1$), which apply to the last two digits, shown in parentheses. These units are in common use in certain specialized fields.

Table 7. Non-SI units accepted for use with the International System, whose values in SI units are obtained experimentally

Name	Symbol	Definition	Value in SI units
electronvolt(*a*)	eV	(*b*)	$1\ \mathrm{eV} = 1.602\ 177\ 33(49) \times 10^{-19}\ \mathrm{J}$
unified atomic mass unit(*a*)	u	(*c*)	$1\ \mathrm{u} = 1.660\ 540\ 2(10) \times 10^{-27}\ \mathrm{kg}$
astronomical unit(*a*)	ua	(*d*)	$1\ \mathrm{ua} = 1.495\ 978\ 70(30) \times 10^{11}\ \mathrm{m}$

(*a*) For the electronvolt and the unified atomic mass unit, values are quoted from *CODATA Bulletin,* 1986, No. 63.

Editor's note: The most recent (1998) CODATA values are given in: P. J. Mohr and B. N. Taylor, *J. Phys. Chem. Ref. Data* **28**, 1713 (1999) and *Rev. Mod. Phys.* **72**, 351 (2000). They are: $1.602\ 176\ 462(63) \times 10^{-19}$ J and $1.660\ 538\ 73(13) \times 10^{-27}$ kg.

The value given for the astronomical unit is quoted from the IERS Conventions (1996), D. D. McCarthy ed., *IERS Technical Note* 21, Observatoire de Paris, July 1996.

(*b*) The electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of 1 V in vacuum.

(*c*) The unified atomic mass unit is equal to 1/12 of the mass of an unbound atom of the nuclide $^{12}\mathrm{C}$, at rest, and in its ground state. In the field of biochemistry, the unified atomic mass unit is also called the dalton, symbol Da.

Editor's note: The dalton is not recognized by the CGPM, CIPM, IEC, or ISO.

(*d*) The astronomical unit is a unit of length approximately equal to the mean Earth-Sun distance. Its value is such that, when used to describe the motion of bodies in the Solar System, the heliocentric gravitational constant is $(0.017\ 202\ 098\ 95)^2\ \mathrm{ua}^3 \cdot \mathrm{d}^{-2}$.

Table 8 lists some other non-SI units which are currently accepted for use with the SI to satisfy the needs of commercial, legal, and specialized scientific interests. These units should be defined in relation to the SI in every document in which they are used. Their use is not encouraged.

Table 8. Other non-SI units currently accepted for use with the International System

Name	Symbol	Value in SI units
nautical mile(*a*)		1 nautical mile = 1852 m
knot,[†]		1 nautical mile per hour = (1852/3600) m/s
are(*b*)	a	$1\ \mathrm{a} = 1\ \mathrm{dam}^2 = 10^2\ \mathrm{m}^2$
hectare(*b*)	ha	$1\ \mathrm{ha} = 1\ \mathrm{hm}^2 = 10^4\ \mathrm{m}^2$
bar(*c*)	bar	$1\ \mathrm{bar} = 0.1\ \mathrm{MPa} = 100\ \mathrm{kPa} = 1000\ \mathrm{hPa} = 10^5\ \mathrm{Pa}$
ångström	Å	$1\ \text{Å} = 0.1\ \mathrm{nm} = 10^{-10}\ \mathrm{m}$
barn(*d*)	b	$1\ \mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-28}\ \mathrm{m}^2$
curie	Ci	**Editor's note:** Although these last four units do not appear in Table 8 of the BIPM SI Brochure, they are included in this version of Table 8 because they are still accepted for use with the SI in the United States; see 63 FR 40334-40340. For their values in SI units, see Table 10.
roentgen	R	
rad	rad	
rem	rem	

(*a*) The nautical mile is a special unit employed for marine and aerial navigation to express distance. The conventional value given above was adopted by the First International Extraordinary Hydrographic Conference, Monaco, 1929, under the name "International nautical mile." As yet there is no internationally accepted symbol. This unit was originally chosen because one nautical mile on the surface of the Earth subtends approximately one minute of angle at the center.

(*b*) The units are and hectare and their symbols were adopted by the CIPM in 1879 (PV, 1879, 41) and are used to express areas of land.

(*c*) The bar and its symbol are included in Resolution 7 of the 9th CGPM (1948; CR, 70).

(*d*) The barn is a special unit employed in nuclear physics to express effective cross-sections.

[†] Editor's note: As yet there also is no internationally accepted symbol for the knot.

4.2 Other non-SI units

Certain other non-SI units are still occasionally used. Some are important for the interpretation of older scientific texts. These are listed in Tables 9 and 10, but their use is not encouraged.

Table 9 deals with the relationship between CGS units and the SI, and lists those CGS units that were assigned special names. In the field of mechanics, the CGS system of units was built upon three quantities and the corresponding base units: the centimeter, the gram and the second. In the field of electricity and magnetism, units were expressed in terms of these three base units. Because this can be done in different ways, it led to the establishment of several different systems, for example the CGS Electrostatic System, the CGS Electromagnetic System and the CGS Gaussian System. In these three last-mentioned systems, the system of quantities and the corresponding system of equations differ from those used with SI units.

Table 9. Derived CGS units with special names

Name	Symbol	Value in SI units
erg (*a*)	erg	1 erg = 10^{-7} J
dyne (*a*)	dyn	1 dyn = 10^{-5} N
poise (*a*)	P	1 P = 1 dyn · s/cm^2 = 0.1 Pa · s
stokes	St	1 St = 1 cm^2/s = 10^{-4} m^2/s
gauss (*b*)	G	1 G $\mathrel{\hat{=}}$ 10^{-4} T
oersted (*b*)	Oe	1 Oe $\mathrel{\hat{=}}$ $(1000/4\pi)$ A/m
maxwell (*b*)	Mx	1 Mx $\mathrel{\hat{=}}$ 10^{-8} Wb
stilb (*a*)	sb	1 sb = 1 cd/cm^2 = 10^4 cd/m^2
phot	ph	1 ph = 10^4 lx
gal (*c*)	Gal	1 Gal = 1 cm/s^2 = 10^{-2} m/s^2

(*a*) This unit and its symbol were included in Resolution 7 of the 9th CGPM (1948; CR, 70).

(*b*) This unit is part of the so-called "electromagnetic" three-dimensional CGS system and cannot strictly be compared with the corresponding unit of the International System, which has four dimensions when only mechanical and electric quantities are considered. For this reason, this unit is linked to the SI unit using the mathematical symbol for "corresponds to" ($\mathrel{\hat{=}}$).

(*c*) The gal is a special unit employed in geodesy and geophysics to express acceleration due to gravity.

Table 10 lists units which are common in older texts. For current texts, it should be noted that if these units are used the advantages of the SI are lost. The relation of these units to the SI should be specified in every document in which they are used.

Table 10. Examples of other non-SI units[†]

Name	Symbol	Value in SI units
curie(*a*)	Ci	1 Ci = 3.7 × 10^{10} Bq
roentgen(*b*)	R	1 R = 2.58 × 10^{-4} C/kg
rad(*c,f*)	rad	1 rad = 1 cGy = 10^{-2} Gy
rem(*d,f*)	rem	1 rem = 1 cSv = 10^{-2} Sv
X unit(*e*)		1 X unit ≈ 1.002×10^{-4} nm
gamma(*f*)	γ	1 γ = 1 nT = 10^{-9} T
jansky	Jy	1 Jy = 10^{-26} W · m^{-2} · Hz^{-1}
fermi(*f*)		1 fermi = 1 fm = 10^{-15} m
metric carat(*g*)		1 metric carat = 200 mg = 2×10^{-4} kg
torr	Torr	1 Torr = (101 325/760) Pa
standard atmosphere	atm(*h*)	1 atm = 101 325 Pa
calorie	cal	various(*i*)
micron(*f*)	μ(*j*)	1 μ = 1 μm = 10^{-6} m

(*a*) The curie is a special unit employed in nuclear physics to express activity of radionuclides (12th CGPM, 1964, Resolution 7; CR, 94).

(*b*) The roentgen is a special unit employed to express exposure to x or γ radiation.
Editor's note: Outside the United States this unit is spelled "röntgen," and this is the spelling used in the original BIPM text.

(*c*) The rad is a special unit employed to express absorbed dose of ionizing radiation. When there is risk of confusion with the symbol for radian, rd may be used as the symbol for the rad.

(*d*) The rem is a special unit used in radioprotection to express dose equivalent.

(*e*) The X unit was employed to express the wavelengths of x rays. Its relationship with the SI unit is an approximate one.

(*f*) Note that this non-SI unit is exactly equivalent to an SI unit with an appropriate submultiple prefix.

(*g*) The metric carat was adopted by the 4th CGPM in 1907 (CR, 89-91) for commercial dealings in diamonds, precious stones, and pearls.

(*h*) Resolution 4 of the 10th CGPM (1954; CR, 79). The designation "standard atmosphere" for a reference pressure of 101 325 Pa is still acceptable.

(*i*) Several "calories" have been in use:

- a calorie labeled "at 15 °C'': 1 cal_{15} = 4.1855 J (value adopted by the CIPM in 1950; PV, 1950, **22**, 79-80);
- a calorie labeled "IT" (International Table): 1 cal_{IT} = 4.1868 J (5th International Conference on the Properties of Steam, London, 1956);
- a calorie labeled "thermochemical'': 1 cal_{th} = 4.184 J.

Editor's note: The calorie commonly used to express the energy content of food is the kilocalorie, but in practice the prefix "kilo" is omitted.

(*j*) The micron and its symbol, adopted by the CIPM in 1879 (PV, 1879, 41) and repeated in Resolution 7 of the 9th CGPM (1948; CR, 70) were abolished by the 13th CGPM (1967-1968, Resolution 7; CR, 105 and *Metrologia,* 1968, **4**, 44).

[†] Editor's note: The curie, roentgen, rad, and rem are included only in Table 10 of the original BIPM text, but these four units are also included in Table 8, "Other non-SI units currently accepted for use with the International System," of this U.S. version of the BIPM text to be in accord with the U.S. interpretation of the SI.

5 The writing of SI unit names and symbols

5.1 General principles

General principles for the writing of unit symbols and numbers were first proposed by the 9th CGPM (1948, Resolution 7). These were subsequently adopted and elaborated by ISO/TC 12 (ISO 31, *Quantities and units*).

5.2 SI unit symbols

SI unit symbols (and also many non-SI unit symbols) are written as follows:

1. Roman (upright) type is used for the unit symbols. In general, unit symbols are written in lower case but, if the name of the unit is derived from the proper name of a person, the first letter of the symbol is a capital. When the name of a unit is spelled out, it is always written in lower case, except when the name is the first word of a sentence or is the name "degree Celsius."
2. Unit symbols are unaltered in the plural.
3. Unit symbols are not followed by a full stop (period), except as normal punctuation at the end of a sentence.

5.3 Algebra of SI unit symbols

In accord with the general principles adopted by ISO/TC 12 (ISO 31), the CIPM recommends that algebraic expressions involving SI unit symbols be expressed in standard forms.

1. Half-high dots or spaces are used to express a derived unit formed from two or more other units by multiplication.

   Example: $\mathrm{N \cdot m}$ or $\mathrm{N\ m}$.

2. A solidus (oblique stroke, /), a horizontal line, or a negative exponent is used to express a derived unit formed from two other units by division.

   Example: $\mathrm{m/s}$ or $\dfrac{\mathrm{m}}{\mathrm{s}}$ or $\mathrm{m \cdot s^{-1}}$.

3. The solidus is not followed by a multiplication sign or by a division sign on the same line unless ambiguity is avoided by parentheses. In complicated cases, negative exponents or parentheses are used to avoid ambiguity.

   Examples: $\mathrm{m/s^2}$ or $\mathrm{m \cdot s^{-2}}$ *but not* $\mathrm{m/s/s}$

   $\mathrm{m \cdot kg/(s^3 \cdot A)}$ or $\mathrm{m \cdot kg \cdot s^{-3} \cdot A^{-1}}$ *but neither* $\mathrm{m \cdot kg/s^3/A}$

   nor $\mathrm{m \cdot kg/s^3 \cdot A}$.

5.4 Rules for using SI prefixes

In accord with the general principles adopted by the ISO (ISO 31), the CIPM recommends that the following rules be observed when using the SI prefixes:

1. Prefix symbols are printed in roman (upright) type with no space between the prefix symbol and the unit symbol.
2. The grouping formed by the prefix symbol attached to the unit symbol constitutes a new inseparable symbol (of a multiple or submultiple of the unit concerned) which can be raised to a positive or negative power and combined with other unit symbols to form compound unit symbols.

   Examples:

   $1\ \mathrm{cm}^3 = (10^{-2}\ \mathrm{m})^3 = 10^{-6}\ \mathrm{m}^3$
   $1\ \mu\mathrm{s}^{-1} = (10^{-6}\ \mathrm{s})^{-1} = 10^6\ \mathrm{s}^{-1}$
   $1\ \mathrm{V/cm} = (1\ \mathrm{V})/(10^{-2}\ \mathrm{m}) = 10^2\ \mathrm{V/m}$
   $1\ \mathrm{cm}^{-1} = (10^{-2}\ \mathrm{m})^{-1} = 10^2\ \mathrm{m}^{-1}$.

3. Compound prefixes, i.e., prefixes formed by the juxtaposition of two or more SI prefixes, are not used.

   Example: 1 nm *but not* 1 mµm

4. A prefix is never used in isolation.

   Example: $10^6/\mathrm{m}^3$ *but not* $\mathrm{M/m}^3$.

Appendix 1. Decisions of the CGPM and the CIPM

This appendix lists those decisions of the CGPM and the CIPM which 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 which 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 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.

1 Decisions relating to the establishment of the International System of Units, SI

1.1 Practical system of units: establishment of the SI

■ **9th CGPM, 1948, Resolution 6** (CR, 64)**: proposal for establishing a practical system of units of measurement**

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 inquiry 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 Meter Convention.

■ **10th CGPM, 1954, Resolution 6** (CR, 80)**: practical system of units***

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

* The unit name “degree kelvin” was changed to “kelvin” in 1967 (13th CGPM, Resolution 3, see p. 34).

1.2 The SI

■ **CIPM, 1956, Resolution 3** (PV, **25**, 83)**: Système International d’Unités**

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 Meter Convention,
- the documents received from twenty-one countries in reply to the inquiry 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, Resolution 12 (CR, 87): Système International d'Unités*

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

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

- 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,

The name and symbol for the unit of thermodynamic temperature were modified by the 13th CGPM (1967-1968, Resolution 3, see p. 34).

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 (1971, Resolution 3, see p. 35).

	Prefix			Prefix	
Multiplying factor		Symbol	Multiplying factor		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}	deka	da	0.000 000 000 001 = 10^{-12}	pico	p

Further prefixes were adopted by the 12th CGPM (1964, Resolution 8, see p. 41), the 15th CGPM (1975, Resolution 10, see p. 41) and the 19th CGPM (1991, Resolution 4, see p. 41).

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 abrogated the class of supplementary units in the SI (1995, Resolution 8, see p. 40). These are now considered to be derived units.

Derived units

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

The 13th CGPM (1967-1968, Resolution 6, see p. 37) specified other units which should be added to this list. In principle, this list of derived units is without limit.

■ CIPM, 1969, Recommendation 1 (PV, 37, 30 and *Metrologia,* 1970, 6, 66): Système International d'Unités, Rules for application of Resolution 12 of the 11th CGPM (1960)*

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 20th CGPM decided to abrogate the class of supplementary units in the SI (1995, Resolution 8, see p. 40).

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.

2 Decisions relating to base units of the International System

2.1 Length

■ **1st CGPM, 1889** (CR, 34-38)**: sanction of the international prototypes of the meter and the kilogram***

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 Meter Commission and of the CIPM, the fundamental measurements of the international and national prototypes of the meter 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 meter 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 Meter and the equality in mass of the international Kilogram with the length of the Meter and the mass of the Kilogram kept in the Archives of France;
- that the differences between the national Meters and the international Meter lie within 0.01 millimeter 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 Meter and Kilogram and the national Meters and Kilograms fulfill the requirements of the Meter Convention,

sanctions

A. As regards international prototypes:

1. The Prototype of the meter 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 Meters have been established.

B. As regards national prototypes:

. . .

* The definition of the meter was abrogated in 1960 (11th CGPM, Resolution 6, given below).

■ **7th CGPM, 1927** (CR, 49)**: definition of the meter by the international Prototype***

The unit of length is the meter, 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 meter 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 centimeter diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other.

* This definition was abrogated in 1960 (11th CGPM, Resolution 6, given below).

■ **11th CGPM, 1960, Resolution 6** (CR, 85)**: definition of the meter***

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

considering

- that the international Prototype does not define the meter 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 meter 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 meter in force since 1889, based on the international Prototype of platinum-iridium, is abrogated.
3. The international Prototype of the meter sanctioned by the 1st CGPM in 1889 shall be kept at the BIPM under the conditions specified in 1889.

* This definition was abrogated in 1983 (17th CGPM, Resolution 1, given below).

■ **15th CGPM, 1975, Resolution 2** (CR, 103 and *Metrologia,* 1975, **11**, 179-180)**: recommended value for the speed of light**

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 meter,
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 $c = 299\,792\,458$ meters per second.

The relative uncertainty quoted here is believed to correspond to three standard deviations in the data considered.

■ **17th CGPM, 1983, Resolution 1** (CR, 97 and *Metrologia,* 1984, **20**, 25)**: definition of the meter**

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

considering

- that the present definition does not allow a sufficiently precise realization of the meter 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 meter,
- 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 meter 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 meter,
- that these various forms, making reference either to the path traveled 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 Consultative Committee 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,

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

decides

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

■ **17th CGPM, 1983, Resolution 2** (CR, 98 and *Metrologia,* 1984, **20,** 25-26)**: on the realization of the definition of the meter**

See Recommendation 1 (CI-1997) of the CIPM on the revision of the practical realization of the definition of the meter (Appendix 2, p. 45).

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 meter,
- 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.

2.2 Mass

■ **1st CGPM, 1889** (CR, 34-38)**: sanction of the international prototypes of the meter and the kilogram**
(see p. 26)

■ **3rd CGPM, 1901** (CR, 70)**: declaration on the unit of mass and on the definition of weight; conventional value of g_n**[†]

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

■ **CIPM, 1967, Recommendation 2** (PV, **35,** 29 and *Metrologia,* 1968, **4,** 45)**: decimal multiples and submultiples of the unit of mass**

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."

2.3 Time

■ **CIPM, 1956, Resolution 1** (PV, **25,** 77)**: definition of the unit of time (second)***

* This definition was abrogated in 1967 (13th CGPM, Resolution 1, given below).

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 favor of linking the second to the tropical year,

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[†] Editor's note: g_n is the quantity symbol for the standard acceleration due to gravity.

[‡] Editor's note: In the United States the term "weight" is used to mean both force and mass. In science and technology this declaration of the 1st CGPM is usually followed, with the newton (N) the SI unit of force and thus weight. In commercial and everyday use, and especially in common parlance, weight is usually used as a synonym for mass, the SI unit of which is the kilogram (kg).

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 $\frac{12\ 960\ 276\ 813}{408\ 986\ 496} \times 10^{-9}$ 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."

■ 11th CGPM, 1960, Resolution 9 (CR, 86): definition of the unit of time (second)*

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."

■ 12th CGPM, 1964, Resolution 5 (CR, 93): atomic standard of frequency

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 cesium 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.

■ Declaration of the CIPM, 1964 (PV, 32, 26 and CR, 93)

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 cesium 133 atom, unperturbed by external fields, and that the frequency of this transition is assigned the value 9 192 631 770 hertz.

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* This definition was abrogated in 1967 (13th CGPM, Resolution 1, given below).

■ **13th CGPM, 1967-1968, Resolution 1** (CR, 103 and *Metrologia,* 1968, **4,** 43)**: SI unit of time (second)**

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 Comité International des Poids et Mesures (CIPM), empowered by Resolution 5 of the 12th CGPM (1964), recommended, in order to fulfill these requirements, a cesium 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 cesium 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 cesium atom in its ground state at a thermodynamic temperature of 0 K. **Editor's note:** See Section 2.1.1.3, p. 6, for the current wording of the CIPM affirmation.

■ **14th CGPM, 1971, Resolution 1** (CR, 77 and *Metrologia,* 1972, **8,** 35)**: International Atomic Time, function of CIPM**

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.

For the CIPM and CCDS (now the CCTF) recommendations concerning the definition of International Atomic Time, see Appendix 2, p. 53.

■ **15th CGPM, 1975, Resolution 5** (CR, 104 and *Metrologia,* 1975, **11,** 180)**: Coordinated Universal Time (UTC)**

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.

2.4 Electric current

■ **CIPM, 1946, Resolution 2** (PV, **20,** 129-137)**: definitions of electric units**

. . .

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

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

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

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 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} MKS unit of force [newton] per meter 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.

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.

■ **14th CGPM, 1971** (CR, 78)**: pascal, siemens**

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

2.5 Thermodynamic temperature

■ **9th CGPM, 1948, Resolution 3** (CR, 55 and 63)**: triple point of water; thermodynamic scale with a single fixed point; unit of quantity of heat (joule)**

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 Committé 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).

■ **CIPM, 1948** (PV, **21,** 88) **and 9th CGPM, 1948** (CR, 64)**: adoption of "degree Celsius"**

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).

■ **10th CGPM, 1954, Resolution 3** (CR, 79)**: definition of the thermodynamic temperature scale***

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.

* The 13th CGPM (1967-1968, Resolution 4, given below) explicitly defined the kelvin.

■ **10th CGPM, 1954, Resolution 4** (CR, 79)**: definition of the standard atmosphere**

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 centimeter,
> i.e., 101 325 newtons per square meter.

■ **13th CGPM, 1967-1968, Resolution 3** (CR, 104 and *Metrologia,* 1968, **4,** 43)**: SI unit of thermodynamic temperature (kelvin)***

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,

* 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.

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.

■ **13th CGPM, 1967-1968, Resolution 4** (CR, 104 and *Metrologia,* 1968, **4**, 43)**: definition of the SI unit of thermodynamic temperature (kelvin)***

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 (Appendix 2, p. 59).

2.6 Amount of substance

■ **14th CGPM, 1971, Resolution 3** (CR, 78 and *Metrologia,* 1972, **8**, 36)**: SI unit of amount of substance (mole)***

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.

2.7 Luminous intensity

■ **CIPM, 1946, Resolution** (PV, **20,** 119-122)**: definitions of photometric units***

. . .

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 centimeter.

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

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 . . .

“new” was later abandoned. This definition was modified by the 13th CGPM (1967-1968, Resolution 5, given below).

■ **13th CGPM, 1967-1968, Resolution 5** (CR, 104 and *Metrologia,* 1968, **4,** 43-44)**: SI unit of luminous intensity (candela)***

* This definition was abrogated by the 16th CGPM (1979, Resolution 3, given below).

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,

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 meter.”

■ **16th CGPM, 1979, Resolution 3** (CR, 100 and *Metrologia,* 1980, **16**, 56)**: SI unit of luminous intensity (candela)**

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,

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.

3 Decisions relating to SI derived and supplementary units

3.1 SI derived units

■ **12th CGPM, 1964, Resolution 7** (CR, 94)**: curie***

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 $3.7 \times 10^{10}\ s^{-1}$. The symbol for this unit is Ci.

* The name "becquerel" (Bq) was adopted by the 15th CGPM (1975, Resolution 8, given below) for the SI unit of activity: $1\ Ci = 3.7 \times 10^{10}$ Bq.

■ **13th CGPM, 1967-1968, Resolution 6** (CR, 105 and *Metrologia,* 1968, **4**, 44)**: SI derived units***

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

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

■ **15th CGPM, 1975, Resolutions 8 and 9** (CR, 105 and *Metrologia,* 1975, **11**, 180)**: SI units for ionizing radiation (becquerel, gray)***

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:

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

* 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.

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 also be used with other physical quantities that are also expressed in joules per kilogram; the Comité Consultatif des Unités is made responsible for studying this matter in collaboration with the competent international organizations.

■ **16th CGPM, 1979, Resolution 5** (CR, 100 and *Metrologia,* 1980, **16**, 56)**: special name for the SI unit of dose equivalent (sievert)***

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.

* The CIPM (1984, Recommendation 1) decided to accompany this Resolution with an explanation, given below.

■ **CIPM, 1984, Recommendation 1** (PV, **52**, 31 and *Metrologia,* 1985, **21**, 90)**: concerning the sievert**

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.

■ **21st CGPM, 1999, Resolution 12: Special name for the SI derived unit mole per second, the katal, for the expression of catalytic activity**[†]

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 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 respresents 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.

3.2 SI supplementary units

■ **CIPM, 1980, Recommendation 1** (PV, **48**, 24 and *Metrologia,* 1981, **17**, 72)**: SI supplementary units (radian and steradian)***

* The class of SI supplementary units was abrogated by decision of the 20th CGPM (1995, resolution 8 given below).

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,

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[†] Editor's note: This resolution is given in *Supplement 2000: addenda and corrigenda to the 7th edition (1998)*; June 2000.

- 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.

■ **20th CGPM, 1995, Resolution 8** (CR, 223 and *Metrologia,* 1996, **33**, 83)**: elimination of the class of supplementary units in the SI**

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.

4 Decisions concerning terminology and the acceptance of units for use with the SI

4.1 SI prefixes

■ **12th CGPM, 1964, Resolution 8** (CR, 94)**: SI prefixes femto and atto***

* New prefixes were added by the 15th CGPM (1975, Resolution 10, given below).

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

■ **15th CGPM, 1975, Resolution 10** (CR, 106 and *Metrologia,* 1975, **11**, 180-181)**: SI prefixes peta and exa***

* New prefixes were added by the 19th CGPM (1991, Resolution 4, given below).

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

■ **19th CGPM, 1991, Resolution 4** (CR, 185 and *Metrologia,* 1992, **29**, 3)**: SI prefixes zetta, zepto, yotta and yocto**

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

The name 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.

4.2 Unit symbols and numbers

■ **9th CGPM, 1948, Resolution 7** (CR, 70)**: writing and printing of unit symbols and of numbers***

* The CGPM abrogated certain decisions on units and terminology,

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 period.

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.

in particular, micron, degree absolute and the terms "degree" and "deg," 13th CGPM (1967-1968, Resolutions 7 and 3, see below and p. 34), and the liter, 16th CGPM (1979, Resolution 6, see p. 43).

Unit	Symbol	Unit	Symbol
• meter	m	ampere	A
• square meter	m^2	volt	V
• cubic meter	m^3	watt	W
• micron	μ	ohm	Ω
• liter	l	coulomb	C
• gram	g	farad	F
• metric ton[†]	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.

4.3 Unit names

■ **13th CGPM, 1967-1968, Resolution 7** (CR, 105 and *Metrologia,* 1968, **4**, 44)**: abrogation of earlier decisions (micron, new candle)**

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."

[†] Editor's note: See footnote (*e*) of Table 6, p. 16. The name "tonne" appears in the original BIPM text.

4.4 Units accepted for use with the SI; an example: the liter

■ **3rd CGPM, 1901** (CR, 38-39)**: declaration concerning the definition of the liter***

. . .

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 “liter.”
2. . . .

* This definition was abrogated by the 12th CGPM (1964, Resolution 6, given below).

■ **11th CGPM, 1960, Resolution 13** (CR, 88)**: cubic decimeter and liter**

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

considering

- that the cubic decimeter and the liter 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 decimeter and the liter,

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

■ **CIPM, 1961, Recommendation** (PV, **29**, 34)**: cubic decimeter and liter**

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 liters.

■ **12th CGPM, 1964, Resolution 6** (CR, 93)**: liter**

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 liter given in 1901 by the 3rd CGPM,
2. **declares** that the word “liter” may be employed as a special name for the cubic decimeter,
3. **recommends** that the name liter should not be employed to give the results of high-accuracy volume measurements.

■ **16th CGPM, 1979, Resolution 6** (CR, 101 and *Metrologia,* 1980, **16**, 56-57)**: symbols for the liter**

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 liter 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 liter,

considering that the name liter, 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 liter,

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.

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

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

This appendix concerns the practical realization of the definitions of some key units of the SI. It lists CGPM and CIPM decisions relevant to current realizations and presents the framework within which standards laboratories must work if units they realize are to be in conformity with those defined by the SI.

1 Length

Recommendation 1 (CI-1997) was adopted by the Comité International des Poids et Mesures (CIPM) in 1997 to specify and update the rules for the practical realization of the definition of the meter:

> The Comité International des Poids et Mesures,
>
> **recalling**
>
> - that in 1983 the 17th Conférence Générale des Poids et Mesures (CGPM) adopted a new definition of the meter;
> - that in the same year the CGPM invited the Comité International des Poids et Mesures (CIPM)
>   - to draw up instructions for the practical realization of the meter,
>   - 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 meter) to the effect:
>   - that the meter 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

Current practice is to use c_0 to denote the speed of light in vacuum (ISO 31). In the original Recommendation of 1983, the symbol c was used for this purpose.

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 the CIPM had recommended a list of radiations for this purpose;

recalling also that in 1992 the CIPM revised the practical realization of the definition of the meter;

considering

- that science and technology continue to demand improved accuracy in the realization of the meter;
- that since 1992 work in national laboratories, in the BIPM and elsewhere has identified new radiations and methods for their realization which lead to lower uncertainties;
- that such work has also substantially reduced the uncertainty in the determined value of the frequency and wavelength in vacuum of one of the previously recommended radiations;
- that a revision of the list of recommended radiations is desirable for many applications, which include not only the direct realization of the meter by means of optical interferometry for practical length measurement, but also spectroscopy, atomic and molecular physics and the determination of fundamental physical constants;

recommends

- that the list of recommended radiations given by the CIPM in 1992 [Recommendation 3 (CI-1992)] be replaced by the list of radiations given below;
- that to the rules for the realization of the meter the following note be added concerning general relativity:

  In the context of general relativity, the meter 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. In this case, the effects to be taken into account are those of special relativity only. The local methods for the realization of the meter recommended in *b*) and *c*) provide the proper meter 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 CCDS working group on the application of general relativity to metrology (Application of general relativity to metrology, *Metrologia,* 1997, **34**, 261-290).

CIPM list of approved radiations for the practical realization of the meter, 1997: frequencies and vacuum wavelengths

This list replaces those published in PV, 1983, **51**, 25-28, 1992, **60**, 141-144 and *Metrologia,* 1984, **19**, 165-166, 1993/94, **30**, 523-541.

In this list, the values of the frequency f and of the vacuum wavelength λ should be related exactly by the relation $\lambda f = c_0$, with $c_0 = 299\,792\,458$ m/s, but the values of λ are rounded.

The data and analysis used for the compilation of this list are set out in the associated Appendix: Source Data for the List of Recommended Radiations, 1997 and its Annotated Bibliography.

For this Appendix, see the CCDM Report (1997).
Editor's note: See also *Metrologia,* 1999, **36**, 211-244.

It should be noted that for several of the listed radiations, few independent values are available, so the estimated uncertainties may not reflect all sources of variability.

Each of the listed radiations can be replaced, without degrading the accuracy, by a radiation corresponding to another component of the same transition or by another radiation, when the frequency difference is known with sufficient accuracy. It should be also noted that to achieve the uncertainties given here it is not sufficient just to meet the specifications for the listed parameters. In addition, it is necessary to follow the best practice concerning methods of stabilization as described in numerous scientific and technical publications. References to appropriate articles, illustrating accepted good practice for a particular radiation, may be obtained by application to a member laboratory of the CCDM or to the BIPM.

At its 1997 meeting, the CIPM changed the name of the Comité Consultatif pour la Définition du Mètre (CCDM) to Comité Consultatif des Longueurs, Consultative Committee for Length (CCL).

1. Recommended radiations of stabilized lasers

1.1 Absorbing atom ^{1}H, 1S – 2S, two-photon transition

The values $f = 1\,233\,030\,706\,593.7$ kHz
$\lambda = 243\,134\,624.6260$ fm

with a relative standard uncertainty of 8.5×10^{-13} apply to radiation stabilized to the two-photon transition in a cold hydrogen beam, corrected to zero laser power, and for atoms which are effectively stationary, i.e., the values are corrected for second-order Doppler shift.

Other hydrogen-absorbing transitions may be similarly used and are given in Appendix M 3 to the CCDM Report.

1.2 Absorbing molecule ^{127}I$_2$, transition 43-0, P(13), component a$_3$ (or s)

The values $f = 582\,490\,603.37$ MHz
$\lambda = 514\,673\,466.4$ fm

with a relative standard uncertainty of 2.5×10^{-10} apply to the radiation of an Ar$^+$ laser stabilized with an iodine cell external to the laser, having a cold-finger temperature of (-5 ± 2) °C.

For the specification of operating conditions, such as temperature, modulation width and laser power, the symbols ± refer to a tolerance, not an uncertainty.

1.3 Absorbing molecule $^{127}I_2$, transition 32-0, R(56), component a_{10}

The values f = 563 260 223.48 MHz
λ = 532 245 036.14 fm

with a relative standard uncertainty of 7 × 10^{-11} apply to the radiation of a frequency-doubled Nd:YAG laser, stabilized with an iodine cell external to the laser, having a cold-finger temperature between –10 °C and –20 °C.

Other $^{127}I_2$ absorbing transitions close to this transition may also be used by making reference to the following frequency differences, for which the standard uncertainty is u_c = 2 kHz.

Wavelengths for $^{127}I_2$ transitions

Transition	Frequency difference
x	[f(x) – f(32-0, R(56), a_{10})]/kHz
32-0, R(57), a_1	–50 946 880.4
32-0, P(54), a_1	–47 588 892.5
35-0, P(119), a_1	–36 840 161.5
33-0, R(86), a_1	–32 190 404.0
34-0, R(106), a_1	–30 434 761.5
36-0, R(134), a_1	–17 173 680.4
33-0, P(83), a_{21}	–15 682 074.1
32-0, R(56), a_{10}	0
32-0, P(53), a_1	+2 599 708.0

Here, f(x) represents the frequency of the transition denoted x and f(32-0, R(56), a_{10}) the frequency of the reference transition.

1.4 Absorbing molecule $^{127}I_2$, transition 26-0, R(12), component a_9

The values f = 551 579 482.96 MHz
λ = 543 516 333.1 fm

with a relative standard uncertainty of 2.5 × 10^{-10} apply to the radiation of a frequency-stabilized He-Ne laser with an external iodine cell having a cold-finger temperature of (0 ± 2) °C.

1.5 Absorbing molecule $^{127}I_2$, transition 9-2, R(47), component a_7 (or o)

The values f = 489 880 354.9 MHz
λ = 611 970 770.0 fm

with a relative standard uncertainty of 3 × 10^{-10} apply to the radiation of a He-Ne laser stabilized with an iodine cell, within or external to the laser, having a cold-finger temperature of (–5 ± 2) °C.

1.6 Absorbing molecule $^{127}I_2$, transition 11-5, R(127), component a_{13} (or i)

The values f = 473 612 214 705 kHz
λ = 632 991 398.22 fm

with a relative standard uncertainty of 2.5 × 10^{-11} apply to the radiation of a He-Ne laser with an internal iodine cell, stabilized using the third-harmonic detection technique, subject to the conditions:

- cell-wall temperature (25 ± 5) °C;
- cold-finger temperature (15 ± 0.2) °C;
- frequency modulation width, peak to peak (6 ± 0.3) MHz;
  one-way intracavity beam power (i.e., the output power divided by the transmittance of the output mirror) (10 ± 5) mW for an absolute value of the power shift coefficient ≤1.4 kHz/mW.

These conditions are by themselves insufficient to ensure that the stated standard uncertainty will be achieved. It is also necessary for the optical and electronic control systems to be operating with the appropriate technical performance. The iodine cell may also be operated under relaxed conditions, leading to the larger uncertainty specified in Appendix M 2 of the CCDM Report (1997).

1.7 Absorbing molecule $^{127}I_2$, transition 8-5, P(10), component a_9 (or g)

The values $f = 468\ 218\ 332.4$ MHz
$\lambda = 640\ 283\ 468.7$ fm

with a relative standard uncertainty of 4.5×10^{-10} apply to the radiation of a He-Ne laser stabilized with an internal iodine cell having a cold-finger temperature of (16 ± 1) °C and a frequency modulation width, peak to peak, of (6 ± 1) MHz.

1.8 Absorbing atom ^{40}Ca, transition $^1S_0 - {}^3P_1$; $\Delta m_J = 0$

The values $f = 455\ 986\ 240\ 494.15$ kHz
$\lambda = 657\ 459\ 439.2917$ fm

with a relative standard uncertainty of 6×10^{-13} apply to the radiation of a laser stabilized to Ca atoms. The values correspond to the mean frequency of the two recoil-split components for atoms which are effectively stationary, i.e., the values are corrected for second-order Doppler shift.

1.9 Absorbing ion $^{88}Sr^+$, transition $5\ ^2S_{1/2} - 4\ ^2D_{5/2}$

The values $f = 444\ 779\ 044.04$ MHz
$\lambda = 674\ 025\ 590.95$ fm

with a relative standard uncertainty of 1.3×10^{-10} apply to the radiation of a laser stabilized to the transition observed with a trapped and cooled strontium ion. The values correspond to the centre of the Zeeman multiplet.

1.10 Absorbing atom ^{85}Rb, $5S_{1/2}$ ($F = 3$) – $5D_{5/2}$ ($F = 5$), two-photon transition

The values $f = 385\ 285\ 142\ 378$ kHz
$\lambda = 778\ 105\ 421.22$ fm

with a relative standard uncertainty of 1.3×10^{-11} apply to the radiation of a laser stabilized to the center of the two-photon transition. The values apply to a rubidium cell at a temperature below 100 °C, are corrected to zero laser power, and for second-order Doppler shift.

Other rubidium absorbing transitions may also be used, and are given in Appendix M 3 to the CCDM Report.

1.11 Absorbing molecule CH_4, transition ν_3, P(7), component $F_2^{(2)}$

1.11.1 The values $f = 88\ 376\ 181\ 600.18$ kHz
$\lambda = 3\ 392\ 231\ 397.327$ fm

with a relative standard uncertainty of 3×10^{-12} apply to the radiation of a He-Ne laser stabilized to the central component [(7-6) transition] of the resolved hyperfine-structure triplet. The values correspond to the mean frequency of the two recoil-split components for molecules which are effectively stationary, i.e., the values are corrected for second-order Doppler shift.

1.11.2 The values f = 88 376 181 600.5 kHz
λ = 3 392 231 397.31 fm

with a relative standard uncertainty of 2.3×10^{-11} apply to the radiation of a He-Ne laser stabilized to the center of the unresolved hyperfine structure of a methane cell, within or external to the laser, held at room temperature and subject to the following conditions:

- methane pressure ≤ 3 Pa;
- mean one-way intracavity surface power density (i.e., the output power density divided by the transmittance of the output mirror) $\leq 10^4\ \mathrm{W \cdot m^{-2}}$;
- radius of wavefront curvature ≥ 1 m;
- inequality of power between counter-propagating waves ≤ 5 %;
- servo referenced to a detector placed at the output facing the laser tube.

1.12 Absorbing molecule OsO_4, transition in coincidence with the $^{12}C^{16}O_2$, R(12) laser line

The values f = 29 096 274 952.34 kHz
λ = 10 303 465 254.27 fm

with a relative standard uncertainty of 6×10^{-12} apply to the radiation of a CO_2 laser stabilized with an external OsO_4 cell at a pressure below 0.2 Pa.

Other transitions may also be used, and are given in Appendix M 3 of the CCDM Report (1997).

2. Recommended values for radiations of spectral lamps and other sources

2.1 Radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the atom of ^{86}Kr

The value λ = 605 780 210.3 fm

with a relative expanded uncertainty, $U = ku_c$ ($k = 3$), of 4×10^{-9} [equal to three times the relative standard uncertainty of 1.3×10^{-9}] , applies to the radiation emitted by a discharge lamp operated under the conditions recommended by the CIPM in 1960 (PV, **28**, 71-72 and CR, 1960, 85). These are as follows:

The uncertainty quoted in the 1960 document was 1×10^{-8} and was subsequently improved to 4×10^{-9} (*BIPM Com. Cons. Déf. du Mètre,* 1973, **5**, M 12).

The radiation of ^{86}Kr is obtained by means of a hot cathode discharge lamp containing ^{86}Kr, of a purity not less than 99 %, in sufficient quantity to assure the presence of solid krypton at a temperature of 64 K, this lamp having a capillary with the following characteristics: inner diameter from 2 mm to 4 mm, wall thickness about 1 mm.

It is estimated that the wavelength of the radiation emitted by the positive column is equal, to within 1 part in 10^8, to the wavelength corresponding to the transition between the unperturbed levels, when the following conditions are satisfied:

1. the capillary is observed end-on from the side closest to the anode;
2. the lower part of the lamp, including the capillary, is immersed in a cold bath maintained at a temperature within one degree of the triple point of nitrogen;
3. the current density in the capillary is (0.3 ± 0.1) A/cm^2.

2.2 Radiations for atoms of ^{86}Kr, ^{198}Hg and ^{114}Cd

In 1963 the CIPM (*BIPM Com. Cons. Déf. Mètre,* 1962, **3**, 18-19 and PV, **52**, 26-27) specified values for the vacuum wavelengths, λ, operating conditions, and corresponding uncertainties, for certain transitions in ^{86}Kr, ^{198}Hg and ^{114}Cd.

The uncertainties quoted throughout Section 2.2 are judged to correspond to relative expanded uncertainties $U = ku_c$ ($k = 3$), equal to three times the relative combined standard uncertainties.

Vacuum wavelengths, λ, for ^{86}Kr transitions

Transition	λ/pm
$2p_9 - 5d'_4$	645 807.20
$2p_8 - 5d_4$	642 280.06
$1s_3 - 3p_{10}$	565 112.86
$1s_4 - 3p_8$	450 361.62

For ^{86}Kr, the above values apply, with a relative uncertainty of 2×10^{-8}, to radiations emitted by a lamp operated under conditions similar to those specified in Section 2.1.

Vacuum wavelengths, λ, for ^{198}Hg transitions

Transition	λ/pm
$6^1P_1 - 6^1D_2$	579 226.83
$6^1P_1 - 6^3D_2$	577 119.83
$6^3P_2 - 7^3S_1$	546 227.05
$6^3P_1 - 7^3S_1$	435 956.24

For ^{198}Hg, the above values apply, with a relative uncertainty of 5×10^{-8}, to radiations emitted by a discharge lamp when the following conditions are met:

a) the radiations are produced using a discharge lamp without electrodes containing ^{198}Hg, of a purity not less than 98 %, and argon at a pressure from 0.5 mm Hg to 1.0 mm Hg (66 Pa to 133 Pa);

b) the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;

c) the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature less than 10 °C;

d) it is preferred that the volume of the lamp be greater than 20 cm^3.

Vacuum wavelengths, λ, for ^{114}Cd transitions

Transition	λ/pm
$5^1P_1 - 5^1D_2$	644 024.80
$5^3P_2 - 6^3S_1$	508 723.79
$5^3P_1 - 6^3S_1$	480 125.21
$5^3P_0 - 6^3S_1$	467 945.81

For ^{114}Cd, the above values apply, with a relative uncertainty of 7×10^{-8}, to radiations emitted by a discharge lamp under the following conditions:

a) the radiations are generated using a discharge lamp without electrodes, containing ^{114}Cd of a purity not less than 95 %, and argon at a pressure of about 1 mm Hg (133 Pa) at ambient temperature;

b) the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;

c) the lamp is excited by a high-frequency field of moderate power and is maintained at a temperature such that the green line is not reversed.

2.3 Absorbing molecule $^{127}I_2$, transition 17-1, P(62) component a_1, as recommended by the CIPM in 1992 (*BIPM Com. Cons. Déf. Mètre,* 1992, **8**, M18 and M137, and *Mise en Pratique* of the Definition of the Meter (1992), *Metrologia,* 1993/94, **30**, 523-541).

The values $f = 520\,206\,808.4$ MHz
$\lambda = 576\,294\,760.4$ fm

with a relative standard uncertainty of 4×10^{-10}, apply to the radiation of a dye laser (or frequency-doubled He-Ne laser) stabilized with an iodine cell, within or external to the laser, having a cold-finger temperature of (6 ± 2) °C.

2 Mass

The unit of mass, the kilogram, is the mass of the international prototype of the kilogram kept at the BIPM. It is a cylinder made of an alloy for which the mass fraction of platinum is 90 % and the mass fraction of iridium is 10 %. The masses of 1 kg secondary standards of the same alloy or of stainless steel are compared with the mass of the international prototype by means of balances with a relative uncertainty approaching 1 part in 10^9.

The mass of the international prototype increases by approximately 1 part in 10^9 per year due to the inevitable accumulation of contaminants on its surface. For this reason, the CIPM declared that, pending further research, the reference mass of the international prototype is that immediately after cleaning and washing by a specified method (PV, 1989, **57**, 104-105 and PV, 1990, **58**, 95-97). The reference mass thus defined is used to calibrate national standards of platinum-iridium alloy (*Metrologia,* 1994, **31**, 317-336).

In the case of stainless-steel 1 kg standards, the relative uncertainty of comparisons is limited to about 1 part in 10^8 by the uncertainty in the correction for air buoyancy. The results of comparisons made in vacuum, though unaffected by air buoyancy, are subject to additional corrections to account for changes in mass of the standards when cycled between vacuum and atmospheric pressure.

Mass standards representing multiples and submultiples of the kilogram can be calibrated by a conceptually simple procedure.

3 Time

3.1 Unit of time

A small number of national metrology laboratories realize the unit of time with the highest accuracy. To do so, they design and build primary frequency standards that produce electric oscillations at a frequency whose relationship to the transition frequency of the atom of cesium 133, which defines the second, is known. In 1997, the best of these primary standards produces the SI second with a relative combined standard uncertainty of 2 parts in 10^{15}. It is important to note that the definition of the second should be understood as the definition of the unit of proper time: it applies in a small spatial domain which shares the motion of the cesium atom. In a laboratory sufficiently small to allow the effects of the non-uniformity of the gravitational field to be neglected when compared to the uncertainties of the realization of the second, the proper second is obtained after application of the special relativistic correction for the velocity of the atom in the laboratory. It is wrong to correct for the local gravitational field.

Primary frequency standards can also be used for calibration of the frequency of secondary time standards used in national time-service laboratories. These are generally commercial cesium clocks characterized by extreme long-term stability: able to maintain a frequency with a stability better than 1 part in 10^{14} over a few months, they constitute very good “time-keepers.” The relative uncertainty of their frequencies is on the order of 10^{-12}. Time metrology laboratories also use hydrogen masers with good short-term stability. These instruments are used in all applications which require a stable reference over intervals of less than one day (stability of 1 part in 10^{15} at 10 000 s). In their basic form, hydrogen masers are subject to frequency drifts that become apparent when their mean frequencies are compared with that of a cesium clock over a few days. This drift is greatly reduced when the masers are operated in an active mode with a self-servo-controlled cavity. Cesium clocks and hydrogen masers must be operated under carefully controlled environmental conditions.

3.2 Clock comparisons, time scales

National laboratories usually operate a number of clocks. These are run independently of one another and their data are combined to generate a perennial time scale. This scale is more stable and more accurate than that of any individual contributing clock. The scale is based on the results of local clock comparisons in the laboratory, and often has an uncertainty of less than 100 ps. These time scales are generally designated TA(k) for laboratory k.

The synchronization of clocks operating in widely separated laboratories is an important concern for time metrology. It calls for accurate methods of clock comparison that can be operated everywhere on Earth, at any time. The satellite system of the Global Positioning System (GPS) provides a satisfactory solution to this problem: made up of twenty-four non-geostationary satellites, this system is designed for positioning, but has the particular feature that the satellites are equipped with cesium clocks which broadcast time signals. These signals are used in the following way: clocks in two distant laboratories are compared individually with a clock on board a satellite which is visible simultaneously from both laboratories and the difference is calculated. For a comparison extending over ten minutes, the uncertainty thus obtained may be a few nanoseconds, even for clocks which are separated by several thousand kilometers. To reduce these uncertainties to this limit the data must be considered very carefully: results obtained from views that are not strictly simultaneous must be systematically rejected and a correction must be applied to take account of the exact position of the satellite, data known only a few days later.

The GPS is used on a regular basis to link national laboratories in many countries and it will shortly be complemented by a similar Russian system: the Global Navigation Satellite System (GLONASS). Among other methods under study are bidirectional techniques based on the transmission of an optical or radiofrequency signal from one laboratory to another and back, via a satellite. Such methods should lead to subnanosecond accuracy before the end of the century. All these methods of time comparison are subject to relativistic effects which may exceed 100 ns, so corrections must be applied to take them into account.

Optimal combination of all the results of comparisons between the clocks maintained in the national time-service laboratories results in a world reference time scale, International Atomic Time (TAI), approved by the 14th CGPM in 1971 (Resolution 1; CR, 77 and *Metrologia,* 1972, **8**, 35). The first definition of TAI was that submitted by the then CCDS in 1970 to the CIPM (Recommendation S2; PV, **38**, 110 and *Metrologia,* 1971, **7**, 43):

> 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 the framework of general relativity, TAI must be regarded as a time coordinate (or *coordinate time*): its definition was therefore completed as follows (declaration of the CCDS, *BIPM Com. Cons. Déf. Seconde*, 1980, **9**, S15 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 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.

For details see the proceedings of the 21st General Assembly of the IAU, Buenos Aires, *IAU Trans.* 1991, vol. **XXIB** (Kluwer).

Responsibility for TAI was accepted by the CIPM from the Bureau International de l'Heure on 1 January 1988. TAI is processed in two steps. A weighted average based on some 200 clocks maintained under metrological conditions in about fifty laboratories is first calculated. The algorithm used is optimized for long-term stability, which requires observation of the behavior of clocks over a long duration. In consequence, TAI is a deferred-time time scale, available with a delay of a few weeks. In 1997, the relative frequency stability of TAI was estimated to be 2 parts in 10^{15} for mean durations of two months. The frequency accuracy of TAI is evaluated by comparing the TAI scale unit with various realizations of the SI second of primary frequency standards. This requires the application of a correction to compensate for the relativistic frequency shift between the location of the primary standard and a point fixed on the rotating geoid. The magnitude of this correction is, between points fixed on the surface of the Earth, of the order of 1 part in 10^{16} per meter of altitude. In 1997, the difference between the TAI scale unit and the SI second on the rotating geoid was $+2 \times 10^{-14}$ s, and was known with an uncertainty of 5×10^{-15} s. This difference is reduced by steering the frequency of TAI by the application of corrections, of magnitude 1 part in 10^{15}, every two months. This method improves the accuracy of TAI while not degrading its middle-term stability.

3.3 Legal time

TAI is not distributed directly in everyday life. The time in common use (broadcast by radio, television, the telephone . . .) is referred to a time scale called Coordinated Universal Time (UTC) as recommended by the 15th CGPM in its Resolution 5 in 1975 (CR, 104 and *Metrologia,* 1975, **11**, 180). UTC differs from TAI by a whole number of seconds, equal to –31 s on 1 July 1997. This difference can be modified in steps of 1 s, using a positive or negative leap second, in order to keep UTC in agreement with the time defined by the rotation of the Earth such that, when averaged over a year, the Sun crosses the Greenwich meridian at noon UTC to within 0.9 s. In addition, the legal time of most countries is offset from UTC by a whole number of hours (time zones and "summer time"). National time-service laboratories maintain an approximation of UTC known as UTC(k) for laboratory k. The differences between UTC(k) and UTC are in general no more than a few hundreds of nanoseconds.

4 Electrical quantities

The realization to high accuracy of the ampere (a base unit of the SI), the ohm and the volt (derived units of the SI) directly in terms of their definitions is difficult and time-consuming. The best such realizations of the ampere are now obtained through combinations of realizations of the watt, the ohm and the volt. The watt realized electrically is compared by beam-balance experiments with the watt realized mechanically. These experiments employ a coil in a magnetic flux and are devised in such a way that it is not necessary to know either the dimensions of the coil or the magnitude of the flux density. The ohm is realized using a Thompson-Lampard capacitor whose value can be changed by an amount that depends only on the magnitude of a linear displacement of a guard electrode. The volt is realized by means of a balance in which an electro-static force is measured in terms of a mechanical force. The ampere may thus be deduced from combinations of any two of these units. The relative uncertainty in the value of the ampere obtained in this way is estimated to be a few parts in 10^7. The ampere, ohm and volt may also be determined from measurements of various combinations of physical constants. Laboratory reference standards for the volt and the ohm based upon the Josephson and quantum-Hall effects are, however, significantly more reproducible and stable than a few parts in 10^7. In order to take advantage of these highly stable methods of maintaining laboratory reference standards of the electrical units while at the same time taking care not to change their SI definitions, the 18th CGPM in 1987 adopted Resolution 6 which calls for representations of the volt and the ohm to be based on conventional values for the Josephson constant K_J and the von Klitzing constant R_K.

■ **18th CGPM, 1987, Resolution 6** (CR, 100 and *Metrologia,* 1988, **25**, 115)**: forthcoming adjustment to the representations of the volt and of the ohm**

The 18th Conférence Générale des Poids et Mesures,

considering

- that world-wide 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.

In 1988 the CIPM adopted Recommendations 1 (CI-1988) and 2 (CI-1988) which set exact values for the Josephson and von Klitzing constants, and called for laboratories to base their standards on these values from 1 January 1990.

■ **CIPM, 1988, Recommendation 1** (PV, **56**, 44 and *Metrologia,* 1989, **26**, 69)**: representation of the volt by means of the Josephson effect**

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-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.

■ **CIPM, 1988, Recommendation 2** (PV, **56**, 45 and *Metrologia,* 1989, **26**, 70)**: representation of the ohm by means of the quantum Hall effect**

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 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.

At its meeting in 1988 the CCE carefully considered the way in which the recommended conventional values $K_{J\text{-}90}$ and $R_{K\text{-}90}$ should be used and made additional statements to clarify the implications of the Recommendations. These statements may be summarized as follows:

1. Recommendations 1 (CI-1988) and 2 (CI-1988) do not constitute a redefinition of SI units. The conventional values $K_{J\text{-}90}$ and $R_{K\text{-}90}$ cannot be used as bases for defining the volt and the ohm [meaning the present units of electromotive force and electrical resistance in the Système International d'Unités (SI)]. To do so would change the status of μ_0 from that of a constant having an exactly defined value (and would therefore abrogate the definition of the ampere) and would also produce electrical units which would be incompatible with the definition of the kilogram and units derived from it.
2. Concerning the use of subscripts on symbols for quantities or units, the CCE considers that symbols for electromotive force (electric potential, electric potential difference) and electric resistance, and for the volt and the ohm, should not be modified by adding subscripts to denote particular laboratories or dates.

These statements were subsequently endorsed by the CIPM. The 19th CGPM (1991, Resolution 2) recommended the continuation of research into the basic theory of the Josephson and the quantum-Hall effects.

5 Temperature

Direct measurements of thermodynamic temperature can only be made by using one of a small number of so-called primary thermometers. These are thermometers whose equation of state can be written down explicitly without having to introduce unknown temperature-dependent constants.

Primary thermometers that have been used to provide accurate values of thermodynamic temperature include the constant-volume gas thermometer, the acoustic gas thermometer, the spectral- and total-radiation thermometers and the electronic-noise thermometer. Uncertainties of a few millikelvins have been achieved with such thermometers up to about 373 K, beyond which the uncertainties increase progressively. The use of such thermometers to high accuracy is difficult and time-consuming and there exist secondary thermometers, such as the platinum resistance thermometer, whose reproducibility can be better by a factor of ten than that of any primary thermometer. In order to allow the maximum advantage to be taken of these secondary thermometers the CGPM has, in the course of time, adopted successive versions of an international temperature scale. The first of these was the International Temperature Scale of 1927 (ITS-27); this was replaced by the International Practical Temperature Scale of 1948 (IPTS-48) which in turn was replaced by the International Practical Temperature Scale of 1968 (IPTS- 68). In 1976 the CIPM adopted, for use at low temperatures, the 1976 Provisional 0.5 K to 30 K Temperature Scale (EPT-76). On 1 January 1990 the IPTS-68 and the EPT-76 were replaced by the International Temperature Scale of 1990 (ITS-90) adopted by the CIPM in 1989 in its Recommendation 5 (CI-1989). The 19th CGPM (1991, Resolution 3) recommended that national laboratories continue their efforts to improve the world-wide uniformity and long-term stability of temperature measurements by rapid implementation of the ITS-90.

■ **CIPM, 1989, Recommendation 5** (PV, **57**, 115 and *Metrologia,* 1990, **27**, 13)**: the International Temperature Scale of 1990**

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.

The ITS-90 extends upwards from 0.65 K to the highest temperature measurable using an optical pyrometer. The scale is based on 1) a set of defining fixed points and 2) specified methods of interpolating between them. The defining fixed points are the temperatures assigned by agreement to a number of experimentally realizable thermodynamic states and the interpolations are defined in terms of the helium vapor-pressure equations from 0.65 K to 5 K, interpolating constant-volume gas thermometers from 3 K to 24.5561 K, platinum resistance thermometers from 13.8033 K to 961.78 °C and the Planck radiation law at higher temperatures. In several ranges of temperature more than one definition of T_{90}, the temperature defined by the Scale, exists. The various definitions have equal validity.

Advice on the realization and implementation of the ITS-90 is given in two documents, *Supplementary Information for the ITS-90* and *Techniques for Approximating the ITS-90,* which are approved and updated periodically by the CCT and published by the BIPM.

6 Amount of substance

All quantitative results of chemical analyses or of dosages can be expressed in units of amount of substance of the elementary entities, for which the base unit is the mole. The principle of physical measurement based on this unit is explained below.

The simplest case is that of a sample of a pure substance that is considered to be formed of atoms; call X the chemical symbol of these atoms. A mole of atoms X contains by definition as many atoms as there are ^{12}C atoms in 0.012 kg of carbon 12. As neither the mass $m(^{12}\mathrm{C})$ of an atom of carbon 12 nor the mass $m(\mathrm{X})$ of an atom X can be measured accurately, we use the ratio of these masses, $m(\mathrm{X})/m(^{12}\mathrm{C})$, which can be determined accurately, for example by means of a Penning trap. The mass corresponding to 1 mol of X is then $[m(\mathrm{X})/\mathrm{m}(^{12}\mathrm{C})] \times 0.012$ kg, which is expressed by the statement that the molar mass $M(\mathrm{X})$ of X (quotient of mass by amount of substance) is

$$M(\mathrm{X}) = [m(\mathrm{X})/m(^{12}\mathrm{C})] \times 0.012\ \mathrm{kg/mol}.$$

For example, the atom of fluorine ^{19}F and the atom of carbon ^{12}C have masses which are in the approximate ratio 18.9984/12. The molar mass of the molecular gas F_2 is:

$$M(\mathrm{F}_2) = \frac{2 \times 18.9984}{12} \times 0.012\ \mathrm{kg/mol} = 0.037\,996\,8\ \mathrm{kg/mol},$$

and the amount of substance corresponding to a given mass, for example 0.0500 kg of F_2 is:

$$\frac{0.0500\ \mathrm{kg}}{0.037\,996\,8\ \mathrm{kg \cdot mol^{-1}}} = 1.316\ \mathrm{mol}.$$

In the case of a pure substance that is supposed made up of molecules B, which are combinations of atoms X, Y, … according to the chemical formula $B = X_\alpha\, Y_\beta \ldots$, the mass of one molecule is $m(\mathrm{B}) = \alpha m(\mathrm{X}) + \beta m(\mathrm{Y}) + \cdots$. This mass is not known precisely but the ratio $m(\mathrm{B})/m(^{12}\mathrm{C})$ can be determined accurately. The molar mass of a molecular substance B is then:

$$M(\mathrm{B}) = \frac{m(\mathrm{B})}{m(^{12}\mathrm{C})} \times 0.12\,\mathrm{kg/mol} = \left(\alpha \frac{m(\mathrm{X})}{m(^{12}\mathrm{C})} + \beta \frac{m(\mathrm{Y})}{m(^{12}\mathrm{C})} + \ldots\right) \times 0.012\,\mathrm{kg/mol}.$$

The same procedure is used in the more general case when the composition of substance B is specified as $X_\alpha\, Y_\beta$ even if $\alpha, \beta \ldots$ are not integers. If we denote the mass ratios $m(\mathrm{X})/m(^{12}\mathrm{C})$, $m(\mathrm{Y})/m(^{12}\mathrm{C})$, … by $r(\mathrm{X})$, $r(\mathrm{Y})$, … , the molar mass of substance B is given by the formula:

$$M(\mathrm{B}) = [\alpha r(\mathrm{X}) + \beta r(\mathrm{Y}) + \ldots\,] \times 0.012\ \mathrm{kg/mol}.$$

Other methods for the measurement of amount of substance are based on the laws of physics and physical chemistry. Three examples are:

1. With perfect gases, 1 mol of particles of any gas occupies the same volume at a temperature T and a pressure p (approximately 0.0224 m^3 at $T = 273.15$ K and $p = 101\,325$ Pa): this provides a method of measuring the ratio of amounts of substance for any two gases (the corrections to apply if the gases are not perfect are well known).
2. For quantitative electrolytic reactions the ratio of amounts of substance can be obtained by measuring quantities of electricity. For example, 1 mol of Ag and (1/2) mol of Cu are deposited on a cathode by the same quantity of electricity (approximately 96 485 C).
3. Application of the laws of extremely dilute solutions is yet another method of determining ratios of amounts of substance.

7 Photometric quantities

The definition of the candela given on page 9 is expressed in strictly physical terms. The objective of photometry, however, is to measure light in such a way that the result of the measurement correlates closely with the visual sensation experienced by a human observer of the same radiation. For this purpose, the International Commission on Illumination (CIE) introduced two special functions $V(\lambda)$ and $V'(\lambda)$, referred to as spectral luminous efficiency functions, which describe, respectively, the relative spectral responsivity of the average human eye for photopic (light adapted) and scotopic (dark adapted) vision. The more important of these two, the light-adapted function $V(\lambda)$, is expressed relative to its value for the monochromatic radiation to which the eye is most sensitive when adapted to high levels of illuminance. That is, it is defined relative to radiation at 540×10^{12} Hz which corresponds to a wavelength of 555.016 nm in standard air.

See "Principles governing photometry," *Monographie BIPM,* 1983, 31 p.

The CIPM has approved the use of these functions with the effect that the corresponding photometric quantities are defined in purely physical terms as quantities proportional to the integral of a spectral power distribution, weighted according to a specified function of wavelength.

Since the inception of the SI, the candela has been one of its base units: it remained a base unit even after being linked, in 1979, to the derived SI unit of power, the watt. The original photometric standards were light sources, the earliest ones being candles, hence the name candela as the name of the photometric base unit. From 1948 to 1979 the radiation from a black body, Planck radiation, at the temperature of freezing platinum was used to define the candela. Today the definition is given in terms of monochromatic radiation rather than the broadband radiation implied by the black-body definition. The value 1/683 watt per steradian which appears in the present definition was chosen in 1979 so as to minimize any change in the mean representations of the photometric units maintained by the national standards laboratories.

The definition gives no indication as to how the candela should be realized, which has the great advantage that new techniques to realize the candela can be adopted without changing the definition of the base unit. Today, national metrology institutes realize the candela by radiometric methods. Standard lamps are still used, however, to maintain the photometric units: they provide either a known luminous intensity in a given direction, or a known luminous flux.

Appendix 3. The BIPM and the Meter Convention[†]

The International Bureau of Weights and Measures (BIPM, *Bureau International des Poids et Mesures*) was set up by the Meter Convention (*Convention du Mètre*, often called the Treaty of the Meter in the United States) signed in Paris on 20 May 1875 by seventeen States during the final session of the diplomatic Conference of the Meter. 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 Meter Convention.

As of 31 December 1997, forty-eight States were members of this Convention: Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Czech Republic, Denmark, Dominican Republic, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran (Islamic Rep. of), Ireland, Israel, Italy, Japan, Korea (Dem. People's Rep. of), Korea (Rep. of), Mexico, Netherlands, New Zealand, Norway, Pakistan, Poland, Portugal, Romania, Russian Federation, Singapore, Slovakia, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, United States, Uruguay, Venezuela.

Editor's note: Greece joined the Meter Convention at the beginning of 2001, bringing the number of Member States to forty-nine.

The task of the BIPM is to ensure world-wide unification of physical measurements; its function is thus to:

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

The BIPM operates under the exclusive supervision of the International Committee for Weights and Measures (CIPM, *Comité International des Poids et Mesures*) which itself comes under the authority of the General Conference on Weights and Measures (CGPM, *Conférence Générale des Poids et Mesures*) and reports to it on the work accomplished by the BIPM.

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

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

The International Committee has eighteen members each from a different State: at present, it meets every year. The officers of this committee present an Annual

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[†] Editor's note: In the original BIPM text, this material appeared before the Contents under the title "The BIPM and the Convention du Mètre." Further, the names of organizations and the name of the Meter Convention were in French only.

Report on the administrative and financial position of the BIPM to the Governments of the Member States of the Meter Convention. The principal task of the CIPM is to ensure world-wide uniformity in units of measurement. It does this by direct action or by submitting proposals to the CGPM.

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) and to time scales (1988). 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 and in 1984 for the laser work. In 1988 a new building for a library and offices was opened.

Some forty-five physicists and technicians work in the BIPM laboratories. They mainly carry out metrological research, international comparisons of realizations of units and calibrations of standards. An annual report, published in the *Procès-Verbaux des Séances du Comité International des Poids et Mesures*, 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 (*Comités Consultatifs*), 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 co-ordinating the international work carried out in their respective fields and for proposing recommendations to the CIPM concerning units.

The Consultative Committees have common regulations (PV, 1963, **31**, 97). They meet at irregular intervals. The chairman 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 to by the CIPM, which send delegates of their choice (Criteria for membership of Consultative Committees, PV, 1996, **64**, 124). In addition, there are individual members appointed by the CIPM, and a representative of the BIPM. At present, there are ten such committees:

1. The Consultative Committee for Electricity and Magnetism (CCEM, *Comité Consultatif d'Électricité et Magnétisme*), a new name given in 1997 to the Consultative Committee for Electricity (CCE, *Comité Consultatif d'Électricité*) set up in 1927.
2. The Consultative Committee for Photometry and Radiometry (CCPR, *Comité Consultatif de Photométrie et Radiométrie*), new name given in 1971 to the Consultative Committee for Photometry set up in 1933 [between 1930 and 1933 the preceding Committee (CCE) dealt with matters concerning photometry].
3. The Consultative Committee for Thermometry (CCT, *Comité Consultatif de Thermométrie*), which for a time was called Consultative Committee for Thermometry and Calorimetry (CCTC) set up in 1937.
4. The Consultative Committee for Length (CCL, *Comité Consultatif des Longueurs*), new name given in 1997 to the Consultative Committee for the Definition of the Meter (CCDM, *Comité Consultatif pour la Définition du Mètre*), set up in 1952.

5. The Consultative Committee for Time and Frequency (CCTF, *Comité Consultatif du Temps et des Fréquences*), new name given in 1997 to the Consultative Committee for the Definition of the Second (CCDS, *Comité Consultatif pour la Définition de la Seconde*) set up in 1956.
6. The Consultative Committee for Ionizing Radiation (CCRI, *Comité des Rayonnements Ionisants*), new name given in 1997 to the Consultative Committee for the Standards of Measurement of Ionizing Radiation (CCEMRI, *Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants*) set up in 1958. In 1969 this committee established four sections: Section I (Measurement of 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, *Comité Consultatif des Unités*), 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, *Comité Consultatif pour la Masse et les grandeurs apparentées*), set up in 1980;
9. The Consultative Committee for Amount of Substance (CCQM, *Comité Consultatif pour la Quantité de Matière*), set up in 1993.
10. The Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV, *Comité Consultatif de l'Acoustique, des Ultrasons et des Vibrations*), set up in September 1998.[†]

The proceedings of the General Conferences, the International Committee and the Consultative Committees are published by the BIPM in the following series:

- *Comptes Rendus des Séances de la Conférence Générale des Poids et Mesures (CR)*;
- *Procés-Verbaux des Séances du Comité International des Poids et Mesures (PV)*;
- *Sessions des Comités Consultatifs.*

The Bureau International also publishes monographs on special metrological subjects and, under the title *Le Système International d'Unités (SI)*, this brochure, periodically updated, in which are collected all the decisions and recommendations concerning units.

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

The scientific work of the BIPM is published in the open scientific literature and an annual list of publications appears in the *Procès-Verbaux* of the CIPM.

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 and work on standards and units, as well as reports concerning the activities, decisions and recommendations of the various bodies created under the Meter Convention.

[†] Editor's note: This entry has been added to the origninal BIPM text.

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[†] Editor's note: This Index contains minor changes to the Index in the original BIPM text.

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