

Draft Chapter 2 for SI Brochure, following redefinitions of the base units.

This is a draft specification for the SI, prepared by the CCU, which would follow from the proposed redefinition of the kilogram, ampere, kelvin and mole to fix the values of the Planck constant h , elementary charge e , Boltzmann constant k and Avogadro constant N_A . The changes described include changes in the words used to present the definitions of the units, in addition to the fundamental changes proposed for the four base units described above. All the changes described here would need to be applied to the current 8th edition of the BIPM SI Brochure, and this draft should therefore be read with a copy of the current Brochure at hand.

The history of this document is as follows. The original draft was prepared by Ian Mills with assistance from Terry Quinn and Barry Taylor, and was presented to the CCU at its 19th meeting in May 2009. That meeting appointed a working group consisting of Richard Davis, Marc Himbert, Ian Mills, Terry Quinn and Jörn Stenger, who met at the University of Reading in August 2009 and revised the whole text in detail. The draft was then presented to the 98th CIPM as part of the CCU's report on recommended changes to the SI in October 2009. Lack of time at the CIPM meeting restricted discussion, but a few comments were made which led to further revisions which were circulated to all members of the CIPM in December 2009.

Small further revisions were made in the summer of 2010 as a result of further comments from members of the CCU, and it was discussed yet again and further revised at the 20th CCU meeting in September 2010. The version below is now presented to the CIPM at its 99th meeting in October 2010, as a specification of the new SI following the changes to the definitions of the units and to their presentation which the CCU is recommending. When these changes have been adopted this draft may become the basis of a new edition of the SI Brochure.

Ian Mills, President of the CCU

27 September 2010

1 Introduction

1.1 through 1.7: these sections all stand unchanged

1.8 Historical note

- all this text stands unchanged, except that we should add an extra final dot point to this section, as follows:
- Since the establishment of the SI in 1960, extraordinary advances have been made in relating SI units to truly invariant quantities such as the fundamental constants of physics and the properties of atoms. Recognising the importance of linking SI units to such invariant quantities, the XXth CGPM, in 20XX, adopted new definitions of the kilogram, ampere, kelvin, and mole in terms of fixed numerical values of the Planck constant h , elementary charge e , Boltzmann constant k , and Avogadro constant N_A , respectively. Additionally, because the XXth CGPM chose words for the four new definitions that made those links explicit, believing that doing so would aid in their understanding, it also changed the words of the remaining three definitions of the base units second, metre, and candela so that the invariant quantities to which they are linked are also explicit in their definitions. These invariants are the hyperfine splitting of the caesium 133 atom $\Delta\nu(^{133}\text{Cs})_{\text{hfs}}$, the speed of light in vacuum c , and the luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} Hz, respectively. As a consequence, the definitions of all seven base units of the SI now have a common format. In what follows we refer to this set of invariant quantities as “fundamental constants”, or “constants of nature”, but it is recognized that while they can all be considered invariant, they do not all have the same significance in physics. The order in which the seven base units are presented was also revised, the new order being second, metre, kilogram, ampere, kelvin, mole, and candela, so that no base-unit definition involves any of the other base units that come later in the list. Thus in the next chapter, Chapter 2, a list of the SI values of the seven fundamental constants that have been chosen to set the scale of the SI is presented. This is followed by the individual definitions that are implied for the seven base units.

2 SI units

The International System of Units, the SI, is a coherent system of units for use throughout science and technology. It is defined by specifying the values of seven *base units*, and then treating all other units as *coherent derived units* whose values are given as products of powers of the base units without including any numerical factors, following the corresponding relations between the quantities involved. The present definitions of the seven base units are made in terms of the values of seven fundamental constants that are believed to be true invariants throughout time and space,

available to anyone, anywhere, at any time, who wishes to realise and make use of the values of the units to make measurements.

2.1 Definitions of the SI units

Formal definitions of the SI units are adopted by the CGPM. These definitions are modified from time to time as science advances. The first two definitions were adopted in 1889, and the most recent in 20XX. The formal definitions of the SI base units are presented in sections 2.3.1 to 2.3.7 below and are shown indented in a bold-face sans-serif type. The accompanying text in a normal font is intended to provide further information to assist in understanding the definitions, and to provide a brief record of the historical development of the definitions.

The choice of which units to take as base units is to some extent arbitrary. This choice has been governed by history and tradition in the development of the SI over the last 120 years. The three key features of the SI are now recognized to be

- (i) the seven fundamental constants, or constants of nature, to which exact numerical values are assigned when the values of these constants are expressed in their respective SI units, in order to set the scale of the entire system of units, listed in section 2.2 below;
- (ii) the formal definitions of the seven base units of the SI, listed in section 2.3, and their symbols listed in section 2.4 below;
- (iii) the 22 coherent derived units of the SI that have special names and symbols and the relations among them that are presented in the tables in section 2.5 below.

As in the past, the units of the SI provide the framework for measuring all the quantities that occur in the equations of the physical sciences. The equations among the quantities are independent of the way in which the units are defined. They are extended and developed as new fields of science develop, so that it will never be practical to present a complete table or list of the quantities and equations of science. For this reason the reader is referred to the many texts currently available on the diverse fields of modern science, and no attempt is made to list them here.

The scaling of the entire system of units by fixing the numerical values of the seven chosen fundamental constants is a new feature of the presentation of the SI, adopted in 20XX by the XXth CGPM (Resolution XX, CR, XXX and *Metrologia*, 20XX, XX, XX), and thus appears for the first time in this edition of the SI Brochure. The fixed values of the seven constants are given in section 2.2. While such a list is sufficient in itself to define an entire system of units, the XXth CGPM chose to maintain the historical structure of the SI with its set of defined base units, and coherent derived units obtained as products of powers of base units without numerical factors, because it is considered to be more convenient and understandable for the general user. The traditional choice of base units is followed, but their definitions are presented in section 2.3 in a common format, and each

definition refers to the value of one of the fixed constants that are given first in section 2.2. The symbols for the base units are given in section 2.4, and derived units are discussed in section 2.5. The base-units and the derived units obtained from the base units as described in Chapter 1 necessarily form a coherent set.

Preserving continuity is an essential feature of any changes to the International System of Units, and this has always been assured in all changes to the definitions of the base units by choosing the numerical values of the constants that appear in the definitions to be consistent with the earlier definitions.

2.2 The seven fixed constants that set the scale of the SI

The international system of units, the SI, is the system of units scaled so that

- the ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu(^{133}\text{Cs})_{\text{hfs}}$ is exactly 9 192 631 770 hertz, Hz,
- the speed of light in vacuum c is exactly 299 792 458 metre per second, m s^{-1} ,
- the Planck constant h is exactly $6.626\ 06\text{X} \times 10^{-34}$ joule second, J s,
- the elementary charge e is exactly $1.602\ 17\text{X} \times 10^{-19}$ coulomb, C,
- the Boltzmann constant k is exactly $1.380\ 65\text{X} \times 10^{-23}$ joule per kelvin, J K^{-1} ,
- the Avogadro constant N_{A} is exactly $6.022\ 14\text{X} \times 10^{23}$ reciprocal mole, mol^{-1} ,
- the luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} hertz is exactly 683 lumen per watt, lm W^{-1} .

[The symbol X throughout this section and section 2.3 below represents one or more additional digits to be added to the numerical values of h , e , k , and N_{A} at the time that these revised definitions and this revised text for Chapter 2 of the SI Brochure is finally adopted.]

Note that the units hertz, joule, coulomb, lumen and watt referred to here are coherent derived units as defined in Table 3 in Section 2.5 below.

Although the choice of these seven constants is to some extent arbitrary, the choice made here for the SI is based on history, on convenience for the practical realization of units, and to reflect the significance of these constants in modern physics.

The values of all the fundamental constants are invariants of nature, but their numerical values depend on the units in which they are expressed. Fixing the numerical values of the set of constants above defines a particular set of units, which is the SI. This also has the effect of fixing the numerical values of all other constants that can be written as products and

ratios of these constants. It is important to note that for those constants whose numerical values have not been fixed, their values still remain invariants of nature, although their numerical values have to be determined by experiment.

2.3 Definitions of the SI base units

The choice of the seven base units presented below is that which has been adopted in previous presentations of the system. These seven units and their corresponding quantities are the second, unit of time; metre, unit of length; kilogram, unit of mass; ampere, unit of electric current; kelvin, unit of thermodynamic temperature; mole, unit of amount of substance; and candela, unit of luminous intensity. The definitions of these seven units are as follows.

2.3.1 second, unit of time

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 left to astronomers. However measurements showed that irregularities in the rotation of the Earth made this an unsatisfactory definition. In order to define the unit of time more precisely, the 11th CGPM (1960, Resolution 9, CR, 86) adopted a definition given by the International Astronomical Union based on the tropical year 1900. Experimental work, however, had already shown that an atomic standard of time, based on a transition between two energy levels of an atom or a molecule, could be realized and reproduced much more accurately. Considering that a very precise definition of the unit of time is indispensable for science and technology, the 13th CGPM (1967-1968, Resolution 1, CR, 103 and *Metrologia*, 1968, 4, 43) chose a new definition of the second referenced to the frequency of the hyperfine transition in the caesium 133 atom. The XXth CGPM in 20XX (Resolution XX, CR, XXX and *Metrologia*, 20XX, XX, XX) chose to re-draft the words without changing the sense of this definition, and thus to define the second as follows:

The second, s, is the unit of time; its magnitude is set by fixing the numerical value of the ground state hyperfine splitting frequency of the caesium 133 atom, at rest and at a temperature of 0 K, to be equal to exactly 9 192 631 770 when it is expressed in the unit s^{-1} , which is equal to Hz.

Thus we have the exact relation $\Delta\nu(^{133}\text{Cs})_{\text{hfs}} = 9\,192\,631\,770\text{ Hz}$. The effect of this definition is that the second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

The reference to an atom at rest at 0 K is intended to make it clear that the definition of the SI second is based on a caesium atom unperturbed by black body radiation, in an environment whose thermodynamic temperature is 0 K. The frequencies of all primary frequency standards should therefore

The symbol $\Delta\nu(^{133}\text{Cs})_{\text{hfs}}$ is used to denote the value of the frequency of the hyperfine transition in the ground state of the caesium 133 atom at rest at a temperature of 0 K.

be corrected for the shift due to ambient radiation, as stated at the meeting of the Consultative Committee for Time and Frequency in 1999.

The second so defined is a proper time in the sense of General Relativity. A non-local time scale is a coordinate time scale. However, generally, the unit of such a scale is also called "second". Whenever this is the case, the word "second" must be followed by the name of the time scale: e.g. second of TCB (barycentric coordinate time used within the solar system). The unit of Universal Time, compiled by the BIPM, the second of UT, is the second as realized on the geoid on which, and only on which, it coincides with the second defined above.

The CIPM has adopted various secondary representations of the second, based on trapped ions or cold atoms, which have reproducibilities rather better than that of the caesium clock. These are revised from time to time by the CIPM.

2.3.2 metre, unit of length

The 1889 definition of the metre, based on the international prototype of platinum-iridium, was replaced by the 11th CGPM (1960) using a definition based on the wavelength of the radiation corresponding to a particular transition in krypton 86. This change was adopted in order to improve the accuracy with which the definition of the metre could be realized, the realization being achieved using an interferometer with a travelling microscope to measure the optical path difference as the fringes were counted. In turn, this was replaced in 1983 by the 17th CGPM (Resolution 1, CR, 97, and *Metrologia*, 1984, **20**, 25) with a definition referenced to the distance that light travels in vacuum in a specified interval of time. The XXth CGPM in 20XX (Resolution XX, CR, XXX and *Metrologia*, 20XX, **XX**, XX) chose to re-draft the words without changing the sense of this definition, and thus to define the metre as follows:

The metre, m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299 792 458 when it is expressed in the unit m s^{-1} .

Thus we have the exact relation $c = 299\,792\,458 \text{ m/s}$. The effect of this definition is that the metre is the length of the path travelled by light in vacuum during a time interval of $1/299\,792\,458$ of a second.

The original international prototype of the metre, which was sanctioned by the first CGPM in 1889 (CR, 34-38), is still kept at the BIPM under conditions specified in 1889.

The symbol c (or sometimes c_0) is the conventional symbol for the value of the speed of light in vacuum.

2.3.3 kilogram, unit of mass

The 1889 definition of the kilogram was in terms of the mass of the international prototype of the kilogram, an artefact made of platinum-iridium. This is still kept at the BIPM under the conditions specified by the 1st CGPM in 1889 (CR, 34-38) when it sanctioned the prototype and

declared that “this prototype shall henceforth be considered to be the unit of mass”. Forty similar prototypes were made at about the same time, and these were all machined and polished to have closely the same mass as the international prototype. At the CGPM in 1889, after calibration against the international prototype, most of these were individually assigned to Member States of the BIPM, and some also to the BIPM itself. The 3rd CGPM (1901, CR, 70), in a declaration intended to end the ambiguity in popular usage concerning the use of the word “weight”, confirmed that “the kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram”. The complete version of these declarations appears on p.XXX.

By the time of the second verification of national prototypes in 1949, however, it was found that on average the masses of these prototypes were diverging from that of the international prototype. This was confirmed by the third verification from 1989 to 1991, the median difference being about 25 micrograms for the set of original prototypes sanctioned by the first CGPM in 1889. In order to assure the long-term stability of the unit of mass, to take full advantage of quantum electrical standards, and to be of more utility to modern science, it was therefore decided to adopt a new definition for the kilogram referenced to the value of a fundamental constant, for which purpose the Planck constant h was chosen. The XXth CGPM in 20XX (Resolution XX, CR, XXX and *Metrologia*, 20XX, XX, XX) chose to define the kilogram as follows:

The kilogram, kg, is the unit of mass; its magnitude is set by fixing the numerical value of the Planck constant to be equal to exactly $6.626\,06\text{X} \times 10^{-34}$ when it is expressed in the unit $\text{s}^{-1} \text{m}^2 \text{kg}$, which is equal to J s.

Thus we have the exact relation $h = 6.626\,06\text{X} \times 10^{-34} \text{ J s}$
 $= 6.626\,06\text{X} \times 10^{-34} \text{ s}^{-1} \text{m}^2 \text{kg}$. The value of the Planck constant is a constant of nature, which may be expressed as the product of a number and the unit joule second, where $\text{J s} = \text{s}^{-1} \text{m}^2 \text{kg}$. The effect of this definition, together with those for the second and the metre which are based on fixed numerical values for the caesium frequency $\Delta\nu(^{133}\text{Cs})_{\text{hfs}}$ and the speed of light c , is to open the way to a definition of the unit of mass through two of the most fundamental equations of physics, namely $E = mc^2$ and $E = h\nu$, which relate energy E to mass and to frequency, and which together lead to $m = h\nu/c^2$.

The number chosen for the numerical value of the Planck constant is such that at the time of the redefinition the mass of the international prototype was one kilogram, $m(\mathcal{K}) = 1 \text{ kg}$, with a relative standard uncertainty equal to that of the best determination of the value of the Planck constant in terms of the previous definition of the kilogram at that time (a few parts in 10^8). Subsequently, the mass of the international prototype has become a quantity to be determined experimentally. One possible method for such a determination, which takes advantage of quantum electrical standards, is through the direct comparison of electrical and mechanical power.

The symbol h is used to denote the value of the Planck constant.

The symbol $m(\mathcal{K})$ is used to denote the mass of the international prototype of the kilogram, \mathcal{K} .

Future drifts in $m(\mathcal{K})$, if detected by experiment, will thus lead to it no longer having a value of exactly 1 kg, but a value close to 1 kg, with an uncertainty given by the uncertainty of the experiment linking its mass to the fixed value of the Planck constant in the definition. The magnitude of such possible changes is not well quantified, as has been the case since 1889, and may be much larger than the observed divergences between prototypes.

2.3.4 ampere, unit of electric current

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

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”, because some laboratories had not yet completed experiments needed to determine the ratios between the international and absolute units the Conference gave authority to the CIPM to decide at an appropriate time both these ratios and the date at which the new units would come into force. This the CIPM did in 1946 (1946, Resolution 2, PV, 20, 129-137) and decided that the new units would come into force on 1 January 1948. In October 1948 the 9th CGPM approved the decisions taken by the CIPM. The definition of the ampere chosen by the CIPM was referenced to the force between wires carrying an electric current, and it had the effect of fixing the value of the magnetic constant μ_0 (the permeability of vacuum). The value of the electric constant ϵ_0 (the permittivity of vacuum) became fixed as a consequence of the new definition of the metre adopted in 1983.

However the 1948 definition of the ampere proved difficult to realise, and practical quantum standards based on the Josephson and quantum-Hall effects, which link the volt and the ohm to particular combinations of the Planck constant h and elementary charge e , have become almost universally used as a practical realisation of the ampere through Ohm’s law. As a consequence, it became natural to not only fix the numerical value of h to redefine the kilogram, but to fix the numerical value of e to redefine the ampere in order to improve the accuracy of the quantum electrical standards. Hence the XXth CGPM, in 20XX, chose a new definition to define the ampere which is referenced to the value of the elementary charge, the charge on a proton. The new definition of the ampere, XXth CGPM (20XX, Resolution XX, CR, XXX and *Metrologia*, 20XX, XX, XX) is as follows:

The symbol e is used to denote the value of the elementary charge, which is the charge of a proton.

The ampere, A, is the unit of electric current; its magnitude is set by fixing the numerical value of the elementary charge to be equal to exactly $1.602\ 17X \times 10^{-19}$ when it is expressed in the unit s A, which is equal to C.

Thus we have the exact relation $e = 1.602\,17\text{X} \times 10^{-19}$ C. The effect of this definition is that the ampere is the electric current corresponding to the flow of $1/(1.602\,17\text{X} \times 10^{-19})$ elementary charges per second.

The previous definition of the ampere based on the force between current carrying conductors had the effect of fixing the value of μ_0 to be exactly $4\pi \times 10^{-7}$ H m⁻¹, or equivalently $4\pi \times 10^{-7}$ N A⁻², where H and N denote the coherent derived units henry and newton, respectively. The new definition of the ampere fixes the value of e instead of μ_0 , and as a result μ_0 is no longer exactly known but must be determined experimentally. At the time of adopting the new definition of the ampere, μ_0 was equal to $4\pi \times 10^{-7}$ H/m, with a relative standard uncertainty less than 1×10^{-9} . Although the value of μ_0 may change by a small amount as a result of new experiments, it is unlikely to ever change by more than one part in 10^9 . It also follows that since the electric constant ϵ_0 , also known as the permittivity of vacuum, is equal to $1/\mu_0 c^2$, the value of ϵ_0 must also be determined experimentally, and will be subject to the same relative standard uncertainty as μ_0 , although the product $\epsilon_0 \mu_0 = 1/c^2$ will be known exactly as a consequence of the definition of the metre.

2.3.5 kelvin, unit of thermodynamic temperature

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, T_{TPW} , as a fundamental fixed point and assigned to it the temperature 273.16 K, so defining the unit kelvin. The 13th CGPM (1967-1968, Resolution 3; CR, 104 and *Metrologia*, 1968, 4, 43) adopted the name kelvin, symbol K, instead of “degree kelvin”, symbol °K, for the unit defined in this way. However the difficulties in realising this definition, requiring a sample of pure water of well defined isotopic composition, and the development of new primary methods of thermometry that are difficult to link directly to the triple point of water, led the XXth CGPM (20XX, Resolution XX, CR, XXX and *Metrologia*, 20XX, XX, XX) to adopt a new definition for the kelvin referenced to the value of the Boltzmann constant k . The definition chosen is as follows:

The kelvin, K, is the unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the Boltzmann constant to be equal to exactly $1.380\,6\text{X} \times 10^{-23}$ when it is expressed in the unit s⁻² m² kg K⁻¹, which is equal to J K⁻¹.

Thus we have the exact relation $k = 1.380\,6\text{X} \times 10^{-23}$ J/K. The effect of this definition is that the kelvin is equal to the change of thermodynamic temperature that results in a change of energy per degree of freedom kT by $1.380\,6\text{X} \times 10^{-23}$ J.

The temperature of the triple point of water thus becomes a quantity to be determined experimentally. The value chosen for k in the definition above was consistent with a temperature for the triple point of water of 273.16 K with a relative standard uncertainty nearly equal to that of the measured

The symbol k , or k_{B} , is used to denote the value of the Boltzmann constant.

value of the Boltzmann constant at the time of the redefinition, of the order 1×10^{-6} . Subsequent measurements in terms of the new definition of the kelvin may result in a slightly different value of T_{TPW} , but this is not expected to differ from 273.16 K by more than 0.25 mK.

Because of the manner in which 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 difference is called the Celsius temperature, symbol t , which is defined by the quantity equation

$$t = T - T_0$$

The unit of Celsius temperature is the degree Celsius, symbol $^{\circ}\text{C}$, 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 the temperature difference being the same. However, the numerical value of a Celsius temperature expressed in degrees Celsius is related to the numerical value of the thermodynamic temperature expressed in kelvins by the relation

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

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

2.3.6 mole, unit of amount of substance

Following the discovery of the fundamental laws of chemistry, units called, for example, “gram-atom” and “gram molecule”, were used to specify amounts of chemical elements or compounds. These units had a direct connection with “atomic weights” and “molecular weights”, which are in fact relative atomic and molecular masses. “Atomic weights” were originally referred to the atomic weight of oxygen, by general agreement taken as 16. But whereas physicists separated the isotopes in a mass spectrometer and attributed the value 16 to one of the isotopes of oxygen, chemists attributed the same value to the (slightly variable) mixture of isotopes 16, 17 and 18, which 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 1959-1960. Physicists and chemists have ever since agreed to assign the value 12, exactly, to the so-called atomic weight, correctly called the relative atomic mass A_r , of the isotope of carbon with mass number 12 (carbon 12, ^{12}C). The unified scale thus obtained gives the relative atomic and molecular masses, also known as the atomic and molecular weights, respectively.

The quantity used by chemists to specify the amount of chemical elements or compounds is now called “amount of substance”. Amount of substance, symbol n , is defined to be proportional to the number of specified

The recommended symbol for relative atomic mass (atomic weight) of an entity X is $A_r(X)$, where the entity X should be specified, and the recommended symbol for the molar mass of entity X is $M(X)$.

The recommended symbol for the quantity amount of substance is n .

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

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

However this definition of the mole was dependent on the artefact definition of the kilogram, with the consequences described in 2.3.3.

The numerical value of the Avogadro constant defined in this way was equal to the number of atoms in 12 grams of carbon 12. This value is now known with such precision that the CGPM in 20XX decided to adopt a simpler definition of the mole by specifying exactly the number of entities in one mole of any substance, thus specifying exactly the value of the Avogadro constant. This has the further advantage that the new definition of the mole, and the value of the Avogadro constant, are no longer dependent on the definition of the kilogram. Also the distinction between the fundamentally different quantities amount of substance and mass is thereby emphasised. For these reasons the XXth CGPM (20XX, Resolution XX, CR, XXX and *Metrologia*, 20XX, XX, XX) adopted the following definition of the mole:

The mole, mol, is the unit of amount of substance of a specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles; its magnitude is set by fixing the numerical value of the Avogadro constant to be equal to exactly $6.022\,14 \times 10^{23}$ when it is expressed in the unit mol^{-1} .

Thus we have the exact relation $N_A = 6.022\,14 \times 10^{23} \text{ mol}^{-1}$. The effect of this definition is that the mole is the amount of substance of a system that contains $6.022\,14 \times 10^{23}$ specified elementary entities.

The symbol N_A is used to denote the value of the Avogadro constant.

This definition has the effect that the molar mass of carbon 12 is no longer 0.012 kg/mol by definition, but has to be determined experimentally. However the value chosen for N_A in the definition is such that the molar mass of carbon 12 was equal to 0.012 kg/mol at the time of the adoption of the new definition, $M(^{12}\text{C}) = 0.012 \text{ kg/mol}$, with a relative standard uncertainty of somewhat less than 1×10^{-9} . Although it may change by a small amount as a result of later experiments it is unlikely to ever change by more than a few parts in 10^9 . The molar mass of any atom or molecule X may still be obtained from its relative molar mass from the equation

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

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

$$M(X) = N_A m(X) = N_A A_r(X) m_u$$

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

$$M_u = N_A m_u$$

In the name “amount of substance”, the words “of substance” could for simplicity be replaced by words to specify the substance concerned in any particular application, so that one may for example talk of “amount of hydrogen chloride, HCl”, or “amount of benzene, C₆H₆”. It is important to always give a precise specification of the entity involved (as emphasized in the definition of the mole); this should preferably be done by giving the molecular chemical formula of the material involved. Although the word “amount” has a more general dictionary definition, this abbreviation of the full name “amount of substance” to “amount” may often be used for brevity. This also applies to derived quantities such as “amount-of-substance concentration”, which may simply be called “amount concentration”. However, in the field of clinical chemistry the name “amount-of-substance concentration” is generally abbreviated to “substance concentration”.

2.3.7 candela, unit of luminous intensity

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) and by the CIPM before 1937, and the decision was promulgated by the CIPM in 1946. It was then ratified in 1948 by the 9th CGPM which adopted a new international name for this unit, the *candela*, symbol cd; in 1967 the 13th CGPM (Resolution 5, CR, 104 and *Metrologia*, 1968, 4, 43-44) gave an amended version of this definition.

In 1979, because of the difficulties in realizing a Planck radiator at high temperatures, and the new possibilities offered by radiometry, i.e. the measurement of optical radiation power, the 16th CGPM (1979, Resolution 3, CR, 100 and *Metrologia*, 1980, 16, 56) adopted a new definition of the candela. The XXth CGPM (20XX, Resolution XX, CR, XXX and *Metrologia*, 20XX, XX, XX) chose to re-draft the words without changing the sense of this definition, and thus to define the candela as follows:

The candela, cd, is the unit of luminous intensity in a given direction; its magnitude is set by fixing the numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz to be equal to exactly 683 when it is expressed in the unit $\text{s}^3 \text{m}^{-2} \text{kg}^{-1} \text{cd sr}$, or cd sr W^{-1} , which is equal to lm W^{-1} .

Thus we have the exact relation $K_{\text{cd}} = 683 \text{ lm/W}$ for monochromatic radiation of frequency $\nu = 540 \times 10^{12} \text{ Hz}$. The effect of this definition is that the candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12} \text{ Hz}$ and that has a radiant intensity in that direction of $1/683 \text{ W/sr}$.

The symbol K_{cd} is used to denote the value of the luminous efficacy of monochromatic radiation of frequency $540 \times 10^{12} \text{ Hz}$.

2.3.8 relations between the definitions of the base units

Paragraphs 2.3.1 to 2.3.7 present individual definitions of the seven base units of the SI. Of these seven definitions only the first, the definition of the second, and the sixth, the definition of the mole, are independent of the other definitions. In 2.3.2 fixing the numerical value of the speed of light in vacuum actually defines the unit of speed, m/s, so that the definition of the second is required to complete the definition of the metre. In 2.3.3 fixing the numerical value of the Planck constant actually defines the unit of action, $\text{s}^{-1} \text{ m}^2 \text{ kg}$, so that the definitions of the second and the metre are required to complete the definition of the kilogram. In 2.3.4 fixing the numerical value of the elementary charge actually defines the unit of charge, s A, or coulomb, C, so that the definition of the second is required to complete the definition of the ampere. In 2.3.5 fixing the numerical value of the Boltzmann constant actually fixes the value of the unit of energy per temperature interval, J K^{-1} , so that the definitions of the second, kilogram, and metre are required to complete the definition of the kelvin. And finally, in 2.3.7 fixing the numerical value of the luminous efficacy of monochromatic radiation of frequency $540 \times 10^{12} \text{ Hz}$ actually defines the unit of luminous efficacy, cd sr W^{-1} , or $\text{s}^3 \text{ m}^{-3} \text{ kg}^{-1}$, so that the definitions of the second, kilogram, and metre are required to complete the definition of the candela.

It follows that the definitions in 2.3.1 to 2.3.7 must be taken together as a coherent group of statements for the definitions of the base units of the SI, and should not be regarded as independent definitions of the individual base units. The same was true in all previous editions of the SI Brochure,

[Later sections of Chapter 2 of the Brochure, and most of the later parts of the Brochure, would remain essentially unchanged by these changes to the definitions of the units except for a renumbering of some sections.]

2.4 Symbols for the seven 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 for each of the seven base units [10th CGPM (1954, Resolution 6, CR, 80); 11th CGPM (1960, Resolution 12, CR, 87); 13th CGPM (1967/68, 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

(Table 1 is exactly as Table 1 appears in the current Brochure)

2.5 SI derived units *(This section and all later sections are exactly as in the current Brochure except for a renumbering of the sections 2.5 and 2.5.1 through 2.5.3)*

Derived units are products of powers of base units. Coherent derived units are products of powers of base units that include no numerical factor other than 1. The base and coherent derived units of the SI form a coherent set, designated the set of *coherent SI units* (see 1.4, p. XXX).

2.5.1 Derived units expressed in terms of base units

(copied from section 2.2.1 of the current Brochure, including Table 2)

2.5.2 Units with special names and symbols; units that incorporate special names and symbols

(copied from 2.2.2 of the current Brochure, including Table 3 and Table 4)

2.5.3 Units for dimensionless quantities, also called quantities of dimension one *(copied from 2.2.3 of current Brochure)*

3 Decimal multiples and sub-multiples of SI units

(essentially chapter 3 of the current Brochure)