



The international system of units (SI)

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Abstract

The SI (Système international d'unités), adopted by the Conférence générale des poids et mesures in 1960, was the outcome of almost one century of progress in the establishment of a consistent system of measurement units. We present its main features with its base and derived units, which constitutes a coherent set of units related by rule of multiplication and division with no numeric factor other than one. The historical evolution and the definitions of the seven base units are presented together with a short description of how they are realised in practice. The specific case of the units in ionising radiation is discussed, and some hints of what could be the future of the SI are proposed. *To cite this article: J. Kovalevsky, T.J. Quinn, C. R. Physique 5 (2004).* © 2004 Académie des sciences. Published by Elsevier SAS. All rights reserved.

Résumé

Le Système international d'unités (SI). Le Système international d'unités (SI) adopté par la Conférence générale des poids et mesures en 1960, est le résultat de presque un siècle de progrès dans l'établissement d'un système logique d'unités de mesure. Nous en présentons les principales caractéristiques avec ses unités de base et dérivées constituant un ensemble cohérent d'unités reliées par des multiplications ou des divisions sans autre facteur numérique que 1. L'évolution historique et les définitions des sept unités de base sont présentées avec une courte description de la manière dont elles sont réalisées en pratique. Le cas particulier des unités pour les rayonnements ionisants est discuté et on exprime quelques idées sur ce que pourrait être l'avenir du SI. *Pour citer cet article : J. Kovalevsky, T.J. Quinn, C. R. Physique 5 (2004).* © 2004 Académie des sciences. Published by Elsevier SAS. All rights reserved.

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1. Historical introduction

The need for a commonly adopted system of weights and measures arose as soon as commercial exchanges started and required impartiality. This meant that weighing goods or measuring lengths or capacities had to be referred to a reference accepted by the parties concerned. Similarly, the redistribution of land after floods of the Nile must have required a stable rod to be referred to.

In almost all countries, the highest authority in the land defined the references for weights and measures. Nevertheless, despite such royal edicts, even in centralised countries like England or France, local feet, pounds, livres, toises, etc. . . of various kinds and dimensions continued to be used. Just to give an example, Machabey [1] made a survey of standards either existing in French museums or archives or described in earlier books. Only for length, he found, mainly in the seventeenth and eighteenth centuries, but not only, about 80 different standards in France, 30 in Flanders, 20 in Italy, and this is by far not a complete counting. The situation for weight and capacity was at the least as complex.

So, it is not surprising that the requirement most frequently mentioned in the «*Cahiers de doléances*» written in all parts of France in preparation of the «*États Généraux*», in 1788–1789, was the unification of the system of weights and measures. This led the «*Assemblée nationale*» (after considerable discussion, even including previous contacts between Talleyrand and a British member of parliament) to adopt the principle of the decimal metric system based on the metre equal to the ten millionth part of the quadrant of the Earth's meridian and the kilogram as the weight (mass) of one cubic decimetre of water at the temperature of 4 °C, at which its density is maximum. Standards realising these new units were made in France (metre and kilogram of the Paris Archives). The idea under this choice was that the system should be based on universal natural constants. Note that this property is still sought in the most modern work in metrology.

This metric system soon spread outside France. It became the only legal system in the Netherlands in 1820, then in France in 1834. In the years that followed, several European and American countries adopted it. The developing industrial revolution and rapidly increasing international commerce, led the representatives of 17 nations to meet in Paris in May 1875 and sign the *Metre Convention*, which created the *Bureau international des poids et mesures* (BIPM) and established the formal basis of future developments of an international systems of units. At that time, the system of units included only the metre and the kilogram, whose international prototypes were deposited in the BIPM and copies were distributed to adhering countries. Actually, the system of units was built from three base units: the metre, the kilogram, and the second (MKS system). The determination of the last of these remained in the hands of astronomical observatories, because it was based on the rotation of the Earth. All mechanical units could be derived from these three units.

The situation quickly became much more involved, when there appeared a need to introduce electro-magnetic forces and express them in terms of the three mechanical units. However, the impossibility in such a system to represent simultaneously the magnetic and the electrostatic attractions based on the centimetre, the gram and the second (CGS) gave rise to two systems. These were the electrostatic CGS (starting from the inverse square law between electric charges) and the electromagnetic CGS (starting from the inverse square law between magnetic poles). In the latter, the unit of electric resistance would be the centimetre per second, which was found to be much too small since it corresponds to an electrical unit 10^9 times smaller than the practical unit the ohm. To avoid this drawback, a “*practical electrical set of units*” was introduced by the International Electrotechnical Commission, which included the volt, the ampere and the ohm, but it was no longer consistent with the mechanical derived units of force or energy.

The situation was resolved by a suggestion of the Italian physicist Giorgi, who proposed that an additional electric base unit be added to the MKS system. In the first instance, the ohm was chosen, replaced later by the ampere. Although the electromagnetic CGS is still sometimes convenient in theoretical atomic physics, the principle set up by Giorgi emerged as the most suitable for practical metrology. It was for this reason and following along these lines suggested by Giorgi that the International System of Units (Système international d'unités, SI) was conceived and adopted in 1960 by the *Conférence générale des poids et mesures* (CGPM). This is the governing body of the Metre Convention, in which the governments of all the signatory states are represented. For the realisation of units and scales, the decisions are generally taken by the *Comité international des poids et mesures* (CIPM), elected by the CGPM and acting as the scientific committee of the BIPM.

2. Structure of the SI

The SI is designed in such a way that, in principle, any measurement of a physical quantity can be expressed as a number in some specified unit. To each physical quantity there corresponds a single SI unit, even if this unit may, in some cases, be expressed in different forms. However, it is to be remarked that some properties of matter, particularly in the field of biology, but not only, cannot yet be expressed in SI units. This is always the case because the physical, chemical or biological system in question is not sufficiently well understood so that it is possible to write down an explicit relation between the measured

Table 1
Prefixes for multiples and submultiples

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	deca	da	10^{-24}	yocto	y

quantities and observed effect. For instance, hardness cannot be expressed in units of the SI because hardness is not a well-defined physical quantity. The biological activity of many complex molecules cannot be expressed in terms of SI units because their biological activity depends on fine details of the structure of the molecule that are as yet unknown. The amount of fat in foods cannot be expressed in SI units because there does not exist an adequate definition of fat. Despite these areas where it cannot yet be easily used, the SI provides a convenient units system for the overwhelming majority of practical and scientific measurements today.

The foundation of the SI comprises seven well-defined units, which – by convention – are regarded as being dimensionally independent; these are known as the *base units of the SI*. They are the metre, the kilogram, the second, the ampere, the kelvin, the mole, and the candela. In addition to this class of base units, there is also a class of derived units formed as products of powers of base units, according to the algebraic expressions (generally known as the equations of physics) linking the quantities concerned. There is no limit to the number of possible derived units. For example, the unit of speed is the metre per second (m s^{-1}) and the unit of power, the watt ($\text{W} = \text{m}^2 \text{kg s}^{-3}$). The latter special name can be in turn used to define some other derived unit. For instance, the unit for thermal conductivity is $\text{W}/(\text{m K}) = \text{m kg s}^{-3} \text{K}^{-1}$. The list of derived units with special names and some others are given in [2]. Among the derived units, some have the dimension 1: the radian, the steradian, and the bel. With these two classes of units, the SI constitutes a coherent set of units in the sense that they are mutually related by rules of multiplication and division with no numerical factor other than 1. This is a most important characteristic of the SI and can be a great help in avoiding numerical errors in complex calculations.

It must be emphasised that all the units are defined in a local environment in the sense of the theory of Relativity. This means that they are all so-called proper units: the second is the unit of proper time, the metre is the unit of proper length, etc. The extension to a wider range is studied by Guinot [3] and an example will be given in the next section.

The size of the base or derived units is not necessarily adequate for a given measurement, so that multiples and sub-multiples are needed. Here, another major attribute of the SI enters in the game: the SI is a decimal system. The multiples and the sub-multiples are related to the unit by a factor 10^N , where N is a positive or negative integer. They are formed by adding a prefix to the name of the unit. Table 1 gives the list of the prefixes and their symbols, which are attached to the symbol of the unit.

It is however to be noted that, for large factors, the usage tends not to use the SI prefix, but a factor 10^N . For very small quantities however, the prefixes are commonly used, notably milli-, micro- and, increasingly, nano-, pico-, and femto-.

There are two exceptions to this general rule:

- the multiples and the sub-multiples of the kilogram are written as multiples and sub-multiples of the gram. For example, $10^{-6} \text{ kg} = 1 \text{ mg}$; $10^6 \text{ kg} = 1 \text{ Gg}$ (or 1000 tons);
- decimal sub-multiples of the second are currently used ($1 \text{ fs} = 10^{-15} \text{ s}$), but not multiples for which non-decimal multiples are currently used: day (86 400 s), hour (3600 s) and minute (60 s) or exponential factors (the age of the Universe is of the order of $4 \times 10^{15} \text{ s}$ rather than 4 Ps). The sexagesimal notation is the remnant of the Sumerian and Babylonian reckoning system with 60 as the base. Their knowledge in astronomy and time was so deep, that it was adopted by other nations and perpetuated in the western culture.

More generally, some non-SI units are acceptable. They can be just other names for an SI unit such as the litre, the hectare, the barn (10^{-28} m^2), or the bar (100 kPa). Others are connected to a SI unit in a non-decimal manner: degree, minute and second of angle, the nautical mile (= 1852 m). Occasionally, some are special units used in particular fields of physics: the electron-volt (eV), the unified atomic mass unit (u), and the astronomical unit of length (au). All the particulars of the SI are described in the SI ‘*brochure*’ edited by the BIPM [2]. The next version should be published in 2005.

Let us finally note that common usage in the United States, although it is a member of the Metre Convention, is still not to use the decimal SI for mechanical and thermal units but instead to continue to use the former Imperial System. There exist fixed relationships between the size of the Imperial units of length and mass and those of the SI: 1 foot = 0.3048 m exactly and 1 pound = 0.453 kg exactly. For thermal quantities there is an exact relation between the degree Celsius and the degree Fahrenheit.

3. Time (second)

Time being a continuous, indefinite and irreversible succession of instants, it is not possible to reproduce it, as one can do for most of the other physical phenomena. Consequently, one is led to define an entity that is reproducible. This is the interval of time, or duration. Two intervals of time will be considered as equal if a well-defined physical process (for instance a periodic event) can be reproduced exactly with the same internal and environmental conditions. One of them can be chosen as a unit of time, necessarily proper time. To deal with the succession of instants, one uses time scales, which are built by indefinitely adding the unit of time. Clocks indicate the interval of time elapsed since some initial event.

From time immemorial, time scales were based on the succession of days. Calendars are conventional methods to realise the time scale. Until 1960, the unit of time, the second, was defined as the fraction $1/86400$ of the mean solar day. For this, the concept of a mean Sun was introduced as a point on the celestial equator with a uniform annual motion along the equator at a rate equal to the mean rate of the annual motion of the Sun on the ecliptic. The diurnal motion of this point was called the mean solar time. To determine it, one observed the apparent motion of stars, which gave the so-called sidereal time, that is the right ascension of a star at its transit through the Greenwich meridian. The sidereal time has a well-determined theoretical relation with the mean solar time.

This definition assumed that the rotation of the Earth was uniform. The irregularities of the Earth rotation, discovered in 1936 [4], were present in the determination of the time. To avoid this difficulty, one had to define a time scale that is independent of the Earth rotation. This was achieved in considering the motion of the Earth about the Sun, which was a marker of the dynamical time in the solar system. The particular scale that was chosen was called *ephemeris time* (ET). In 1960, the CGPM gave a new definition of the second:

“The second is the fraction $1/31\,556\,925.9747$ of the tropical year for 1900 January 0 at twelve hours of ephemeris time”.

The theory of motion of the Earth in the solar system gives the formulae for the position of the Sun as seen from the centre of the Earth. In particular, it gives the expression of this position with respect to the mean equinox, that is the equinox freed from all the periodic motions called nutation. However, even the tropical year, the time elapsed between two passages of the Sun through the mean equinox, is not constant. This is why the CGPM fixed its value by a date. For more details on astronomical time scales see, for instance, [5].

It would have been more satisfactory to the mind to choose a definite interval of time to define the unit, but the solution adopted was actually simpler from the algorithmic point of view. The difficulty was elsewhere. The great disadvantage of the ET is that the natural clock to determine it, the Sun, has a very slow motion and the precision of its reading is very low, a few hundredths of a second. Even the use of the motion of the Moon as a secondary standard did not improve significantly the situation. For accurate metrology, this was not satisfactory.

The solution came from the work of Essen and Parry at the National Physical Laboratory (NPL in the UK) who in 1955 built a caesium atomic standard that would run continuously [6]. Several others were subsequently built in different laboratories and compared. So, in 1977, the time was ripe for the CGPM to adopt a new definition of the second:

“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”.

Later, additional explanations stated that the caesium atom should be at rest and at a temperature of zero kelvin. Necessary corrections to the observations are done to obtain the basic frequency.

The second is realised by several types of caesium frequency standards. Fig. 1 sketches the simplest and oldest type. A gaseous caesium beam is produced in an oven and sent through a set of magnets whose magnetic field allows only atoms with the energy level F_4 (or, better, $F = 4$) to enter a magnetically shielded resonant cavity, called a Ramsey cavity. A frequency synthesiser produces a frequency f , close to the frequency $f_0 = 9\,192\,631\,770$ Hz of the definition, and radiowaves of the same frequency are emitted in the cavity. The photons interact with the caesium atoms and a stimulated emission occurs. Atoms fall from the F_4 to the F_3 state with a probability that increases when $|f - f_0|$ decreases. Then, the beam crosses again a strong magnetic field and only atoms in the F_3 state are directed towards a detector. Adjusting the frequency f in such a way that the efficiency of the transition is maximised, one gets the best realisation of the frequency f_0 . The best accuracy obtained with this type of thermal atom beam frequency standards is of the order of parts in 10^{14} . More accurate results are obtained with optically pumped standards and cold atom standards [7].

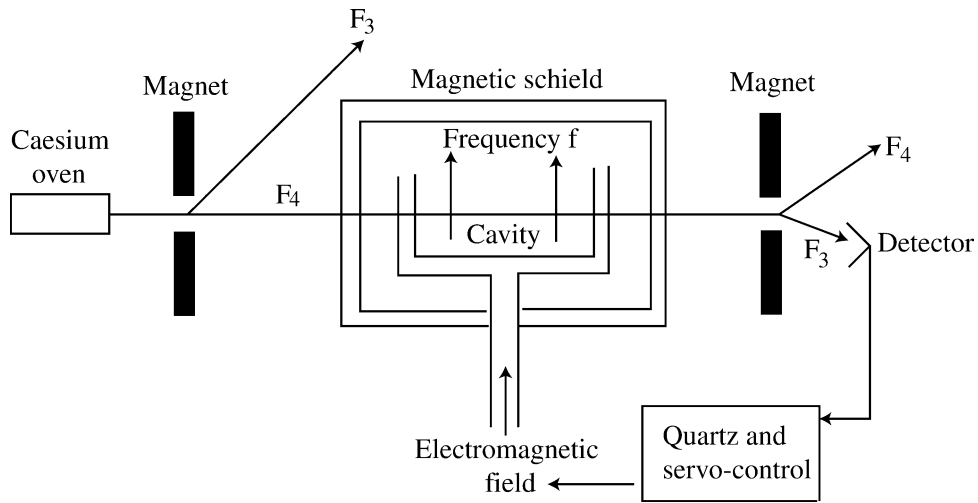


Fig. 1. Principle of a thermal atom beam frequency standard.

A frequency standard is not a clock. A frequency of 5 MHz is synthesised from f and is used to control the frequency of a quartz oscillator, which drives a clock. Additional frequency divisions can produce a 1 Hz frequency, that is the second. This clock is the realisation of the laboratory atomic time scale.

Now, there is a need to define a unique time scale based on the newly defined second. This scale should be valid and accessible all over the Earth, and therefore it is no longer defined to be defined in the local special relativity frame, but in a larger frame consistent with general relativity. The present definition results from successive inputs from the CIPM and the International Astronomical Union (IAU). It can read as follows:

International Atomic Time (TAI) is a coordinate time scale in the geocentric reference frame whose ideal form, neglecting a constant offset of 32.184 s is Terrestrial Time (TT), with the SI second as a scale unit; as realised on the rotating geoid. This calls for some explanation and extensions:

- the geoid is defined as the surface on which the geopotential is $U_G = 62\,636\,856 \text{ m}^2 \text{ s}^{-2}$;
- TAI continues the working atomic time scale produced before the adoption of TAI in 1971, while TT is set to continue without discontinuity ET. Both scales have the same rate, but there is a constant offset;
- TAI can be extended to any fixed or mobile point in the vicinity of the geoid using General Relativity corrections. These corrections include the effects of differences of potential, of the gravity, differences in speed and the rotation of the Earth;
- the basic coordinate time scale is geocentric. It is called Geocentric Coordinate Time (TCG). Due to the difference in potential, TCG differs from TAI by a constant rate equal to $L_G = U_G/c^2 = 6.969\,290\,134 \times 10^{-10}$, where c is the speed of light [4];
- similarly, one defines a Barycentric Coordinate Time (TCB) in a reference system centred at the barycenter (centre of mass) of the solar system, with a constant difference in rate from TCG that is equal to $L_C = 1.480\,826\,857\,41 \times 10^{-8}$.

The construction of TAI by the BIPM is a weighted average based on some 200 clocks maintained in laboratories all around the world. This involves accurate time comparisons between laboratory time scales. The most generally used technique makes use of the GPS system in which each satellite is equipped with rubidium clocks. The signals from a satellite are received in distant laboratories and compared individually to the satellite clock. In the best cases, the accuracy of the comparison is of the order of one or two nanoseconds. Another method is based on the transmission of radio signals from one laboratory to another and back, via a satellite. A sub-nanosecond accuracy is achieved and, although this method needs much more sophisticated equipment than a GPS receiver, it is becoming the principal method for the main links.

The BIPM collects all the results of the comparisons and establishes a weighted mean as a function of the history of the performances of each clock. The scale thus obtained is then adjusted from the data obtained by the clocks driven by atomic frequency standards. The present accuracy of TAI is about 2 parts in 10^{15} and the yearly stability is also about the same.

Let us finally note that legal time scales are based on UTC (Coordinated Universal Time), which is TAI with offsets of an integer number of seconds (now 32) determined in such a way that the difference with the solar time does not exceed 0.9 s.

It is worth noting that the value chosen for the second in fact represents the rate of rotation of the Earth averaged over a good part of the nineteenth century. Now, the Earth's rotation is slowing down, hence the need for relatively frequent leap seconds!

4. Length (metre)

The international prototype of the metre, made from an alloy of platinum with 10% of iridium was the length standard up to 1960. It was defined as the distance at 0 °C (temperature of melting ice) between the axes of the two central lines marked on the bar at standard atmospheric pressure and supported on two cylinders of at least one centimetre diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other. The idea of replacing it by a visible wavelength was proposed already in 1927 by the National Bureau of Standards (USA). This idea was not approved by the CIPM and the suggested red cadmium line was used only as the fundamental standard to calibrate other spectral lines.

So, it was only in 1960 that the following new definition of the metre was decided by the CGPM:

“The metre is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton 86 atom”.

The estimated accuracy of the realisation of the metre with this definition was about 4 parts in 10^9 . After twenty years, this appeared to be insufficient. Meanwhile, the accuracy of time and wavelength measurements drastically increased. The first step, in 1975 was to decide on a conventional value of the speed of light in vacuum, resulting from convergent determinations as $c = 299\,792\,458$ m/s exactly. The next one was taken by the CGPM in 1983 and consisted in giving a new definition of the metre:

“The metre is the length of the path travelled by light in vacuum during a time of interval of $1/299\,792\,458$ of a second”.

Such a definition does not lead to immediate practical realisations. One needs, in order to realise the metre, to have radiations as standards of wavelengths for the interferometric measurements of length. The history of the metre since then is a series of improved measurements for laser wavelengths suitable for such measurements. The latest set of recommended wavelengths of stabilised lasers was approved by the CGPM in 2003 [8].

The definition of the metre links it to the definition of the second. While stabilised lasers are ideal references in optical and infrared wavelengths, they must be linked to the caesium wavelength, which is in the microwave domain. So, one must multiply the caesium frequency by a number of the order of 10^6 . This was carried out through successive comparisons by multiplication and/or mixing of frequencies of a chain of phase-locked oscillators with increasing frequencies throughout the microwave and infrared domains. This was a very heavy and difficult experiment that took place only in few laboratories.

The situation changed with the advent of femtosecond lasers or combs. This technique allows direct comparison of the caesium frequency with a large spectrum of optical frequencies [9].

5. Mass (kilogram)

The international prototype of the kilogram, made in the early 1880s and deposited at the BIPM, is still the international standard for mass. It is a cylinder of the same alloy composition as the metre bar (Pt – 10% Ir) with a mass density of 21.55 kg/dm³. The height, equal to its diameter is approximately 39 mm. This shape, for a cylinder, minimises its surface. The prototype is kept in a safe placed in a vault at the BIPM, protected by two glass bells put on a plateau, the whole being protected by a third glass bell jar (Fig. 2).

Similar cylinders have been distributed among laboratories all over the world and became national standards. Several other are used in the BIPM for current work and comparisons. There are also standards in stainless steel. In addition, national metrology institutes have standards of multiples and sub-multiples of the kilogram between 1 mg and 50 tons.

The mass of a solid body is subjected to variations resulting from surface adsorption and desorption and degassing from the interior to say nothing of the mass changes that can arise from physical damage during handling. Even after careful cleaning and washing by standardised methods, changes of mass still occur. It is worth noting that the mass of a monolayer of water all over the surface of a Pt–Ir prototype weighs just over 2 micrograms, i.e., 2 parts in 10^9 of a kilogram. The uncertainty of comparisons of such standards using the best balances in national metrology institutes is a little less than one microgram.

In addition to individual comparisons of standards, three large-scale comparisons of national Pt–Ir kilogram standards with the international prototype have been carried out by the BIPM. The most recent of these was in the late 1980s organised by the BIPM [10]. Fig. 3 shows the evolution of the masses of many of these national standards at successive comparisons taking as the fixed baseline that of the international prototype. It is evident that the masses of national and other BIPM kilograms are systematically increasing with respect to that of the international prototype.

It is tempting to interpret these results as a change in the mass of the international prototype itself. This would mean that the unit of mass is changing, possibly by half a microgram per year. It could be however, that the masses of, not only the international prototype, but also that of all the national standards were increasing at a rate significantly greater than that apparent in Fig. 3. The independent evidence that we have as to the stability of the international prototype with respect to atomic constants is at the level of one part in 10^6 , some two orders of magnitude greater than what is shown in Fig. 3. It is thus urgent to have a better link of macroscopic mass standards with atomic phenomena. This is a major research activity in modern metrology [11].

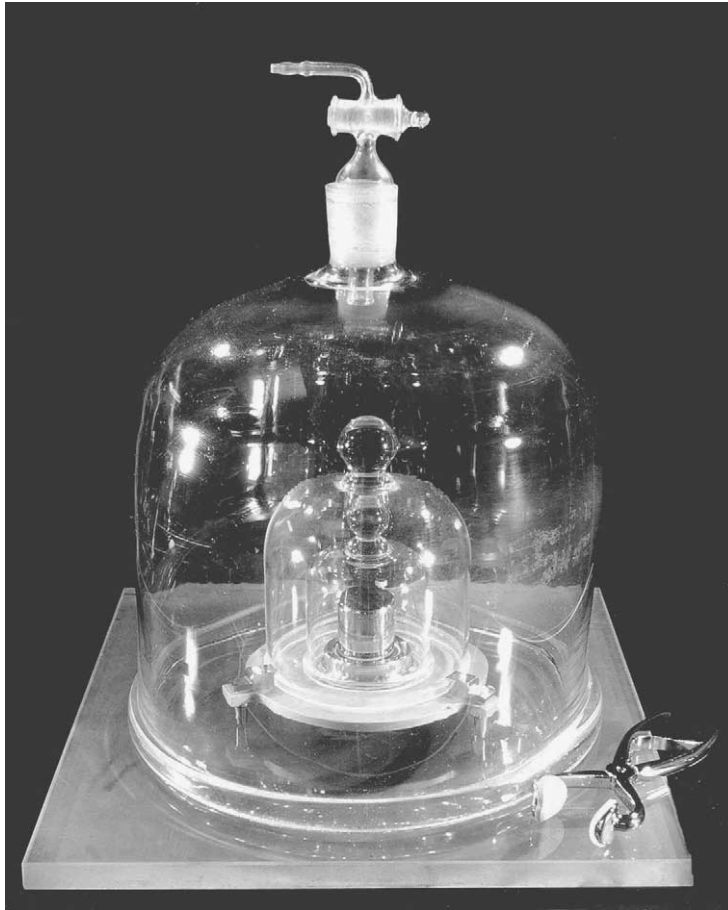


Fig. 2. Photograph of the international prototype.

6. Electricity (ampere)

As already mentioned in the introduction, following Giorgi's views, one electric unit must be present among the SI base units. In 1960, the CGPM decided that the base unit for electricity would be the ampere. Together with other electric units and the related mechanical units the definition of the ampere was given by the CGPM in 1946 as follows:

“The ampere is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} MKS unit of force (now called Newton) per metre of length”.

This is a theoretical definition, whose realisation by means of what used to be called an ‘ampere balance’ is difficult and time consuming. In addition, the accuracy achieved is estimated to be a few parts in 10^{-7} , quite insufficient for present needs. So it is another major challenge to metrologists to propose a definition that would allow much more accurate measurements.

The principles of a change in definition exist based upon the two macroscopic quantum effects, the Josephson effect and the quantum-Hall effect that lead to quantum-based realisations of the volt and the ohm. Before coming to these, however, it is worth examining the formal definitions of the volt and the ohm as given by the CGPM in 1946.

- *“The volt (unit of potential difference and of electromotive force) is the potential difference between two points of a conducting wire carrying a constant current of one ampere, when the power dissipated between these points is equal to 1 watt”.*
- *“The ohm (unit of electric resistance) 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 being not the seat of any electromotive force”.*

In this way, they are tightly linked to the ampere. The realisations of these units can, however be made independently.

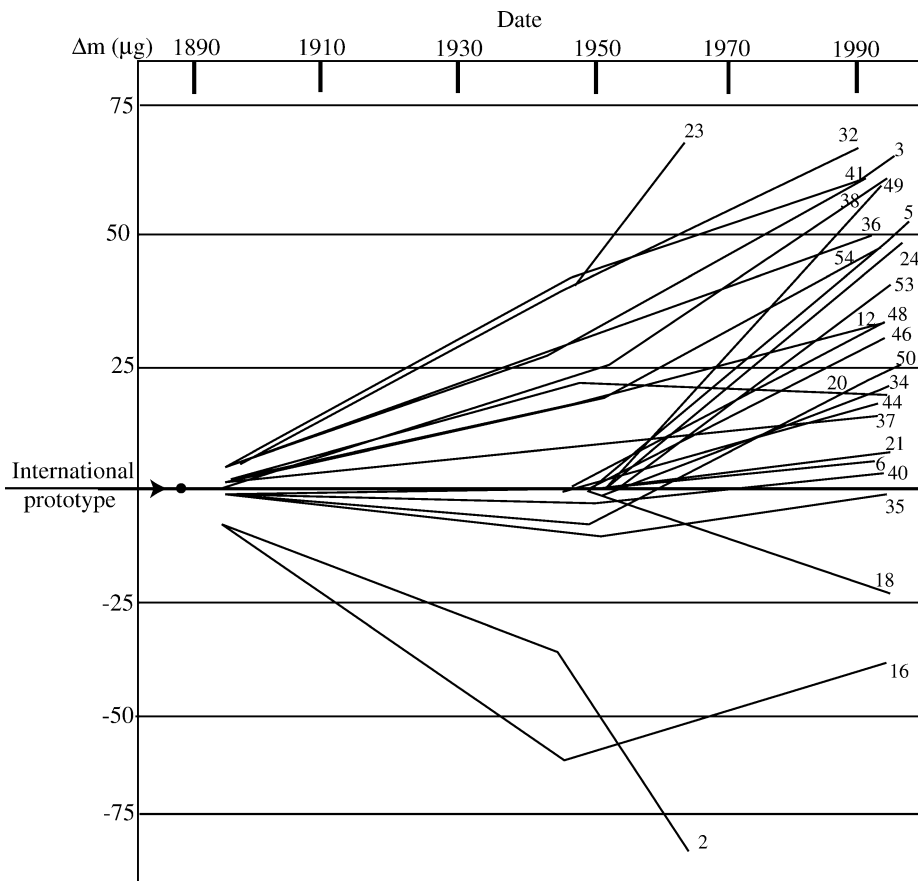


Fig. 3. Change of mass of some national standards designated by their numbers.

6.1. Josephson junction

A Josephson junction is a very thin insulating film, which separates two superconducting substances. The electrons forming the current in one of the sides can leak at very low temperatures through the film as a result of the tunnel effect. If a voltage V is applied across a Josephson junction, the flow is an alternating current at a microwave frequency f . These parameters are related by:

$$f = (2e/h)V = K_J V,$$

where e is the charge of the electron, h the Planck constant, and K_J is known as the Josephson constant. Conversely, if the junction is irradiated by a microwave radiation of frequency f , one observes, increments in the voltage that can take values of the form

$$V = nK_J f,$$

where n is an integer. Josephson junction arrays provide very precise voltages that can be used to calibrate voltage standards. Actually, since 1990, by a decision of the CIPM, which gave to K_J the conventional value $K_{J-90} = 483\,597.9$ GHz/V, exactly. Josephson arrays are secondary realisations of the volt. If this value in the SI has an uncertainty estimated to be 4 parts in 10^{-7} , the precision of measurements is better than 10^{-9} .

6.2. The ohm

A similar situation exists with the ohm. At very low temperatures (< 4.2 K), and in the presence of a very strong magnetic field (of the order of 10 teslas) the electrons are confined to an extremely thin layer and their motion is restricted to a two-dimensional space. If the space is an elongated shape junction and the magnetic field is applied perpendicular to it, then

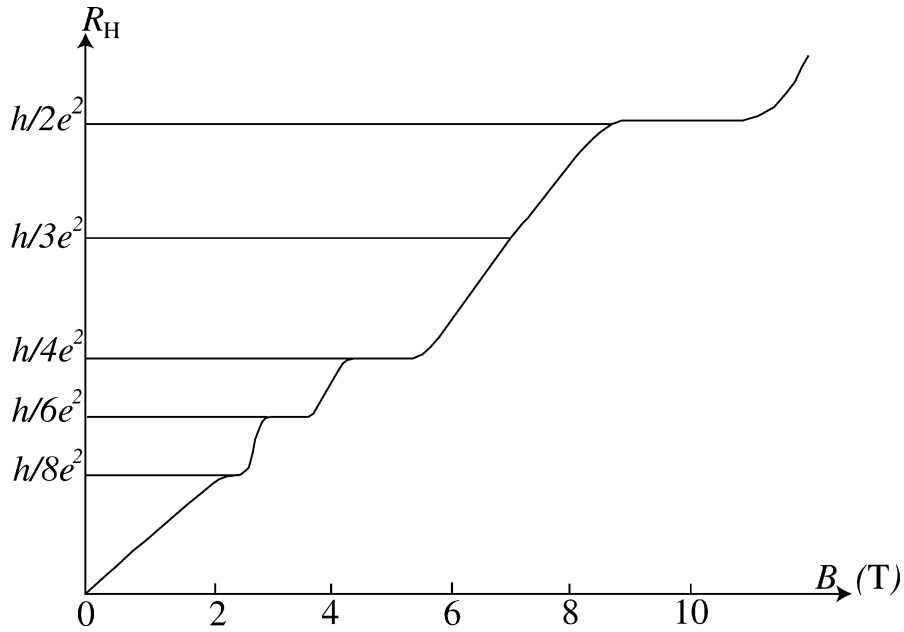


Fig. 4. Quantification of the Hall resistance as a function of the magnetic flux density.

a transverse Hall potential V is created, which is proportional to the intensity of the current in the junction. The ratio of the Hall voltage V_H to the intensity I of the current is the quantised Hall resistance. This quantum Hall effect has the property that a graph of quantised Hall resistance against flux density shows steplike regions (see Fig. 4). One has

$$n(V_H/I) = h/e^2 = R_K$$

where n is an integer and R_K is known as the Von Klitzing constant for which a conventional value was assigned by the CIPM in 1988: $R_{K-90} = 25\,812.807 \, \Omega$. The quantum Hall effect is henceforth a secondary realisation of the ohm, under the same conditions as the use of the Josephson arrays for the volt.

It is to be noted that this does not constitute a redefinition of electric units. Before this can be done, it is necessary to verify that the conventional values assigned to K_J and R_K are consistent. In other words, we need to be sure: (a) that the relations given above are correct; and (b) that we have good values for the ratios of the fundamental constants $2e/h$ and h/e^2 . This is described in [12].

6.3. The Farad

Another important electric unit is the Farad whose definition is:

“The farad (unit of capacitance) 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 (the quantity carried by a current of 1 ampere in 1 second)”.

The capacitance plays an important role in the experiments that should lead to a new definition of electric units. The best realisation of the farad is obtained using a Thompson–Lampard capacitor for which there is an exact relation between the change in capacitance and the distance moved by one of the electrodes, which is about 4 pF per metre. The measurement of the capacitance is therefore reduced to a length measurement. The present accuracy of the best capacitors of this type is a few parts in 10^8 .

The experiments needed to relate the quantum effects to SI units are electro-mechanical experiments. The most promising at present is the so-called watt balance in which an electrical power is compared with a mechanical power; see [11].

7. Temperature (Kelvin)

From the earliest days, thermometry was part of the tasks of the BIPM, because the definition of the metre required a measurement of its temperature and because it was also an important parameter in establishing air density required for accurate

weighing. So, the first CGPM in 1889 defined a “normal hydrogen scale” between the ice point (0°) and the boiling point (100°) of water used to calibrate mercury thermometers with a constant volume hydrogen thermometer. There were several other methods of measuring temperatures: thermocouples, platinum resistance thermometers, and constant pressure gas thermometers. Finally, in 1927, a first practical international temperature scale was established between -180°C and 1060°C . It was followed by another practical scale in 1948.

To go further, one needed a more precise definition of the unit of temperature. In 1954, the CGPM defined a unit of thermodynamic temperature by stating that the triple point of water is the fundamental fixed point and assigned to it the temperature 273.16 K (kelvins) exactly. As a consequence, the kelvin, unit of thermodynamic temperature, is the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water (CGPM, 1967–1968).

The choice of a thermodynamic temperature as the measured quantity is justified because, in contrast with many of the methods mentioned above, changes in temperature are independent of the working substance used. If we consider a reversible engine working in a perfect Carnot cycle, the ratio of the quantity Q_1 of heat that is taken at a thermodynamic temperature T_1 to the quantity Q_2 rejected at the thermodynamic temperature T_2 is equal to the ratio of thermodynamic temperatures:

$$Q_1/Q_2 = T_1/T_2.$$

Again, this temperature is difficult to measure directly. Methods of measurement that give values for thermodynamic temperature directly are known as methods of primary thermometry. For a method to be primary it is necessary that its equation of state be written down explicitly without introducing unknown temperature dependent constants or functions. Among such methods that have been used are constant volume gas thermometry, acoustic gas thermometry, total radiation thermometry, noise thermometry and optical pyrometry. All of these methods are difficult and time consuming when they are used as primary thermometers and other techniques are required for practical thermometry. To meet this need for accurate calibrations of resistance thermometers, thermocouples and practical optical pyrometers a succession of International Practical Temperature Scales have been developed [13]. The current such Scale is the International Temperature Scale of 1990.

The principle behind all such scales is that a certain number of fixed points of temperature are specified whose temperatures have been assigned by means of primary thermometers and interpolation between or extrapolation beyond the fixed points by means of specified equations.

The International Temperature Scale (ITS-90), adopted by the CIPM in 1989 gives the temperatures of 16 fixed points between 13.8033 K (triple point of hydrogen) and 1357.77 K (freezing point of copper). The interpolations are defined as follows:

- (1) From 0.65 K to 5 K, the helium vapour-pressure equations;
- (2) From 3 K to 24.5561 K, interpolating constant-volume gas thermometers;
- (3) From 13.8033 K to 1234.93 K, platinum resistance thermometers;
- (4) Above, apply the Planck radiation law.

A description of the techniques to be used for approximating ITS-90 was published by the BIPM [14].

An extension of the ITS-90 to temperatures lower than 0.65 K, called Provisional Low Temperature Scale (PLTS-2000) was approved by the CIPM in 2000. It is defined by a formula relating the melting pressure of helium 3 to temperature in PLTS-2000 [15]. It ranges between 0.9 mK to 1 K. It is considered as being provisional because its uncertainty below 10 mK is not satisfactory and should be improved. Generally speaking, important research effort is being deployed in this region as well as for very high temperatures.

8. Amount of substance (mole)

On the advice of both International Unions of Pure and Applied Physics (IUPAP) and Chemistry (IUPAC), the CGPM, in 1971, introduced in the SI, as the seventh base unit, a unit of amount of substance, the mole. The definition is:

‘The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12: its symbol is “mol”’.

The CIPM later specified that this refers to unbound atoms of carbon 12, at rest and in their ground state. In addition, when using the mole, it is necessary to specify the elementary entity, which may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. The concept is sometimes even extended to non-material entities like photons.

The number of entities in a mole is the Avogadro constant N_A . International programmes are in progress to improve the value of this number because it is one of the approaches towards a new definition of the kilogram. An approximate value is $N_A = 6.022\,1365 \times 10^{23}$, the last digit being uncertain.

There are several methods of chemical analysis that have the potential to be primary, i.e., that can give amount of substance in moles directly (see thermodynamic temperature above). Among these are:

- (1) Gravimetry: weighting of species after precipitation in a solution;
- (2) Titrimetry: chemical reaction with a known quantity of the reactive species;
- (3) Isotopic dilution mass spectrometry: measurement of the ratio of two stable isotopes, then modified by the addition of a known quantity of one of them.

Chemical analysis or the determination of the amount of one substance when mixed with one or more others is a very complex problem. It is difficult to determine the amount of one substance without the presence of the others biasing to a greater or lesser extent the measured result. There exist also many difficulties in preparing a sample for analysis that is representative of the whole [16]. The Consultative Committee for Amount of Substance (CCQM) is carrying out many studies designed to evaluate the uncertainties of chemical analysis and the reports of these studies should be consulted for further information. The importance of accurate and reliable chemical analysis is, however, very high and much effort is being devoted to this problem.

9. Luminous intensity (candela)

The objective of photometry is to measure light in such a way that the result correlates as well as possible with the visual sensation. In 1948, the definition of the ‘new candela’ was based on a black body at the temperature of freezing platinum. However, when radiometric techniques developed sufficiently and became more precise than the photometric techniques, a drastic change was proposed and led to the following definition adopted by the CGPM in 1979:

“The candela (symbol cd) 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”.

The choice of the wavelength and of the radiant intensity was made in such a way that it ensures satisfactory continuity, despite a change of about 3% with respect to the previous definition. This solution had satisfied the requirements of the International Commission on Illumination.

There are two derived units:

- (1) Luminous flux: lumen (symbol lm), candela per steradian (cd sr^{-1});
- (2) Illuminance: lux (symbol lx), lumen per square metre (lm m^{-2}).

The realisation of the candela consists of the measuring the energy of a source seen through a special filter, which simulates the response of a human eye as a function of the wavelength. The transfer is then ensured by calibrated lamps.

The new definition of the candela links the photometry to mechanical SI units. It opens the way to radiometric measurements that are no longer restricted to visual wavelengths, and can be extended to infrared and ultraviolet radiations, expressing the energetic flux in watts, the energetic intensity in watts per steradians and the energetic illuminance in watts per square metre per steradian. The basic primary instrument is the cryogenic radiometer.

Recently, considerable effort has been devoted to the measurement of light emitted by light emitting diodes that are increasingly being used for public lighting. The particular properties of such light sources require special techniques.

10. Ionising radiation

Although all well-defined physical quantities may be expressed in terms of the base or derived units of the SI, the specificity of some domains and their relation to human health and safety require that certain derived units be given special names for use in these domains. The most important example is given by measurements in the field of ionising radiations.

The reason for introducing special names for units in the field of ionising radiation was to extend the use of the SI in many matters directly related to human health and safety in diagnosis and radiotherapy and radioprotection as well as in the field of research [17]. Two independent types of metrology are considered: the activity of radio-nuclides and the absorbed dose by a patient.

In 1975 and in 1984, the CGPM introduced special names for three units, which are directly connected to the SI. These are:

- (1) The becquerel (symbol Bq) is the activity of a quantity of radioactive nuclides such that the mean number of spontaneous nuclear transitions is 1 per second; $\text{Bq} = \text{s}^{-1}$;

- (2) The gray (symbol Gy) is the absorbed dose in a kilogram of matter inside which ionising radiations produce, in the average, an energy of 1 joule; $\text{Gy} = \text{J kg}^{-1}$;
- (3) The sievert (symbol Sv) is the unit of equivalent dose absorbed in a tissue multiplied by a weighting factor which is a function of the biological efficiency of the considered radiation; $\text{Sv} = \text{J kg}^{-1}$.

These definitions call for several remarks:

- The becquerel is a very small unit. In general, even in apparently inactive regions, the activity is expressed in 10^4 or 10^5 Bq. The average activity of the human body, for example, is some 4000 Bq. Unfortunately these large numbers scare people and lead to many unfortunate misunderstandings in the population.
- Because of the diversity of ionising particles, which can be electrically neutral (X and γ photons, neutrons) or charged (α , β , protons), the methods of measurement are very different.
- The quantity dose equivalent H , expressed in sieverts, is the product of the absorbed dose D expressed in grays and the dimensionless factors Q (quality factor) and N (product of any other factors) stipulated by the International Commission on Radiological Protection. The decision to have two names was intended to avoid a risk of confusion between the absorbed dose and the dose equivalent. Recently it has been decided that it is better to let $N = 1$.

The establishment and the medical use of these units are discussed in [17].

11. The future of the SI

The example of ionising radiations is not unique. In particular, the introduction of the SI in biological domains brings difficulties that can sometimes be resolved by introducing new names of units, but sometimes, as in the case of the sievert, one must admit that other considerations should be taken into account. This is especially true in chemistry, a newcomer in the SI which is due to develop in the future in many directions linked with organic matter and biology (see [16]).

However, this may also occur in physics. We have already touched this problem with the candela. Another example is hardness, which is an intuitive property of matter. But to test it, one needs to define and fully describe the tool that is used to test the hardness by applying a force. The result is a conventional hardness scale, which depends on the tool used. Actually, there are at least three different scales in use.

For the future, one may also ask oneself several questions, among which:

- What will be the metrology of properties of soft matter?
- How one will make the link between the SI and nanometrology, in particular when molecules are seen and manipulated one by one?

These problems are – or will have to be – studied.

Another expected development of the SI is the tendency to replace the present definitions by definitions that use fundamental physical constants such as the speed of light, the Planck and Boltzman constants, the charge of the electron, and the fine structure constant. This was achieved for the metre and will probably be the case for the kilogram and electric units in a decade or two.

So, one should expect an evolution of the SI in its contents and possibly in its logic. But the major objective, namely to be the tool for expanding throughout the world a unified measurement system will remain. Recent events show that the BIPM is more and more recognised as the reference in the rationalisation of measurement standards. Several international organisations in the fields of environment, health, laboratory medicine have concluded mutual arrangements with the BIPM. More will certainly follow. The BIPM is evolving to take into account the new requirements that arise. The SI will inevitably follow this trend.

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