SI Units

Prof. Dr. Werner Bidlingmaier & Dr.-Ing. Christian Springer

Projekt Orbit | Dr. W. Bidlingmaier | Bauhaus Universität Weimar | www.orbit-online.net

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 force 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

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 May, 20 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. 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 base 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 (now CCEM) by the 7th CGPM in 1927, the Giorgi proposal was thoroughly discussed by the IEC and the IUPAP and other international organizations. This led the CCE to recommend, in 1939, the adoption of a four-dimensional system based on the meter, kilogram, second and ampere, 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 International System of Units (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 base unit for amount of substance, bringing the total number of base units to seven.

	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

Definitions and historical background

Unit of length: meter

The origins of the meter go back to at least the 18th century. At that time, there were two competing approaches to the definition of a standard unit of length. Some suggested defining the meter as the length of a pendulum having a half-period of one second; others suggested defining the meter as one ten-millionth of the length of the earth's meridian along a quadrant (one fourth the circumference of the earth). In 1791, soon after the French Revolution, the French Academy of Sciences chose the meridian definition over the pendulum definition because the force of gravity varies slightly over the surface of the earth, affecting the period of the pendulum.

Thus, the meter was intended to equal 10^{-7} or one ten-millionth of the length of the meridian through Paris from pole to the equator. However, the first prototype was short by 0.2 millimeters because researchers miscalculated the flattening of

the earth due to its rotation. Still this length became the standard. (The engraving at the right shows the casting of the platinum-iridium alloy called the "1874 Alloy.") In 1889, a new international prototype was made of an alloy of platinum with 10 percent iridium, to within 0.0001, that was to be measured at the melting point of ice. In 1927, the meter was more precisely defined as the distance, at 0°, between the axes of the two central lines marked on the bar of platinum-iridium kept at the BIPM, and declared Prototype of the meter by the 1st CGPM, 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.

The 1889 definition of the meter, based upon the artifact international prototype of platinum-iridium, was replaced by the CGPM in 1960 using a definition based upon a wavelength of krypton-86 radiation. This definition was adopted in order to reduce the uncertainty with which the meter may be realized. In turn, to further reduce the uncertainty, in 1983 the CGPM replaced this latter definition by the following definition:

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 in vacuum at exactly 299 792 458 $m \cdot s^{-1}$. The original international prototype of the meter, which was sanctioned by the 1st CGPM in 1889, is still kept at the BIPM under the conditions specified in 1889.

Unit of mass: kilogram

At the end of the 18th century, a kilogram was the mass of a cubic decimeter of water. In 1889, the 1st CGPM sanctioned the international prototype of the kilogram, made of platinum-iridium, and declared: This prototype shall henceforth be considered to be the unit of mass. The picture at the right shows the platinum-iridium international prototype, as kept at the International Bureau of Weights and Measures under conditions specified by the 1st CGPM in 1889.

The 3d CGPM (1901), 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.

Unit of time: second

The unit of time, the second, was defined originally as the fraction 1/86 400 of the mean solar day. The exact definition of "mean solar day" was left to 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) adopted a definition given by the International Astronomical Union which was based on the tropical year. Experimental work had, however, 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) decided to replace the definition of the second by the following CIPM in 1997 that this definition refers to a cesium atom in its ground state at a temperature of 0 K):

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.

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 the definitions of the "international" ampere and the "international" ohm were confirmed by the International Conference of 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, 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 in 1946:

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 x 10^{-7} newton per meter of length.

The expression "MKS unit of force" which occurs in the original text has been replaced here by "newton," the name adopted for this unit by the 9th CGPM (1948). Note that the effect of this definition is to fix the magnetic constant (permeability of vacuum) at exactly $4 \pi \times 10^{-7}$ $H \cdot m^{-1}$.

Unit of thermodynamic temperature: kelvin

The definition of the unit of thermodynamic temperature was given in substance by the 10th CGPM (1954) 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) adopted the name kelvin (symbol K) instead of "degree Kelvin" (symbol °K) and defined the unit of thermodynamic temperature as follows:

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 thermodynamic temperature, symbol T, in terms of its difference from the reference temperature T0 = 273.15 K, the ice point. This temperature difference is called a 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). The numerical value of a Celsius temperature t expressed in degrees Celsius is given by

$$t/°C = T/K - 273.15.$$

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.

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 were 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 spectrograph 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, 12C). 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 has been fixed at 0.012 kg, and the unit of the quantity "amount of substance" was given the name mole (symbol mol).

Following proposals of IUPAP, IUPAC, and the International Organization for Standardization (ISO), the CIPM gave in 1967, and confirmed in 1969, a definition of the mole, eventually adopted by the 14th CGPM (1971):

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.**

At its 1980 meeting, the CIPM approved the 1980 proposal by the Consultive Committee on Units of the CIPM specifying that in this definition, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

Unit of luminous intensity: candela

Originally, each country had its own, and rather poorly reproducible, unit of luminous intensity; it was necessary to wait until 1909 to see a beginning of unification on the international level, when the national laboratories of the United States of America, France, and Great Britain decided to adopt the international candle represented by carbon filament lamps. Germany, at the same time, stayed with the Hefner candle, defined by a flame standard, and equal to about nine-tenths of an international candle. But a standard based on incandescent lamps, and consequently dependent upon their stability, would never have been fully satisfactory and could therefore be only provisional; on the other hand, the properties of a blackbody provided a theoretically perfect solution and, as early as 1933, the principle was adopted that new photometric units would be based on the luminous emission of a blackbody at the freezing temperature of platinum (2045 K).

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 blackbody) 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 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 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) 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 x 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

Literatur: US Department of Commerce, National Institut of Standards and Technoloy; Docket No. 980430113-8113-01 Metric Systems of Measuremend: Interpretation of the International System of Units for the US