

Towards Redefining the Kilogram and the Mole in the “New SI”

Jim McQuillan^a

Department of Chemistry, University of Otago, Dunedin 9054
(email: jmcquillan@chemistry.otago.ac.nz)

^a *President of the Physical and Biophysical Chemistry Division of IUPAC for 2010-2011.*

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History and Evolution of the SI system

Some of us will remember the period in the 1960s when the International System of Units, known as SI and based on the old metre-kilogram-second (MKS) system, was established. New Zealand universities were visited by the redoubtable Max McGlashan, a UK-residing Canterbury graduate, who was the Chair of the Commission on Symbols, Terminology and Units of the IUPAC Division of Physical Chemistry.¹ He vigorously promoted the advantages of the SI system and was influential in the general adoption of the SI system within the NZ universities and it being taught with a good deal of zeal.

The SI system is a coherent system built on seven defined base units: the metre, kilogram, second, ampere, kelvin, mole, and candela.² The SI system evolved with unit definitions being modified through international agreement as the precision of measurements improved with progress in technology. The standard metre was once the distance between two lines engraved near the ends of a platinum-iridium bar kept at the melting point of ice and at standard atmospheric pressure. Since 1983 the metre has been defined as the distance traveled by light in a vacuum during 1/299 792 458 of a second.

A definition is different from its realisation, or how it is used in practice. The base unit realisations have become more complicated as the definitions have evolved. For the metre this realisation combines sophisticated laser experiments with interferometry rather than measuring the speed of light as the definition may suggest. In 1967 the second became the duration of 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs. Thus, the SI system has progressively adopted base unit definitions in terms of invariants of nature. While a more satisfactory mass standard has been sought for several decades, the kilogram remains the only base unit tied to a macroscopic artefact and not yet defined by microscopic constraints.

The origins of the SI system date from the adoption of the metre in France in the days of Lavoisier. The Metre Convention³ was signed by seventeen states in 1875 to establish international organisations and a metrology centre for overseeing the maintenance of metric standards. These continue today as the General Conference on Weights and Measures (CGPM – Conférence Générale des Poids et Mesures) of the now 55 member states who meet every 4-6 years at Sèvres, France and its administrative wing the International Committee for Weights and Measures (CIPM – Comité International des Poids et Mesures) which meets annually. The International Bureau of Weights and Mea-

asures (BIPM – Bureau International des Poids et Mesures) at Sèvres houses the international prototype kilogram. New Zealand became a member state of the Metre Convention in 1991 and the Measurements Standards Laboratory (MSL) of Industrial Research Limited in Lower Hutt houses the associated NZ metrology activities.

“New SI” Proposals

The 24th CGPM was held at the BIPM from 12 to 15 October 2011. A key activity at this meeting was a review of progress towards the redefinition of the kilogram and the wider measures foreshadowed in the “New SI”. The CGPM passed unanimously a resolution of intent to redefine the kilogram, the ampere, the kelvin and the mole in terms of fixed numerical values of the Planck constant, h ; the elementary charge, e ; the Boltzmann constant, k ; and the Avogadro constant, N_A .⁴ An important feature of the proposed “new SI” is the fixing of the numerical values of seven chosen fundamental constants, called “SI reference constants”, to scale the entire system of units. The SI reference constants will be the speed of light in a vacuum (c), the Planck constant (h), the elementary charge (e), the Boltzmann constant (k), the Avogadro constant (N_A), the Cs hyperfine splitting ($\Delta\nu(^{133}\text{Cs})_{\text{hfs}}$), and the luminous efficacy of a 540 THz source (K_{cd}). This leads to a totally explicit-constant formulation of the base unit definitions. A series of articles in *Chemistry International*, the IUPAC Newsletter (<http://stage.iupac.org/publications/ci/index.html>), illustrates the debate which has ensued and is a good starting point for further reading.⁵⁻⁸ Fuller details may be found in a recent article by Mills *et al.*⁹

In effect, the SI reference constants will become the basis of the redefined base units of the SI system. Chemists will be particularly interested in how the mole is likely to be redefined. A number of prerequisite conditions have yet to be met before “new SI” implementation, and its introduction is some years away. While these foreshadowed changes will have negligible impact on almost all physical science measurements, they will reform the fundamental basis of these measurements, giving decreased fundamental constant uncertainties as advances in the precision of measurements are made.

Redefining the Kilogram

The international prototype of the kilogram (IPK) remains the mass of a 90 mass% platinum and 10 mass% iridium alloy cylinder created in 1884 and kept in air under three bell jars at the BIPM (Fig. 1).¹⁰ Its main disadvantage is uncertainty in the long term stability of its mass but it could also be damaged or even destroyed. More than 80 national prototype kilograms have been copied and dis-

tributed to member countries. However, comparisons of the mass of official copies with that of the IPK over time have shown average increases corresponding to a drift of about $50 \mu\text{g}$ in 100 years. Thus, alternative definitions of the century-old kilogram artefact have been long sought. Redefinition of the kilogram would also benefit the ampere, the mole, and the candela, the definitions of which depend on the kilogram.

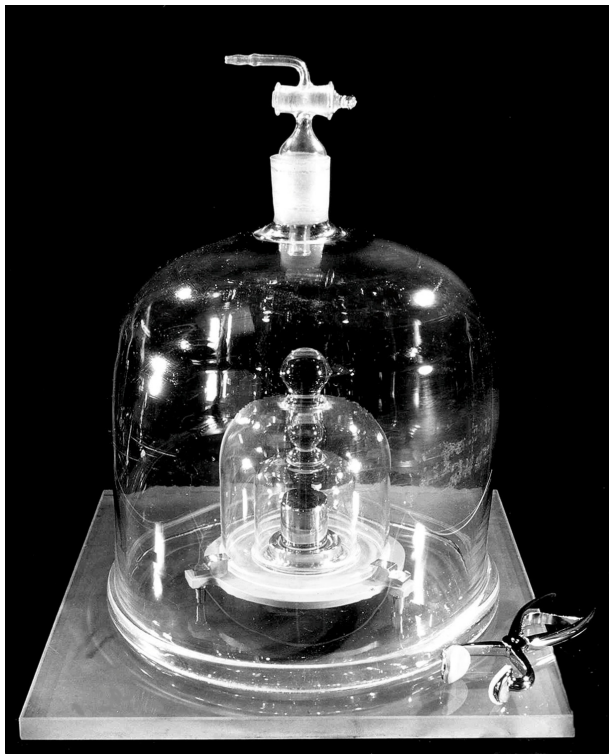


Fig. 1. The kilogram kept by the Bureau International des Poids et Mesures (Photograph courtesy of the BIPM).

Redefining the kilogram depends on refining experiments which link the unit of mass to fundamental or atomic constants through the laws of physics. Redefinition of the kilogram is not as straightforward as for the metre. Presently there are two approaches: the Avogadro project and the watt balance. Both methods have succeeded in linking a fundamental constant to the mass of the IPK with a relative uncertainty of 5 parts in 10^8 , and efforts continue to further reduce this uncertainty. Either of these experimental approaches could provide a realization of a redefined kilogram.

The Avogadro project¹¹ involves a collaboration between Germany, Italy, Belgium, Japan, Australia and USA aiming to measure the ratio of the mass of the silicon 28 atom to the mass of the IPK in order to redefine the kilogram in terms of the Avogadro constant, N_A . The principle of the experiment is to count the number of atoms in a 1 kg nearly perfect single crystal silicon sphere (Fig. 2). Silicon was chosen because it is one of the best known materials and can be grown as large, high purity, and almost perfect single crystals. The precisely known lattice parameter of the crystal allows the number of atoms to be determined from macroscopic measurements. However there are issues with determinations of the natural isotope composition of the silicon.



Fig. 2. A silicon sphere made for the Avogadro project at CSIRO by the Australian Centre for Precision Optics (*csiro.au*)

The moving-coil watt balance¹² links the Planck constant, h , to the mass of the IPK as the Planck constant can be expressed in the unit $\text{s}^{-1} \text{m}^2 \text{kg}$. The watt balance consists of a balance suspending a mass and a coil, with the coil in a magnetic field. In one experiment the mass is balanced by sending a current through the coil and in a second experiment the coil is moved through the magnetic field to generate a voltage (Fig. 3). The product of the current and voltage (power) is directly related to the mass. The link between the mass and the Planck constant is obtained via the Josephson effect and the quantum Hall effect. The Measurement Standards Laboratory of New Zealand at Lower Hutt is carrying out research on the watt balance approach.¹³ Critics of this esoteric approach who favour retaining a ^{12}C -based kilogram do not like an “electronic kilogram”, and say that the new definition must be comprehensible to its audience.

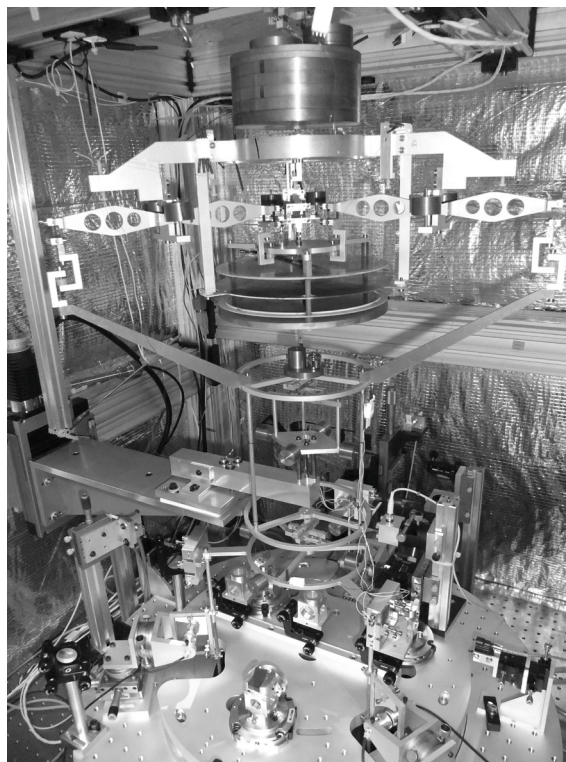


Fig. 3. The watt balance under construction at the Bureau International des Poids et Mesures. (Photograph courtesy of the BIPM)

It is now generally considered that h will be chosen. Once the fundamental constants h and N_A are accurately measured in the present SI system, it will be possible to numerically fix the value of the chosen fundamental constant instead of the mass of the IPK and so redefine the kilogram. After the redefinition, a number of watt balances will be needed to realise the new definition of the kilogram in practice. A new role of the BIPM will be to permanently operate a watt balance to facilitate the operation of the new definition for national metrology institutes. One important outcome of the redefinitions of the units will be to reduce by more than an order of magnitude the uncertainty with which almost all of the fundamental constants of physics are known.⁸

Redefining the Mole

The mole, the unit for “amount of substance”, was introduced in 1971 as the seventh base unit. This base unit differs in many respects from the others and is essentially a convenient number of elementary entities for macroscopic experiments. Although widely used, there has been some reluctance to adopt the name “amount” and discussion persists about alternative names. Presently the mole is defined as the amount of substance containing as many entities as there are atoms in 0.012 kg of ^{12}C , which implies a fixed ^{12}C molar mass of exactly 12 g mol^{-1} . In the “new SI” the mole will be redefined by fixing the Avogadro constant as exactly $6.022\,141\,79 \times 10^{23}\text{ mol}^{-1}$.⁸ The mole will become the amount of substance containing $6.022\,141\,79 \times 10^{23}$ of a specified elementary entity. The new definition will have the advantage of decoupling the mole from the kilogram. The molar mass of ^{12}C will no longer be fixed by definition, but will be an experimental quantity.

Conclusion

In the “New SI” four of the SI base units, namely the kilogram, the ampere, the kelvin, and the mole will be re-

defined in terms of invariants of nature; the new definitions will be based on fixed numerical values of the Planck constant (h), the elementary charge (e), the Boltzmann constant (k), and the Avogadro constant (N_A). Further, the definitions of all seven base units of the SI will be uniformly expressed using an explicit constant formulation based on fixed values for seven reference constants, and procedures will be drawn up to explain the realization of the definitions of each of the base units in a practical way. The CIPM has encouraged communication, awareness, and debate about aspects of the “new SI” through draft documents posted on its website.¹⁴

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