Towards a new SI: a review of progress made since 2011

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Review Article

Towards a new SI: a review of progress made since 2011

Martin J T Milton, Richard Davis and Nick Fletcher

BIPM, Pavillon de Breteuil, Sèvres, France

E-mail: martin.milton@bipm.org

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Abstract

In 2011, the General Conference on Weights and Measures (CGPM) confirmed its intention to adopt new definitions for four of the base units of the SI based on fixed numerical values of selected constants. These will be the kilogram, the ampere, the kelvin and the mole. The CGPM was not able to adopt the new definitions at that time because certain experimental and coordination work was not complete. This paper reviews criteria proposed by the Consultative Committees of the CIPM for such a 'new SI' to be adopted and reports on recent progress with work to address them. We also report on work being undertaken to demonstrate that the most important technical aspects of realizing such a new system are practicable. The progress reported here confirms the consensus developing amongst the Consultative Committees and the National Metrology Institutes that it will be possible for the CGPM to adopt these new definitions in 2018.

Keywords: SI units, metrology, kilogram

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(Some figures may appear in colour only in the online journal)

1. Introduction

There has been much debate about the benefits of revising the definitions of four of the base units of the SI [1] so that they are articulated in terms of fixed numerical values of certain constants [2, 3]. The limitations of the present system, in particular the use of a physical artefact to define one of the base units, have been critiqued and the benefits of such an alternative approach have been presented by many authors [4, 5].

The proposal that four of the base units of the SI might be redefined with respect to fixed values of certain constants became the subject of much discussion in the early years of this century. Since that time, the General Conference on Weights and Measures, the forum for decision making between the Member States of the Metre Convention on all matters of measurement science and measurement units, has passed resolutions at four of its meetings [6a–6d]. In 1995, at its 20th Meeting, it recommended that national metrology institutes (NMIs) work on experiments that would 'open the way for a new definition of the kilogram based on fundamental or atomic constants' [6a]. At its next meeting, in 1999, it invited the NMIs to continue efforts to 'link the unit of mass to fundamental or atomic constants' [6b]. Subsequently, in 2007, at its 23rd meeting, it recognized the possibility of redefining four base units in terms of fixed values of four fundamental constants and invited the NMIs 'to come to a view on whether it is possible' [6c].

Most recently, in 2011, at its 24th meeting, it noted [6d] that a redefinition of four base units had been considered in detail and that the International Committee for Weights and Measures (CIPM) intended to propose a revision in which the numerical values of four constants would be fixed in order to define the magnitude of four base units. The resolution is long and detailed and is summarized in an appendix to this paper. In summary, it proposes that the kilogram, the ampere, the kelvin and the mole should be defined with respect to fixed numerical values of

- the Planck constant h of exactly $6.626\,06X \times 10^{-34}$ joule second,
- the elementary charge e of exactly $1.602\,17X \times 10^{-19}$ coulomb,
- the Boltzmann constant k of exactly $1.3806X \times 10^{-23}$ joule per kelvin,

- the Avogadro constant N_A of exactly $6.022\,14X \times 10^{23}$ reciprocal mole,

(where the symbol X represents one or more digits to be added to each numerical value based on a CODATA adjustment specially carried out prior to the redefinition). These will join the fixed numerical values of three constants that currently form the definitions of the second, the metre and the candela:

- the ground state hyperfine splitting frequency of the caesium 133 atom $\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$ of exactly 9192 631 770 hertz,
- the speed of light in vacuum c of exactly 299 792 458 metre per second,
- the spectral luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} hertz of exactly 683 lumens per watt,

Although discussion about the principles behind such changes has continued in many different forums, it has always been clear that a set of new definitions could not be adopted until the experimental data and particularly those for the value of the Planck constant were consistent at a level that could justify making the change without any risk that users deriving traceability to the base units from different NMIs would be using inconsistent values. Criteria have been set for such a change to be implemented by the Consultative Committees for Mass and Related Quantities (CCM) and for Thermometry (CCT). These criteria impose quantitative requirements on the results of experimental work presently underway at several of the NMIs. In this paper we explain these criteria and report on recent progress with this experimental work.

Additionally, it has been recognized that significant attempts must be made to show that the 'new SI' can be implemented without significant inconvenience in the provision of traceability to the most critical users. Also that a wider community including those involved in science education as well as users should be informed about the proposed changes. In these respects we also consider the activities of the Consultative Committees for Electricity and Magnetism (CCEM) and for Metrology in Chemistry (CCQM).

We show that a consensus is emerging that the technical criteria should be met and also the work of demonstrating the feasibility of implementing the new definitions should be sufficiently complete that these new definitions could be adopted in 2018.

2. The kilogram

2.1. The CCM Recommendation G1 (2013)

Amongst the four base units proposed for redefinition, it is the kilogram that has generated the greatest concern about the maintenance of continuity with values disseminated traceable to the SI by the existing definition. The first attempt to review and quantify all of the necessary elements to achieve continuity was published in 2010 [7] and foresaw the necessity to realize and disseminate mass at the level of 1 kg with a standard uncertainty of 20 µg. This formed the basis for a recommendation made by the CCM in 2010 [8].

'that the following conditions be met before the CIPM asks CODATA to adjust the values of the fundamental physical constants from which a fixed numerical value of the Planck constant will be adopted,

1. *at least three independent experiments, including work from watt balance and XRCD experiments, yield consistent values of the Planck constant with relative standard uncertainties not larger than 5 parts in 10^8,*
2. *at least one of these results should have a relative standard uncertainty not larger than 2 parts in 10^8,*
3. *the BIPM prototypes, the BIPM ensemble of reference mass standards, and the mass standards used in the watt balance and XRCD (x-ray crystal density) experiments have been compared as directly as possible with the international prototype of the kilogram,*
4. *the procedures for the future realization and dissemination of the kilogram, as described in the mise en pratique, have been validated in accordance with the principles of the CIPM-MRA.'*

The recommendation includes footnotes to specify *inter alia* that the technical basis for points 1 and 2 can be found in [7].

Proposals towards meeting the criteria laid down by this recommendation were reviewed at a two-day workshop organized by the CCM in November 2012. This brought together a diverse group of researchers and mass metrologists with the goal of seeking a common understanding of the steps needed to achieve the redefinition of the kilogram and to draft the *mise en pratique* for the new definition of the kilogram referred to in point 4. At its subsequent meeting, in February 2013, the CCM agreed the general principles developed for the *mise en pratique* and produced a further recommendation [9]. This noted that consultation with the OIML and other major stakeholders was underway. It then confirmed the conditions set out in 2010 (as reported above) and recognized that some progress had been made towards meeting them. Finally, a roadmap to reach all of the conditions necessary for a redefinition by 2018 was agreed.

In the following paragraphs we review the progress made towards meeting the four conditions laid down by the CCM. We also discuss the development of the *mise en pratique* and introduce the main elements of the CCM roadmap.

2.2. Progress with the determination of the Planck constant

The first two conditions laid down by the CCM refer to the results of experimental determinations of the Planck constant. The most recent results of experiments measuring the Planck constant are shown in figure 1. The value from the most recent evaluation of the fundamental constants is shown as CODATA 2010 [10] together with the points that were most influential in determining it. Three of these are indicated as 'WB' and were from watt-balance experiments; the fourth was from the International Avogadro Coordination (IAC) based on the XRCD method. As can be seen in figure 1, at the time of publication of the CODATA 2010 evaluation of the fundamental constants there was a significant discrepancy between the available experimental values for the Planck

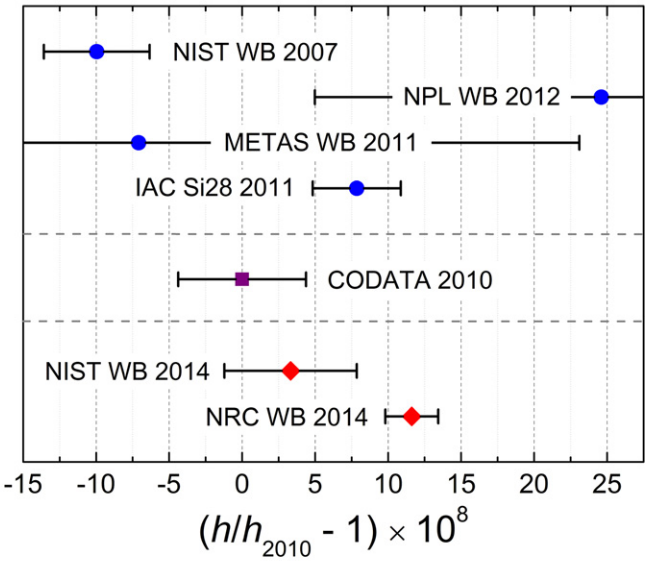

Figure 1. Results of determinations of the Planck constant expressed with respect to the 2010 CODATA value (h_{2010}). The points with filled blue circles were taken into account by CODATA in 2010 and those indicated by filled red diamonds are more recent. The bars indicate standard uncertainties.

constant. For example, the discrepancy between the NIST watt balance and the IAC value based on the XRCD method is 3.8 times the standard uncertainty of the difference. This required the CODATA group to use a statistical procedure to increase the uncertainty of their estimate of the Planck constant beyond that inferred from the estimated uncertainties of the individual experimental data.

After the CODATA 2010 results were published, the NPL watt balance [11] was transferred to the NRC where it was rebuilt. A preliminary result was published from the rebuilt apparatus in 2012 [12] (not plotted in figure 1) that confirmed the NPL value and also confirmed the discrepancy with respect to the NIST result. The attention drawn to the discrepancy between these two results prompted some specific investigations to identify the source. For example, a comparison of gravimeters in North America confirmed that absolute gravimetry could not be the source of the discrepancy [13]. Subsequently, other institutes have published theoretical studies of second-order effects that might be present in some watt balances, and largely ruled them out as sources of error at the level of 50 parts in 10^8 [14, 15]. Also strategies for dealing with gravitational corrections for watt balance experiments have been published [16].

Following the CODATA 2010 evaluation, NIST launched an extensive review of the operation of the NIST-3 watt balance. This included modifications to the knife-edge on the balance beam and upgrading the programmable Josephson voltage standard system. NIST also sent K85, one of their platinum–iridium kilogram prototypes, to the BIPM for recalibration. The result of this review and evaluation of the NIST-3 watt balance was a revised value of the Planck constant published in 2014 [17] with a standard uncertainty of 4.5 parts in 10^8. A full description of the result from the NRC was published in the same month [18] with a standard uncertainty of 1.8 parts in 10^8 uncertainty which is sufficient to contribute to meeting condition 2 laid down by the CCM. These two data are plotted below the CODATA 2010 point in figure 1.

In addition to the determinations of the Planck constant cited above, there are a number of other watt balance experiments [19–22] and also a joule balance [23] that plan to provide independent values of the Planck constant.

Meanwhile, the reformed International Avogadro Coordination project is extremely active in refining the application of the x-ray crystal density (XRCD) method to isotopically enriched ^{28}Si crystals. A summary of work-in-progress is given in [24]. One objective has been to ensure that each of the most important measurands will be measured by more than one institute. For example, the PTB is developing the capability to confirm lattice-constant measurements, which are presently made only at INRIM, while INRIM is working to quantify the impurity concentrations of all chemical elements in the silicon crystals. The PTB is also carrying out additional work aimed at improving the sphericity of the silicon crystals and to characterize their surfaces more accurately.

As highlighted by CODATA [10], previous results from the XRCD method have been limited by uncertainties in the determination of the relative molar mass of the crystals which was only carried out by one institute. This is now the subject of research at five institutes (PTB, NRC, NIST, NMIJ and NIM) which will ensure that different mass spectrometric and chemical preparation methods are applied (e.g. [12]). The overall goal is to reach a relative standard uncertainty of 1.5×10^{-8} in the realization of the new kilogram definition. This collaborative approach to the use of the XRCD method offers the prospect of a value with an uncertainty that is independent of the watt balances, hence meeting both conditions 1 and 2 laid down by the CCM.

2.3. The BIPM ensemble of reference mass standards

In 2011, the CGPM encouraged the BIPM '*to develop a pool of reference standards to facilitate the dissemination of the unit of mass when redefined*' [6]. This was reflected in condition 3 of the CCM resolution cited above.

The rationale for the system [22, 25] is that a combination of mass pieces made from three different materials (platinum/iridium, stainless steel and single-crystal silicon) each with a mass of 1 kg maintained in different gaseous environments (air, nitrogen, argon and *in vacuo*) should provide sufficient data over the long term to identify mass loss effects that might occur in any particular combination of material and gas. The system has a fully automated storage network for the standards with three independent gas circuits (argon, nitrogen and vacuum) and on-line monitoring for possible contamination. In addition to the one kilogram standard masses, two 'surface artefacts' in Pt–Ir and stainless steel have been characterized. Compared to standards of the same material, the increased surface area of these artefacts makes them more sensitive to contamination. The task of tracking the mass of the mass pieces as a function of their material and storage conditions is now underway.

Although not directly related to the objective of redefining the kilogram, it should be noted that there has been an efflorescence of significant new results on the stability of reference mass standards published recently. In particular, the effect of mercury contamination on the mass of platinum–iridium mass standards has received renewed attention, as has the general topic of improved methods of removing carbonaceous surface contamination from artefacts [26–33].

2.4. Development and validation of a mise en pratique

The essential information about how each of the base units should be realized is summarized in a document known as a *mise en pratique*. The need to develop a new one for the kilogram and to validate its practical implementation is reflected in condition 4 of the CCM resolution cited above. Consultation on a draft has begun. It starts from the proposed new definition and outlines how the definition can be realized in practice by means of a watt balance or by the XRCD method [34]. Whilst focussing on these two methods, the *mise en pratique* leaves open the possibility that newer technologies such as the joule balance might be shown to work at a useful level in the future. The dissemination of the unit is also discussed, including the need for some 'quality assurance' by means of an international comparison amongst primary realizations of the kilogram and with the International Prototype of the Kilogram (IPK) itself. This will confirm that apparatus currently in use to measure the Planck constant can be operated effectively in a mode that realizes the kilogram.

At the time of writing, the *mise en pratique* of the new definition of the kilogram is in draft form. Comments have been solicited from those user communities that will be most directly affected. It is expected that the *mise en pratique* will be approved by the CCM at its meeting in February 2015, and updated if necessary immediately prior to the redefinition of the kilogram. Additionally, a special issue of *Metrologia* will be devoted to detailed technical aspects of the *mise en pratique*.

2.5. Roadmap

The CCM Roadmap was developed during 2013 and was presented by the CCM President to the CIPM in October 2013. It is available on the CCM webpage [35] and is reproduced in the supplementary material available from stacks.iop.org/Met/51/R21/mmedia. It is based on likely dates for the completion of the different pieces of technical work described here. These include the planned completion of the campaign of measurements by the BIPM on the International Prototype of the Kilogram (IPK) by the middle of 2015 which is required to meet condition 3. If the dates proposed in the CCM roadmap can be met, then the work of providing traceability to users from the ensemble of reference mass standards at the BIPM, underpinned by the results of the campaign of measurements with the IPK together with the comparisons of primary realizations of the kilogram should be in place in 2016. The roadmap suggests that a period of about 18 months would be available prior to this during which information on traceability to the new definition could be provided to user communities. This period would also provide time for the final approval of the details of the definitions by the CIPM and each of the affected Consultative Committees. Hence, the roadmap shows that the conditions laid down by the CCM to ensure that, after the redefinition, 1 kg can be realized and disseminated with a standard uncertainty not larger than 20 μg could be met in time for a meeting of the CGPM in autumn 2018.

3. The ampere

The ampere will remain the base unit for electricity after the proposed revision, and, as at present, the dissemination of the electrical units will continue to be based on standards for resistance and voltage using the quantum Hall and Josephson effects. However, there will no longer be a need for the conventional values of the Josephson and von Klitzing constants ($K_{\mathrm{J}\text{-}90}$ and $R_{\mathrm{K}\text{-}90}$) [36]. Exact numerical values of K_J and R_K will be derived from the defined numerical values of the constants e and h (using the relationships $K_\mathrm{J} = 2e/h$ and $R_\mathrm{K} = h/e^2$) thus making the quantum realizations of the electrical units fully consistent with the SI. The details of this implementation have been laid out in a draft *mise en pratique* for the electrical units, which has been available since 2009 [37].

A significant issue remaining to be resolved is that there will be a step change in the electrical units realized from quantum standards when the numerical values $K_{\mathrm{J}\text{-}90}$ and $R_{\mathrm{K}\text{-}90}$ that have been in use for more than 20 years are abrogated in favour of the new fixed numerical values. At present, the value of R_K derived from CODATA adjustments is dominated by experiments that determine the fine-structure constant α, and lead to a value of R_K via the relationship $h/e^2 = \mu_0 c/2\alpha$. The value of $R_{\mathrm{K}\text{-}90}$ was chosen giving a little more weight to the direct electrical measurements of R_K [36]. Since then, experimental determinations of α have improved continuously in both precision and variety. No improved direct electrical measurement of R_K has been published recently, although several new calculable capacitor experiments are in progress [38–40]. The relative offset of the best estimate of R_K from the value of $R_{\mathrm{K}\text{-}90}$ has been constant at around 2×10^{-8} over recent CODATA adjustments, and is now known to better than 1×10^{-9}. Whilst quantum Hall systems can be compared to the level of 1×10^{-9}, calibrations of travelling resistance standards rarely have relative uncertainties of less than 2×10^{-8} due to the limitations of the standards themselves [41]. Consequently, a step change of 0.02 $\mu\Omega\,\Omega^{-1}$ in assigned resistor values will probably only be seen on the top-level working standards maintained by NMIs.

The situation for K_J is less clear. Watt balance and XRCD experiments are often compared through the corresponding values of h given by the individual experiments. To see the effect on K_J, we can use the relationship

$$K_\mathrm{J} = \frac{2}{\sqrt{h R_\mathrm{K}}},$$

where the uncertainty in R_K is taken to be negligible. The values of K_J from successive CODATA adjustments are plotted in figure 2, along with those calculated from individual values of h published since CODATA 2010. Data published since CODATA 2010 shown in figure 1 are also shown in figure 2. The values are plotted as relative differences from the value $K_{\mathrm{J}\text{-}90}$, in parts in 10^8, with standard uncertainties.

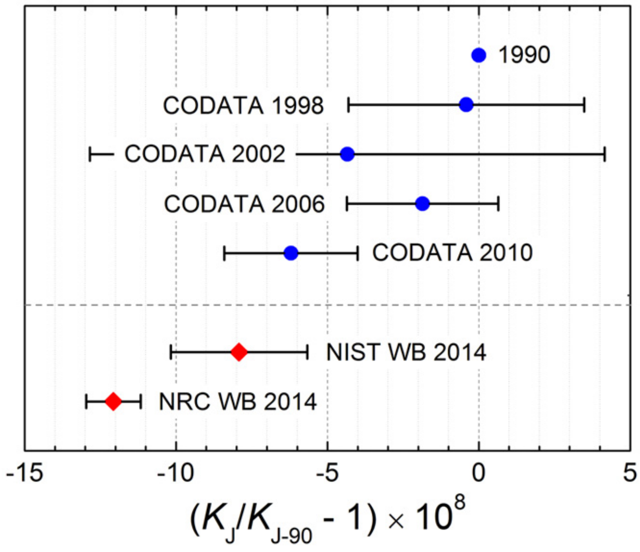

Figure 2. Values of the Josephson constant in terms of the conventional 1990 value ($K_{J\text{-}90}$) derived from different experimental determinations of the Planck constant. The points with filled blue circles are the results of CODATA determinations of the fundamental constants. Those indicated by filled red diamonds are values of the Josephson constant determined from the results of particular determinations of the Planck constant. The bars indicate standard uncertainties.

The convergence of recent results suggests a value of K_J approximately 11 parts in 10^8 below the 1990 value, although the picture is not yet finalized, and continues to change with updated results.

Calibration and Measurement Capabilities (CMCs) of laboratories offering calibrations of Zener voltage standards directly against Josephson systems can be as low as $0.02\,\mu\text{V}\,\text{V}^{-1}$, so a change of $0.1\,\mu\text{V}\,\text{V}^{-1}$ must be carefully considered. On-site comparisons of Josephson systems are routinely used to verify accuracy to parts in 10^{10} [41] or better. A step change of $0.1\,\mu\text{V}\,\text{V}^{-1}$ will be visible on some secondary standards, including those in top-level industrial laboratories [42], but will not be disruptive to the majority of users. There will be no need for the type of large scale programme of education and recalibration that was undertaken on the introduction of the 1990 values [43].

Whilst the relations $K_J = 2e/h$ and $R_K = h/e^2$ do not feature in the revised SI unit definitions, they are taken as exact in the most important practical realizations of the electrical units. There are on-going efforts to test these relations experimentally (via single electron transport and 'metrological triangle' experiments [44], new material dependence tests of the QHR using graphene [45] and several new calculable capacitor experiments [38–40]). A meta-analysis of all available data for possible corrections to K_J and R_K is also included in CODATA adjustments [10]. Some recent theoretical work predicts corrections at the 10^{-20} level [47], but otherwise there are no experimental or theoretical indications of corrections that would affect the realizations of electrical units. Work on these types of test will continue to be important both leading up to and after redefinition. However, if any corrections to the quantum Hall and Josephson relations are found, they could be incorporated into the *mise en pratique*, with no effect on the ampere definition.

In summary, the magnitudes of the volt and ohm units as commonly disseminated will change. This may be visible as a step change in the values assigned to secondary standards calibrated against the quantum references. Whilst this is not consistent with the general approach preferred when updating the SI, it is unavoidable given the established use of the conventional 1990 values. However, the changes are small enough that with good planning and communication the effects on the world measurement system will be minimal. At the meeting of the CCEM in 2013, a task group was established to manage the impact of the changes by preparing a communication campaign addressing: NMIs, industrial calibration laboratories that use Josephson systems and top-level users of voltage and resistance calibrations. This task group has started its work. No other barriers to adoption in electricity following the timescale of the CCM roadmap are foreseen. The benefit of a fully consistent SI that will serve for many years to come will outweigh any short term inconvenience of the change to electrical users.

4. The kelvin

The proposed change to the definition of the kelvin involves an important change in the principle underlying the kelvin, but should not have any practical impact on users of traceable temperature measurements from the NMIs. It will enable primary thermometric methods to realize the kelvin directly with respect to the Boltzmann constant, eliminating the necessity for traceability to the temperature of the water triple point (0.01 °C). However, there are relatively few primary thermometric methods in use and they are difficult to deploy and generally not as precise or reproducible as practical thermometers. Hence the reasoning that led to the introduction of the International Temperature Scales (ITS) will remain valid after the adoption of a new definition of the kelvin. The International Temperature Scales have been developed to give results that are in close agreement with the thermodynamic temperature, but which can be derived from a series of temperature fixed points that are given conventional values approximating the corresponding thermodynamic temperatures, and interpolating functions between these points. Deviations between the ITS and the corresponding thermodynamic temperatures are analysed and made available to the user community by the CCT.

It is therefore not expected that ITS-90 will be replaced as the source of traceability to the SI for the vast majority of temperature measurements, but the new definition will open the possibility that it can be improved as the development of primary thermometric methods progresses. There will also be a new route to direct traceability to the SI in those temperature ranges (for example, below 20 K, or above 1300 K) where the primary thermometric methods can offer lower uncertainties than the ITS-90.

The Consultative Committee for Thermometry (CCT) has considered the proposed definition and has emphasized the importance of the numerical value for the Boltzmann constant

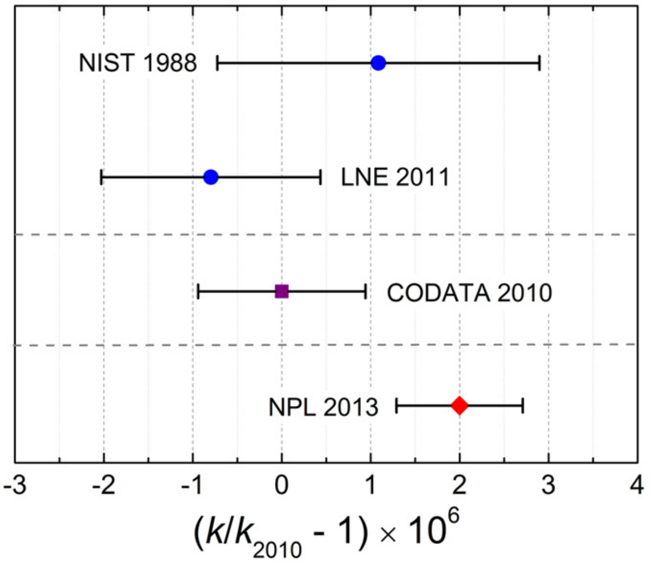

Figure 3. Results of determinations of the Boltzmann constant expressed with respect to the 2010 CODATA value (k_{2010}). The points with filled blue circles were taken into account by CODATA in 2010 and the point indicated by a filled red diamond is more recent. The bars indicate standard uncertainties.

at the time of the redefinition. It has recommended that the following criterion be fulfilled prior to redefinition of the kelvin:

> *'that before proceeding with the redefinition of the kelvin a relative standard uncertainty of the value of k of order one part in 10^6 be obtained, based on measurements applying different methods of primary thermometry'*
>
> (CCT Recommendation T2 from the 25th meeting (2010))

Methods that can contribute to the determination of the Boltzmann constant [48] could include dielectric gas thermometry, refractive index gas thermometry, Johnson noise thermometry and Doppler broadening thermometry. The most accurate published results to date come from the method of acoustic gas thermometry [49] and are plotted in figure 3. The latest data included in the CODATA 2010 evaluation of the fundamental constants were from LNE [50]. More recently NPL have published a result [51] with a relative uncertainty of 0.71 parts in 10^6 for the Boltzmann constant also using this method. The result published by NPL in 2013 shows that acoustic thermometry can meet the criterion laid done by the CCT, although, as can be seen from figure 3, it differs from the current CODATA value by 2 parts in 10^6.

Further results will need to be published before the CODATA value itself meets the criterion. However, the high level of activity in the field as indicated by recent publications [52–55] suggests that this is likely to be achieved.

5. The mole

The general state of the art of chemical measurements is such that no change at the level of uncertainty being considered with the introduction of the definition of the mole would be relevant [56, 57]. Indeed, the additional uncertainty added to the molar masses of the elements is of the same order of magnitude as the binding energy of solids which is almost universally ignored in practical chemistry [58].

The CCQM is active in promoting a debate about the proposed definition and ensuring that it is widely understood. Nevertheless there has been a great deal of discussion about the principle of replacing the present definition which is expressed in terms of the amount of substance of a mass of a pure chemical with a definition in terms of a fixed number of entities. The intensity of this debate may be attributable to two misunderstandings about the proposed definition. Firstly, that it would in any way affect the historic and practical importance of measurements made in terms of mass for practical chemistry, or, secondly that it would change any aspect of the way the conventional scale of atomic weights is used. It has also re-ignited a debate about the meaning of the quantity 'amount of substance' [56, 59].

Many views have been expressed in print. We therefore cite one example of each of the opposing views published by academics from outside the 'NMI community'; one published in *Chemistry World* provides a strong endorsement of the 'new SI' [60], whilst a second, in *Chemistry International*, argues for retaining the present definition of the mole amidst the other elements of the 'new SI' [61].

6. Summary

We have reviewed the progress being made towards the adoption of new definitions for four of the base units of the SI. The work involved is largely technical, but also involves some important coordination and communication tasks. As we have reported, good progress is being made with the experimental work in all areas, and particularly in reconciling the discrepancy observed in recent determinations of the Planck constant.

The four Consultative Committees involved (CCM, CCEM, CCT and CCQM) have all considered the issues in detail.

The CCM laid down technical criteria in 2011 in order to ensure that, after the redefinition, 1 kg can be realized and disseminated with a standard uncertainty not larger than 20 µg. As we have reported here, some key experimental results have been reported during 2014. The other tasks specified by the CCM are either being planned or are underway. These include: the development and validation of a *mise en pratique* for the kilogram, the demonstration of the comparability of primary realizations of the kilogram through a direct comparison and the completion of a campaign of measurements by the BIPM to renew traceability directly to the International Prototype of the Kilogram. When this work is complete, users will be able to benefit from a unit of mass defined in terms if an invariant of nature, rather than with respect to an artefact.

The CCT has also laid down a technical criterion that the Boltzmann constant be determined with a relative standard uncertainty of one part in 10^6. This appears to be close to being met.

The work of the CCEM and CCQM is mainly concerned with communication and is underway. In the case of the CCQM there is now an active debate about the underlying principles, although it is widely recognized that there are no implications at a practical level. In the CCEM, there has been consensus on the underlying principles for some years, and the details of implementation are now being worked out.

In summary, we have shown that very good progress is being made in all areas with the technical work, and plans are in place for the necessary work of coordination and communication. The evidence presented here confirms an emerging consensus that the conditions laid down by the relevant Consultative Committees for the changes to the SI to be implemented should be fulfilled by 2018.

Appendix. Summary of Resolution 1 passed at the 22nd CGPM (2011) 'On the possible future revision of the International System of Units, the SI'

The Resolution begins by setting out the principal benefits of defining units of measurement in terms of fundamental physical constants or the properties of atoms. The redefinition of the metre in terms of an exact value for the speed of light in vacuum (coupled with the definition of the second based on a property of the caesium 133 atom) is given as a prominent example of what will be recommended for other SI base units. A list of major benefits of the proposed redefinitions of the kilogram, ampere, kelvin and mole then follows:

Technology is sufficiently advanced to relate the mass of the international prototype of the *kilogram* (i.e. the mass of a unique artefact dating from the 19th century) to the Planck constant, a fundamental constant of physics, through methods that include 'watt balances' and 'measurements of the mass of a silicon atom.' This opens the way for a redefinition of the kilogram.

Once the kilogram is redefined in terms of a fixed numerical value for Planck constant, redefining the *ampere* by fixing an exact numerical value for the elementary charge, e, will allow SI uncertainties in electrical metrology to be significantly reduced. This is because the Josephson constant K_J and the von Klitzing constant R_K, essential to contemporary electrical metrology, will both have fixed numerical values.

Technology now exists to redefine the *kelvin* so that it is linked to an exact numerical value of the Boltzmann constant, k. A consideration of Resolution 1 is that the definition of the kelvin is presently based on an intrinsic property of water (the temperature at which liquid, vapour and solid coexist in equilibrium, known as the triple point), and that the temperature of the triple point depends on the purity and isotopic composition of the water.

It is possible to redefine the *mole* in terms of an exact numerical value of the Avogadro constant, N_A. Thus the mole would no longer depend on the definition of the unit of mass, emphasizing the different character of the quantities mass and amount of substance.

It is noted that, by defining the above units in terms of a set of constants, the uncertainties of many fundamental constants and conversion factors closely related to the chosen set would become zero or greatly reduced.

Finally, the introductory remarks of Resolution 1 note that, although all the conditions adopted by the CGPM in Resolution 12 (2007) are not yet fulfilled, it is nevertheless possible to present a detailed description of what is likely to be proposed by the CIPM for adoption by a future meeting of the CGPM.

The CGPM then 'takes note' of the CIPM's intention to propose a revision of the SI based on fixing the numerical values of seven quantities: the ground state hyperfine splitting frequency of the caesium atom $\Delta\nu(^{133}\mathrm{Cs})_\mathrm{hfs}$ (unit: s^{-1}), the speed of light in vacuum c (unit: $\mathrm{m\,s}^{-1}$), the Planck constant h (unit: $\mathrm{kg\,m^2\,s^{-1}}$), the elementary charge e (unit: A s), the Boltzmann constant k (unit: $\mathrm{kg\,m^2\,s^{-2}\,K^{-1}}$), the Avogadro constant N_A (unit: mol^{-1}), the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_cd (unit: $\mathrm{cd\,sr\,kg^{-1}\,m^{-2}\,s^{-3}}$). The SI units of these quantities and their exact numerical values are given to the extent possible in the Resolution. For three of these quantities there is no change from the present SI, since $\Delta\nu(^{133}\mathrm{Cs})_\mathrm{hfs}$, c and K_cd already have exact numerical values, which are restated in the Resolution. However, since work is underway to determine more accurate values of h, e, k and N_A, final numerical values cannot yet be given for these, the last digits being shown with the symbol 'X'.

The CGPM makes it clear that the kilogram, ampere, kelvin and mole will continue to be the units of mass, electrical current, thermodynamic temperature and amount of substance respectively but their definitions would be based on the fixed numerical values of the seven quantities. (For example: The kilogram will be defined by a fixed numerical value of the Planck constant, h. However the unit of h is $\mathrm{kg\,m^2\,s^{-1}}$, and thus the fixed numerical values of $\Delta\nu(^{133}\mathrm{Cs})_\mathrm{hfs}$ and c are also needed. This is similar to the present definition of the metre. Since 1983, the metre has been defined in terms of fixed numerical value for c. However, the unit of c is $\mathrm{m\ s^{-1}}$ and thus the fixed numerical value of $\Delta\nu(^{133}\mathrm{Cs})_\mathrm{hfs}$ is also needed. Not all seven quantities are needed to derive each of the seven base units, but all needed quantities are found within the set of seven.)

The Resolution refers to unit definitions based on fixed numerical values for a set of seven quantities as 'definitions… of the explicit-constant type, that is, a definition in which the unit is defined indirectly by specifying explicitly an exact value for a well-recognized fundamental constant' or 'invariant of nature'. The CGPM believes that the new SI would be more readily comprehensible, if the definitions of all base units had similar wording and instructs the CIPM to propose such wording, examples of which are given in the Resolution. Therefore the wording of the definitions of the second, metre and candela will be reformulated in the explicit-constant style.

The present definitions of all seven base units will be abrogated on the day the new definitions, written in the explicit-constant formulation, take effect. In addition, the CIPM is instructed to abrogate its recommendation, made at the request of the 18th meeting of the CGPM (1987), to adopt conventional values for the Josephson and von Klitzing constants to be used for electrical metrology.

The Resolution notes that even the present definitions of the kilogram, ampere, kelvin and mole can be formulated in the explicit-constant way, and this is useful to see what will happen on the day the present definitions of these base units are abrogated and the new definitions, based on a different set of four quantities, takes effect. Viewed in this way:

> The kilogram is presently defined by giving a fixed numerical value of 1 to the mass, m_{IPK} of the international prototype of the kilogram, when expressed in the unit kg.
>
> $$m_{\mathrm{IPK}} = 1\,\mathrm{kg}.$$
>
> The ampere is presently defined by giving a fixed value of $4\pi \times 10^{-7}$ to the magnetic constant (permeability of vacuum), μ_0, when expressed in the unit $\mathrm{kg\,m\,s^{-2}\,A^{-2}}$.
>
> $$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{kg\,m\,s^{-2}\,A^{-2}}.$$
>
> The kelvin is presently defined by giving a fixed numerical value of 273.16 to the temperature of the triple point of water, T_{TPW}, when expressed in the unit K.
>
> $$T_{\mathrm{TPW}} = 273.16\,\mathrm{K}.$$
>
> The mole is presently defined by giving a fixed value of 0.012 to the molar mass of carbon-12, $M(^{12}\mathrm{C})$, when expressed in the unit $\mathrm{kg\,mol^{-1}}$.
>
> $$M(^{12}\mathrm{C}) = 0.012\,\mathrm{kg\,mol^{-1}}.$$

All this will change when the new definitions based on fixed values for h, e, k and N_{A} take effect. The CGPM notes that on that date the following continuity conditions will be imposed:

- 'the mass of the international prototype of the kilogram m_{IPK} will be 1 kg but with a relative uncertainty equal to that of the recommended value of h just before redefinition and that subsequently its value will be determined experimentally,
- that the magnetic constant (permeability of vacuum) μ_0 will be $4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$ but with a relative uncertainty equal to that of the recommended value of the fine-structure constant α and that subsequently its value will be determined experimentally,
- that the thermodynamic temperature of the triple point of water T_{TPW} will be 273.16 K but with a relative uncertainty equal to that of the recommended value of k just before redefinition and that subsequently its value will be determined experimentally,
- that the molar mass of carbon-12 $M(^{12}\mathrm{C})$ will be $0.012\,\mathrm{kg\,mol^{-1}}$ but with a relative uncertainty equal to that of the recommended value of $N_{\mathrm{A}}h$ just before redefinition and that subsequently its value will be determined experimentally.'

(Notes: the unit $\mathrm{H\,m^{-1}}$ is identical to $\mathrm{kg\,m\,s^{-2}\,A^{-2}}$; at present, the relative uncertainty of α, given in CODATA 2010, is 3.2×10^{-10} and that of $N_A h$ is 7.0×10^{-10}.)

The CGPM then encourages NMIs, the BIPM and academic institutions to continue efforts having relevance to the redefinitions of the kilogram, ampere, kelvin and mole, and to publish their results so that the CODATA Task Group on Fundamental Constants can take account of new work in a timely way. The BIPM is also encouraged to continue work to provide traceability of its mass standards to the mass of the international prototype, as well as to develop a pool of reference standards (sometimes referred to in subsequent documents as the BIPM ensemble of reference mass standards) in order to facilitate dissemination of the unit of mass after redefinition of the kilogram.

The CGPM invites CODATA to continue its relevant work, making its results known to the CIPM through the Consultative Committee for Units (CCU). The CODATA recommendations for the values and uncertainties of h, e, k and N_{A} are to be used in the continuity relations described above.

The CGPM invites the CIPM to propose the revision of the SI as soon as the recommendations of the Resolution 12 of the 23rd meeting of the General Conference are fulfilled, in particular the preparation of *mises en pratique* for the kilogram, ampere, kelvin and mole. (note that explicit-constant formulation of the definitions does not hint at how the definition can be realized in practice, making the *mises en pratique* an important complement to the definitions.)

Finally, the CGPM issues two invitations:

To the CIPM, to continue its work to improve formulations of the new definitions 'consistent with scientific rigour and clarity', making them as far as possible more easily understood by general users;

To the CIPM and its Consultative Committees, the BIPM, the International Organization of Legal Metrology and the National Metrology Institutes, 'to initiate awareness campaigns aimed at alerting user communities and the general public to the intention to redefine various units of the SI and to encourage consideration of the practical, technical, and legislative implications of such definitions, so that comments and contributions can be solicited from the wider scientific and user communities.'

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