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Proposed Changes to the SI: A Glimpse into the Future

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Abstract Recent proposals to fundamentally change the international system of units (SI) have generated considerable debate and are now being seriously considered by international committees. These proposals have a common theme—to exactly fix the values of a set of fundamental physical constants and to then base the SI units with respect to these invariant constants. This article will summarize the proposed changes and outline how national standards institutes would typically realize the SI units within the new system. The expected benefits and drawbacks of these changes will be summarized as they pertain to measurement science and fundamental constants. The official positions of different metrological communities as well as possible time schedules and the approval process that must be followed to implement such changes to the SI will be outlined.

Keywords Ampere · Avogadro constant · Boltzmann constant · Fundamental constants · Kelvin · Kilogram · Planck constant · SI · Units

1 Introduction

The international system of units, known simply as the SI, is used throughout the world. It may seem that the SI is a static, unchanging system. Indeed, this is a perception that is actively promoted because it instils confidence in the reliability of all measurements that might otherwise be in jeopardy if the underlying units were not stable and well understood. However, changes to the SI are more common than many realize, and because most changes have such a small numerical effect they tend to go unnoticed

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by the public, and even by many metrologists. In most cases, these changes occur on a time scale of decades, and many are subtle refinements to existing definitions or concepts meant to improve the reliability and realization of units. For example, the kelvin definition now specifies the isotopic content of the water whose triple-point temperature defines the unit, while the second, realized through the hyperfine splitting of ^{133}Cs, now has a specification regarding the thermal radiation of the caesium atom's environment. Usually these changes are so small that only a fraction of the world's national measurement institutes (NMIs) considers them a disruption to their measurements.

Fundamental changes to the underlying concepts of the SI are even less frequent. Though they may cause a minimal numerical perturbation, they pose a greater challenge because of the need to re-educate both metrologists and the general public. We are now facing just such a fundamental change to the SI, and the question is not "if" the change will occur but rather "when" and "how" such a change will occur.

2 The Administrative Structure of the SI

Before examining the details and options of a major change in the SI, it is useful to review some aspects of the history and structure of the SI. The SI formally began with the 1875 Convention of the Meter, originally signed by 17 countries and now consisting of 51 signatories. The treaty established the General Conference on Weights and Measures (CGPM, the acronym is derived from the French term for this committee), a diplomatic body of representatives of each of the signatories that meets every four years and oversees and ratifies any changes or extensions to the SI.

The International Committee for Weights and Measures (CIPM) is a committee of eighteen individually appointed scientists, which meets annually, makes recommendations to the CGPM, and supervises the International Bureau of Weights and Measures (BIPM). The BIPM maintains metrological laboratories and artifacts and coordinates many of the international activities between the national measurement institutes (NMI) of member countries.

While the CIPM can be thought of as the executive administration of the SI, the very diverse nature of the technical issues has resulted in the creation of 10 consultative committees to advise the CIPM. The consultative committees are comprised primarily of technical experts from NMIs with extensive activities in the particular subjects. There are 10 consultative committees:

CCAUV—Consultative Committee for Acoustics, Ultrasound and Vibration
CCEM—Consultative Committee for Electricity and Magnetism
CCL—Consultative Committee for Length
CCM—Consultative Committee for Mass and Related Quantities
CCPR—Consultative Committee for Photometry and Radiometry
CCQM—Consultative Committee for Amount of Substance—Metrology in Chemistry
CCRI—Consultative Committee for Ionizing Radiation
CCT—Consultative Committee for Thermometry
CCTF—Consultative Committee for Time and Frequency

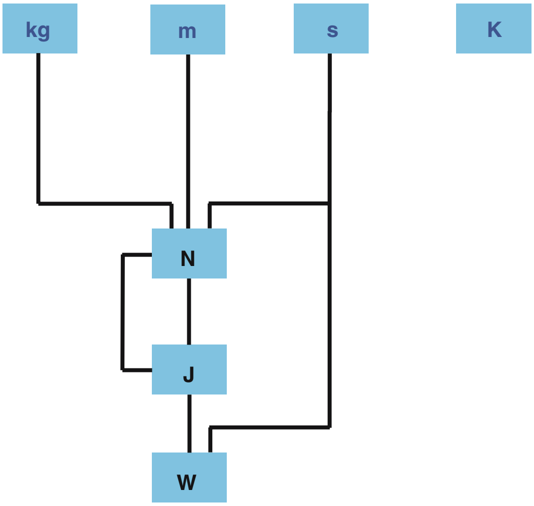

Fig. 1 Original SI consisting of four base units. Black lines indicate common relationships with some derived units

CCU—Consultative Committee for Units

3 The Original SI

Shortly after the original signing of the Convention of the Meter in 1875, four base units were identified, all based on physical artifacts. The approximate sizes of the units were chosen to maintain continuity with previous unit systems. The second was related to the rotation of the earth about its axis and determined astronomically. The kelvin was related to a temperature scale based on fixed points of water.

The size of the meter was related to the circumference of the earth (actually one ten-millionth of a quadrant of the Earth) while the kilogram was related to the mass of a cubic decimeter of water at maximum density. Due to the technical difficulty of precisely measuring the circumference of the earth and the mass of a decimeter of water, artifacts were fabricated that were best estimates of these quantities and had the advantage of being more stable and more easily measured than realizing the defining concepts. Subsequently, the mass of the kilogram artifact, a particular piece of platinum iridium called 'the prototype kilogram' or 'the grand K' (κ) and the length of the meter artifact, a single, precisely scribed metal bar, were adopted as the definition of those units. These defining mass and length artifacts were kept at the BIPM, just outside Paris, and compared to other national standards.

At that time, as shown in Fig. 1, the base units were independent of each other. All other SI units were called derived units and could be made of products or reciprocals of the base units. The base units served several purposes but perhaps the most important was to define the apex of any traceability chain. Traceability of any quantity measured within the SI requires a linked set of measurements or calibrations ending at one or more of the base units, which by their very definition have no intrinsic uncertainty.

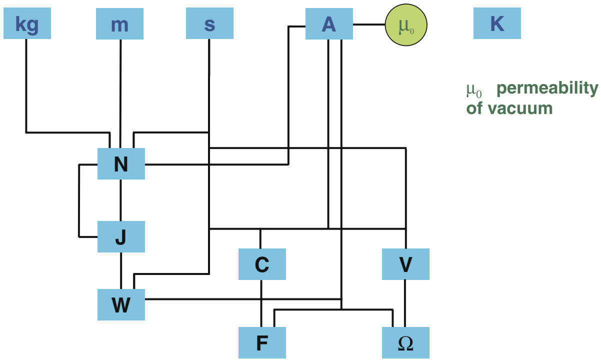

Fig. 2 Schematic of the SI after inclusion of the ampere showing the base units, some derived units, and the defining fundamental constant. Fundamental constants are denoted as circles; the base units are towards the top of the figure. Black lines indicate some of the common interrelationships between various units

4 The Present SI

In the intervening years, the SI has changed substantially. Electrical units were introduced in 1928, mirroring the MKSA system, but not formally ratified until 1948. The ampere was chosen as a base unit for the electrical quantities, but it was defined to ensure equivalence of electrical and mechanical force. This was the first of the base units to be clearly dependent on other base units, see Fig. 2. Also notable was the fixing of the value, without an uncertainty, of the fundamental constant, μ_o, the permeability of vacuum. Although it is not detailed explicitly within the definition, other official documentation of the time discusses the concept that the definition of the ampere in fact fixes μ_o to a value of $4\pi \times 10^{-7}$ N·A^{-2}.

Similarly, the unit of luminous intensity, the candela (cd), and the unit of amount of substance, the mole (mol) were introduced in the 1970s. The mole is related to the kg through another fundamental constant, the Avogadro constant (N_A) and the dalton (u), one twelfth of the mass of a ^{12}C atom, while the candela is directly related to energy, frequency, and dimensional properties.

In the 1980s the speed of light, c, was fixed without an uncertainty and incorporated into the SI within the redefinition of the meter, see Fig. 3. In this way, the artifact of the meter was abandoned and the unit is now maintained by optical interferometry using various sources of known frequency. The meter is now directly dependent on the speed of light and the unit of time.

Figure 3 illustrates the general structure of the SI as it is officially organized today. In this figure, the roles of the fundamental constants that pertain to the SI definitions are graphically illustrated. As well, the derived nature of the meter and the ampere are also shown. The base units are officially described as being 'independent by convention.' This is an awkward way of acknowledging that there is interdependence among some of the base units but, for the purposes of traceability, they are treated as if they were independent.

Unfortunately, the practical situation today is even more complicated, especially in regards to the electrical units of the SI. Three effects have been discovered since the

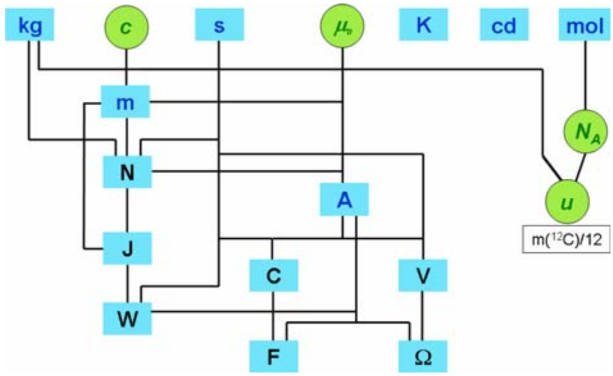

Fig. 3 Schematic of the SI including the candela and mole. Again, fundamental constants are denoted as green characters in circles, the base units are denoted as blue characters and are towards the top of the figure. Black lines indicate some of the common interrelationships between various units

definition of the ampere in 1948 that have had a significant impact on the SI. The first was the calculable capacitor that directly relates the farad to length and the permittivity of vacuum, ε_0, a fundamental constant. It should be noted that with the fixing of c and μ_0, ε_0 also becomes exactly known and fixed. The second was the Josephson effect that directly relates the voltage across a Josephson junction to the frequency of irradiation and the Josephson constant, $h/2e$, where h is the Planck constant and e is the elementary charge. The third was the quantum Hall effect that relates the resistance of a two-dimensional electron gas to the von Klitzing constant, h/e^2, where again h is the Planck constant and e is the elementary charge.

All three of these effects have been realized at a relative uncertainty of $\sim 10^{-8}$ and each has demonstrated no, or at least very small, dependencies on a large variety of influence parameters. Each of these effects have been realized by a significant number of NMIs with such good reproducibility and agreement that they have been used as reference standards superior to the units realized within the formally defined SI. These effects offer reproducibility that is often 10^2–10^3 times better than can be achieved directly from the formally defined SI, and tend to be cheaper and more easily realized around the world.

In 1990, the Josephson and quantum Hall effects were formally acknowledged as a practical means of realizing electrical units. The SI definitions remained unchanged but the effects along with conventional values of the Josephson and von Klitzing constants were accepted as practical ways for national metrology laboratories to realize consistent units of voltage and resistance. The conventional values of these constants were set with respect to the best values of h and e that were available in 1988 and were identified as K_{J-90} and R_{K-90}. This situation is schematically shown in Fig. 4, which also shows the relationship of the calculable capacitor to the present SI. It is important to note that K_{J-90} and R_{K-90} are not fundamental constants but merely good estimates of their values fixed in 1990.

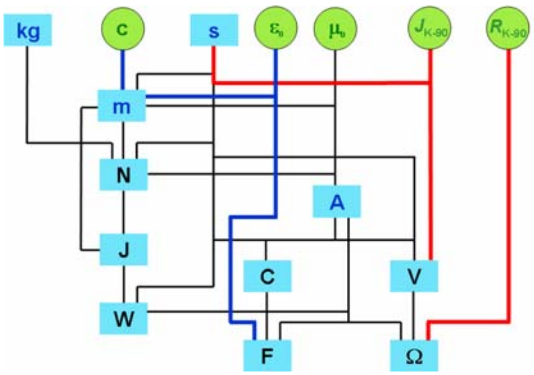

Fig. 4 Schematic of the present SI, but with emphasis added (heavy lines) to show the practical means to realize the farad, volt, and ohm using the calculable capacitor, Josephson volt and the quantum Hall resistance. Fundamental constants are denoted as green characters in circles; the base units are denoted as blue characters

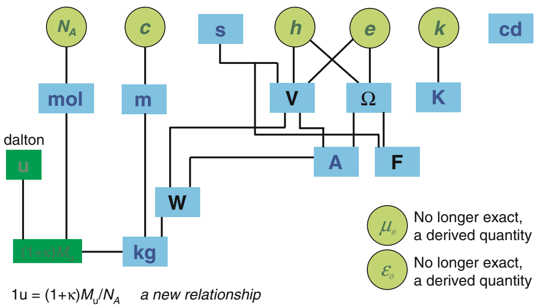

Fig. 5 A simplified schematic of one of the proposed methods of a revised SI based on a set of fixed fundamental constants. Fundamental constants are denoted as green characters in circles; the base units are denoted as blue characters

5 The Newly Proposed SI

Recent publications by Mills et al. [1,2] have recommended that a substantial change be made to the SI by formally introducing four fundamental constants with exactly defined values having no uncertainty. This would be similar to what was done in 1983 with the speed of light and the definition of the meter, but would affect the kilogram, ampere, kelvin, and mole. The four fundamental constants are the Planck constant h, the elementary charge e, the Boltzmann constant k, and the Avogadro constant N_A. This proposal is being seriously considered and initial recommendations concerning this subject have already been issued by the CODATA Task Group on Fundamental Constants and the Consultative Committees for Units, for Mass, for Thermometry, and for Electricity and Magnetism.

There are other ways to change the SI using different combinations of fundamental constants (see the references within [1] and [2] as examples). The purpose of this manuscript is neither to debate different proposals nor to champion a particular one but, instead, to discuss the issues related to such a change. I personally prefer the proposal of fixing h, e, k, and N_A and will use it to illustrate the further discussions, but I must stress that this particular proposal is not the only one being considered and the impacts are somewhat dependent on the particular proposal.

By assigning exact values to the Planck constant h, the elementary charge e, the Boltzmann constant k, and the Avogadro constant N_A and incorporating them directly

Table 1 Relative uncertainties ($\times 10^9$) of various fundamental constants, the mass of the prototype kilogram and the triple point of water in the present SI and in the proposed SI with h, e, k, N_A exactly fixed

Constant or Unit		Present SI (CODATA 2002)	Define h,e,k,N_A
Mass of κ	$m(\kappa)$	exact	170 (>20)
Planck constant	h	170	exact
Avogadro constant	N_A	170	exact
Elementary charge	e	85	exact
Mass of electron	m_e	170	1.4
Flux quantum	$2e/h$	85	exact
Mass of proton	m_p	170	1.4
Dalton (amu)	u	170	1.4
Von Klitzing constant	h/e^2	0.033	exact
Triple point of water	T_{TPW}	exact	915 (0.25 mK)

into the SI, both the definitions of the existing SI units and their inter-relationships will change. Figure 5 is a diagram of the structure of this newly proposed SI system. It must be noted that fixing both h and N_A would normally over-determine the set of equations that relate the fundamental constants and the SI units. However, in this proposed SI system, the constraint has been removed by introducing a variable molar mass that is slightly dependent on the microscopic entities.

In Fig. 5, the present base units continue to be indicated in dark blue. Black lines indicate the relationships among the common electrical units, as well as some mechanical units. The candela remains unchanged, still related to energy, frequency, and dimensional parameters, but because of its vastly larger uncertainty of realization it does not affect the other units. From this point on, I shall ignore further comment about the candela and focus on the other units and fundamental constants.

In this new system, most NMIs will maintain the second, candela, and meter as they did before. The volt and ohm will be derived using the Josephson and quantum Hall effects with the fixed values of h and e. The other electrical quantities will be derived from the volt and ohm. The present kilogram artifacts will probably be periodically assigned values from watt balance experiments and then used to derive the other mechanical quantities. The kelvin, the unit of thermodynamic temperature, will be redefined with respect to the Boltzmann constant ($E = kT$); however, use of ITS-90, the practical temperature scale, will continue without any changes needed at the present time. The unit of amount of substance, the mole, will be derived with respect to the Avogadro constant and related to the mass unit through an atomic mass, perhaps the dalton.

Table 1 lists the relative change in uncertainties of a number of fundamental constants and the following is a list of the advantages expected from such a change.

- Units with longer-term invariance than present artifact units.
- Lower uncertainties in many other fundamental constants [1–3].

- Many units, particularly electrical, will have lower uncertainties and better consistency with other units.
- The present volt and ohm representations will become legitimate SI units rather than only practical implementations.
- Closer ties will be established with the scientific and chemical communities by implementing units that are more easily related to their needs.
- Better utilization of the extreme scaling linearity available from Josephson devices, cryogenic current comparators and quantum Hall resistors.
- The new system should serve well into the future, until we change physics.
- No significant discontinuous changes are expected at implementation.

However, there are also some possible disadvantages as well.

- Prototype kilogram will have a relative uncertainty. ($\sim 0.02 \times 10^{-6}$)
- Triple point of water will have an uncertainty. (~ 0.25 mK)
- One mole of ^{12}C will not be exactly 12 g
- μ_0 and ε_0 will no longer be exact and will have uncertainties ($<10^{-8}$).
- The new definitions may not be as easily comprehended by the general public.
- Many textbooks and other publications will no longer be precisely correct.
- Effort is needed to explain the changes and educate the public.

It is obvious that the ultimate traceability of all units (except the second) in this proposal is to five fundamental constants. Some have proposed abandoning the concept of base units, but the need for an apex of traceability is still required. Fundamental constants cannot be base units because they are not themselves units, but perhaps a new term could be defined to replace the concept. Base units are also used for dimensional analysis. For this purpose, the original base units could continue to be used, but so could many other sets of units.

One issue about the base unit status of the kilogram and the ampere is readily apparent; neither is directly related to the defining fundamental constants. Further, the electrical community does not want any one of the volt, ohm, or ampere to be arbitrarily defined as a base unit for the purposes of traceability. This is because they could each be independently realized using either the Josephson effect, quantum Hall effect or single electron tunnelling and directly traceable to the defining fundamental constants and time. These concerns lead to a secondary issue about fixing the values of the fundamental constants. In the case of $\boldsymbol{c}$, it was defined within the definition of the meter. This does not seem to cause any problem even if one is achieving traceability to the speed of light by going though the meter. However, if $\boldsymbol{h}$ were defined only within the definition of the kilogram, then it might be assumed that traceability for the volt and ohm must be achieved through the kilogram. This is a situation that the electrical community wants to avoid. The simpler solution is to separately fix each of the five fundamental constants and, for the purposes of traceability, make them directly available to any SI unit.

6 What is the Status of the Proposed Change?

The following is a very brief and condensed summary of the stated position of various committees that are directly involved in this change. Much of this information is available from the BIPM website. Preliminary recommendations, in chronological order, have been made by the following committees.

The CCM recommended [4] to the CIPM that the κ should be replaced with some type of determination linked to a fundamental constant as soon as the technical results are comparable to those presently achieved in the reproducibility of κ. They also recommend not proceeding until the present discrepancy between watt balance results and Avogadro experiments are resolved.

The CODATA Task Group on Fundamental Constants has recommended to the CCU and the CIPM that the SI be restructured and based on a fixed set of fundamental constants.

The CCU has recommended to the CIPM that the consultative committees discuss the proposals within their committees and elsewhere and prepare recommendations for presentation back to the CIPM.

The CCT has recommended [5] that the value of the Boltzmann constant, k, be fixed and the kelvin be redefined accordingly.

The CCEM recommended [6] to the CIPM that the values of the Planck constant, h, and the elementary charge, e, be fixed and has proposed a new definition of the ampere.

The CCM, CCU, CODATA, and CIPM are all meeting later this year and should further refine their positions by then. The CGPM meets in November of 2007, and is expected to meet again in October of 2011. No formal proposal has been sent to the CGPM for the 2007 meeting concerning this change and, in fact, it would have to have been sent out almost a year in advance to be seriously considered. Since any change in the SI must be ratified by the CGPM, the most likely times for such a change to become official are January 1, 2012 or 2016.

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