The Units for Mass, Voltage, Resistance, and Electrical Current in the SI

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On May 20, World Metrology Day 2019, the international system of units (SI) underwent a momentous change. The philosophy behind the unit system was altered by replacing the former definitions that rely on seven base units with seven defining physical constants to be used as a basis for realizations of the units. Supported by results from decades of precise measurements, four new definitions and four fixed numerical values were assigned. In this article, we discuss the significance of this change for the unit of mass the kilogram and the electrical units ampere, volt, and ohm.

When the international system of units (SI) was revised to its current definition on May 20, 2019, the international press focused on the fact that the unit of mass was no longer defined via an artifact standard, the international prototype of the kilogram (IPK), but instead can be found from a fixed value assigned to the Planck constant *h*. As discussed in greater detail by R. Davis [1], the present-day SI is defined by fixed values of seven constants. Three constants, the hyperfine transition frequency of an isotope of cesium, the speed of light in vacuum, and a specified luminous efficacy were given exact values several decades before 2019. For the revision, an additional four constants were defined in the SI, namely the Planck constant, the Avogadro constant, the Boltzmann constant, and the elementary electrical charge. The last three of these replaced other constants, but the Planck constant replaced the mass of the IPK.

Undoubtedly, abrogating the IPK mass that was defined in 1889 to be one kilogram and then used for 140 years has historical significance and deserves attention. However, a more significant change, figuratively and literally, occurred to the ampere and its derived units, the volt and ohm. In electrical metrology, exact conventional values for these units were appended to the SI on Jan. 1, 1990, with symbols V_{90} and Ω_{90} indicating this status. With the 2019 redefinition, these units returned to the SI, with this reconciliation requiring a small step-change in each unit's magnitude. No change was necessary for the unit of mass, the kilogram. This is because the values chosen for the fundamental constants forming the basis of the SI were consistent with the former definition of the mass unit [2].

The Situation Leading up to the Revision of the SI

The core tenet of the metric system, whose beginnings can be traced back to before the French Revolution, was to build a system of units "for all times, for all people." While the metric system is a great success for the uniformity of our measurement units for science, technology, and commerce, the tenet "for all times, for all people" was not achieved until the recent revision of the SI. The unit of mass was given by the mass of the international prototype of the kilogram (IPK), a cylinder made from a platinum-iridium alloy and stored in a vault at the International Bureau for Weights and Measures (BIPM). Just to get to the vault, three keys are needed—not a situation that would allow all 7.5 billion humans access to the primary realization of the kilogram. Hence, this definition fails "for all people." But also, the first part of the phrase is questionable. While the mass of the IPK was set to be one kilogram by convention, it is difficult to see how it would be stable—which is what "for all times" means. It is part of the human experience to understand that there is no material object that does not change. Since the IPK is a material object, it is subject to change. Thus, only the number we humans assigned to it is unchanging.

If the mass of the IPK is defined (by convention), then any change in the IPK over time would cause the unit of mass to change. For this reason, the mass of the IPK was disseminated to copies about every 50 years (in 1889, 1946, and 1998). Data that could prove beyond a doubt that the IPK was changing from 1889 to 2019 is difficult to obtain. One would have to compare the kilogram to another stable mass or to a fundamental constant in nature. However, these experiments have only been perfected in the last few decades, not providing a long enough baseline to make a meaningful statement.

The best circumstantial evidence for a possible change in mass of the kilogram comes from the six official copies of the kilogram. The official copies are nominally identical to the IPK and are stored next to the kilogram and are used

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with the same frequency. Only four of the copies, labelled K1, 7, 8(41), and 32, were originally made before 1889. The top graph in Fig. 1 shows the results of measurements of the mass of these four copies with respect to the IPK. The graph indicates that all four official copies gained mass between 1946 and 1991. Interestingly the mass increase between 1991 and 2014 is negligible. The figure clearly indicates that stability at the time scales of centuries cannot be attained at the 0.01 mg level.

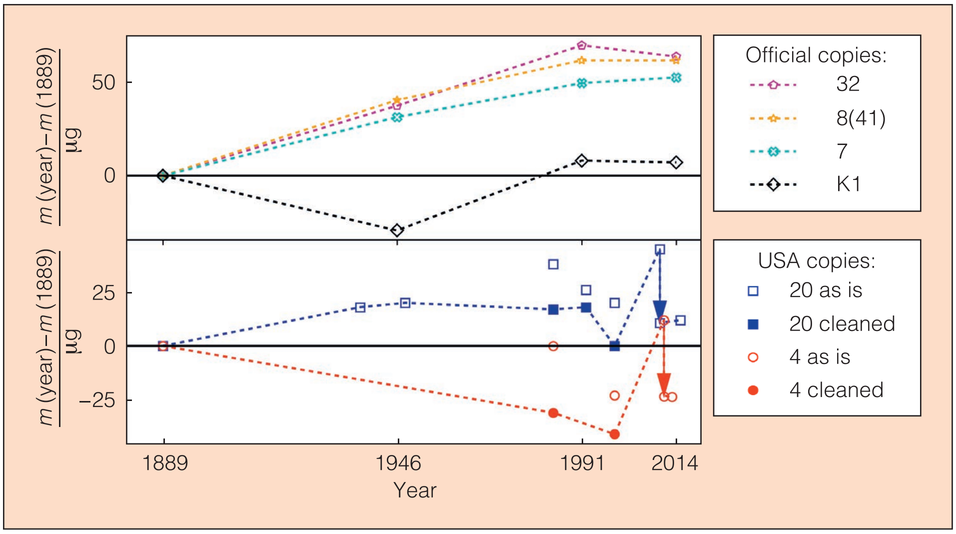

Fig. 1. Top: Mass values of four official copies of the kilogram kept at the BIPM as a function of time. Today, six official copies are kept together with the international prototype of the kilogram (IPK) in a vault. Two prototypes numbered 43 and 47 were made after 1889 and may exhibit different surface properties and therefore different mass drift. Hence, these data are not included in the plot. From 1946 to 1991, all the four copies gained mass. From 1991 to 2014, the masses of the copies have been remarkably stable. All measurements were performed relative to the IPK. Bottom: Mass values of the two original copies assigned to the United States of America. Number 20 was deemed the national standard and number 4 the check standard. The downward pointing arrows indicate corrections that had to be made to the mass values disseminated by BIPM (see text).

The bottom panel of Fig. 1 hints at two other concerns in artifact-based mass metrology. The bottom graph shows the results of calibrations of the two prototypes that were initially designated to the United States of America. Number 20 was deemed the national standard and number 4 the check standard. The first question is whether the masses should be cleaned before the calibration or not. It is well known that without cleaning the mass values of the copies are increasing. The cleaning process takes off about 1 µg per year since the mass was cleaned last. One would think, it is always a good idea to clean the masses. However, it has been shown that the cleaning process resets the slope of the mass drift and hence makes it more difficult to predict its future mass value after calibration. Therefore, in recent years, researchers at the National Institute of Standards and Technology (NIST) have decided not to have the masses cleaned before calibration. In 1989 the International Committee on Weights and Measures agreed that the 1889 definition of the kilogram had to be interpreted as the mass of the international kilogram after cleaning with a specified method. For reference, the IPK has also been cleaned in 1889 for the first measurements of its copies. Hence, the unit of mass is defined for the moment, when the mass is most unstable, shortly after cleaning.

The second concern is indicated by the two downward pointing arrows in the bottom panel of Fig. 1. Since for most of the time, the IPK is in the vault, working standards (different from the official copies) at the BIPM are used to disseminate the mass scale to the member countries of the SI. The masses of the working standards are compared to the IPK at so-called verifications. In between models are applied to account for drift and use of the masses between verifications. However, it was found at the extraordinary calibration campaign in 2014 that some of the working standards have lost mass due to use. This mass lost was very subtle and adiabatic, so it went unnoticed. However, the mass values that had been disseminated just before 2014 were 35 µg too high. A correction was retroactively applied to the standards 4 and 20, which were calibrated at BIPM in 2011 and 2010, respectively. Researchers at NIST suspected a problem when the original values were announced in 2010 and 2011, since the mass increases for both USA copies were unprecedented. However, the BIPM was the ultimate authority, because it was the only place that had the realization of the kilogram, and the USA had to shift its mass scale based on the newly provided numbers. Three years later, the shift had to be reversed.

One other argument for the revision of the SI was to make electrical and mechanical units consistent again. Why were the electrical units used in daily life outside the SI? For electricity, the SI only defines one base unit, the ampere. The previous definition of the ampere was based upon the magnetic force between two current-carrying straight wires one meter apart. In effect, the abstract definition of the ampere fixed the magnetic permeability of vacuum (magnetic constant) μ_0 to be exactly $4\pi\times10^{-7}\,\mathrm{N/A^2}$. In a sense, this definition was already in the spirit of the current SI. The unit was defined by assigning a value to a fundamental constant of nature. Magnetic and electrostatic forces are effects of the same phenomena in different inertial frames according to Maxwell and Einstein. Describing the physics of a stationary frame in a moving reference frame requires the Lorentz transformation, where the velocity is scaled by the speed of light. It is therefore not surprising that the vacuum electric permittivity (electric constant) ε_0 and the magnetic constant μ_0 are linked via the speed of light, $\varepsilon_0\mu_0 = c^{-2}$.

Although the previous definition of the ampere was already based on a fundamental constant, the realization of the unit was tedious. A so-called ampere balance was used to compare the force produced by two nested coils with the weight of a mass. The trouble was that the dimension of the coil system needed to be measured precisely to calculate the proportionality factor between current and force for the experiment. In the example provided by the definition of the ampere, two infinitely long wires, with a negligible but circular cross-section, had a proportionality factor 2×10^{-7} N A^{-2} m^{-1}. Just allowing the wires to have a finite cross section will change the proportionality factor, because the distribution of the current density in the wires must be considered.

As discussed above, realizing the ampere required complex calculations, realistic models, and precise dimensional measurements of the coils—in short, it was impractical. Only larger National Metrology Institutes could afford effort to carry out these experiments. Fortunately, these experiments were made obsolete by two quantum leaps in metrology in the second half of the 20th century. The first appeared in 1962 when Brian Josephson, then a graduate student at Cambridge University, predicted a tunneling effect in adjacent superconductors separated by a thin non-superconducting barrier [3]. If an alternating current of frequency f is driven through such a tunnel barrier, a voltage that is an integer multiple of $hf/(2e)$ develops across the barrier. The experimental confirmation of the Josephson effect was made a year after Josephson's prediction. The quotient $K_J = 2e/h$ was named the Josephson constant.

Unfortunately, the frequency-to-voltage quotient associated with the Josephson constant is very large, approximately 4.8×10^{14} Hz/V. Hence, the voltage produced by one junction is tiny, about 37 µV for a typical microwave frequency of 18 GHz. To produce sizeable voltage, several tens of thousands of junctions have to be connected in series. Today, after decades of research, the state of the art for dc voltage metrology is the programmable Josephson voltages standard (PJVS). In a PJVS, different numbers of junctions can be combined to produce any desired voltage between zero and 10 V with quantum accuracy.

In contrast to the Josephson effect, the second quantum effect discovered in the 20th century is linked to a constant that has a more favorable value for practical applications. In 1980, Klaus von Klitzing discovered the integral quantum Hall effect [4] while measuring semiconductor samples at low temperatures and high magnetic fields. The Hall resistance is the ratio of the potential difference that occurs perpendicular to both the current and the magnetic field direction. At low temperature, if the conductivity of the material is limited to two dimensions by the magnetic field, the Hall resistance becomes quantized in integer fractions of $R_K = h/e^2$. This quotient is named the von-Klitzing constant and has an approximate value of 25.8 kΩ.

In the 1970s, voltage was realized by the Josephson effect, and in the 1980s resistance values were realized from the quantum Hall effect. By 1990, electrical metrology was securely on a quantum foundation. To obtain the unit of current, Ohm's law, $I = U / R$, was used on the quantum-based voltage and resistance. There was one caveat, though. The values of the Planck constant h and the elementary charge e were subject to change. The task group for fundamental constants under the auspices of the Committee on Data for Science and Technology (CODATA) recommends values for fundamental constants. In recent decades a new recommendation was made every four years. New values of h and e would imply that the electrical calibration would have to change also every four years. The electrical community severed the ties between a multimeter on the table and the recommendation by CODATA by deciding to use the values of h and e as they were in 1990 in future years. The units relying on the 1990 fixed values, K_{J-90} and R_{K-90}, were named conventional units. The conventional units were denoted with the subscript 90, e.g., V_{90}, Ω_{90} to differentiate them from the SI units. However, outside metrology, most people were not aware of the existence of conventional units

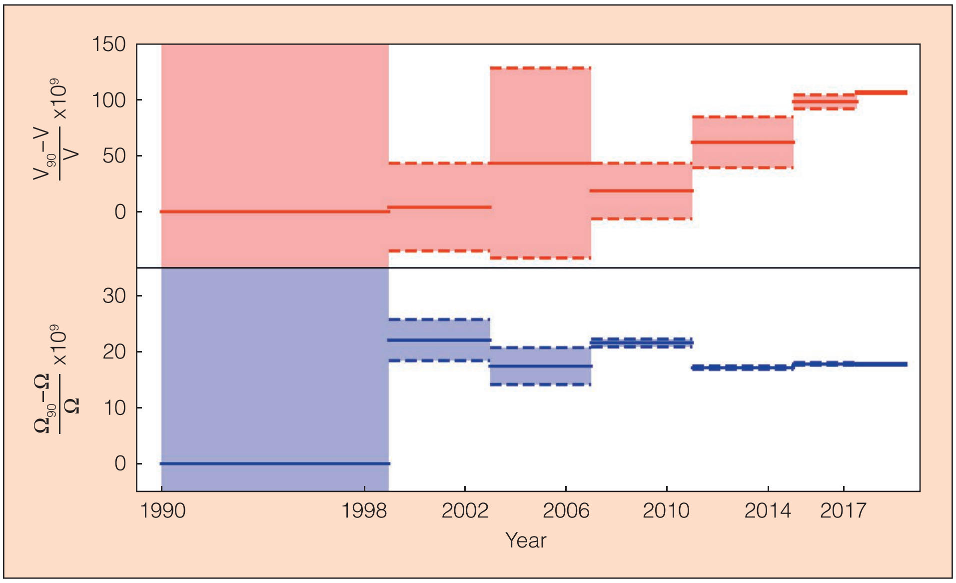

Fig. 2. The solid lines in the top and bottom graphs show the relative difference between the conventional and SI units for the volt and the ohm in red and blue, respectively. The shaded boxes give the ±1-sigma intervals around the mean values. The limits of the 1-sigma interval around the mean are also marked by dashed lines. From Jan. 1, 1990 to 1998 the difference was zero, and the relative uncertainty was 4×10^{-7} for the volt and 2×10^{-7} for the ohm. Both uncertainties exceed the vertical extent of the respective plot. The years are only printed when the task group for fundamental constants under the auspices of the Committee on Data for Science and Technology (CODATA) recommended values for fundamental constants. The year tick marks are placed on Jan. 1 of each year, but the deadline for the task group to take data into account was Dec. 31, except in 2017, when it was July 1. Here, the new values were plotted at the closing dates set by the task group. The conventional units were abrogated on May 20, 2019.

and used the SI symbols, although they were reporting conventional units. Look at an old power bill issued before May 20, 2019 where you will see W, but the traceability chain of the electricity supplier connected back to W_{90}.

For most applications mixing the conventional units with SI units was not a big problem, as the relative difference between a unit in the conventional system and its counterpart in the SI was small. The differences changed every four years with the release of the new recommended values for the fundamental constants by CODATA. Fig. 2 shows the relative difference between the conventional ohm/volt from the SI ohm/volt. By 2014, the relative difference between the conventional volt and the SI volt was almost 10^{-7}.

Having two different unit systems for electrical measurements was an unsatisfactory situation. After all, metrology underpins science, technology, and commerce. It is, hence, unacceptable to have a hairline crack in the foundation of these important endeavors, with two slightly different unit systems. Having two different unit systems, could lead to absurd situations. For example, at NIST, resistors were routinely calibrated in conventional units, but capacitors and inductors in the SI units based on the calculable capacitor [5].

Clearly, between 1990 and 2018 there were three shortcomings in the SI system: The system was not for "all times and for all people;" the stability of the kilogram was unclear; and the existence of the conventional electrical unit system led to confusion and uncertainty. However, to change the status, one puzzle piece was missing. A precise value of the Planck constant.

Realizing the Unit of Mass from the Planck Constant

The Planck constant was postulated in 1900 by Max Planck to solve the discrepancy between experimental data and theoretical calculations of so-called black body radiation. A black body absorbs all incoming electromagnetic radiation. Since the temperature of an isolated black body does not rise indefinitely, it must emit electromagnetic radiation to remain in thermal equilibrium. The electromagnetic spectrum of the emission is a function of temperature, and its spectral shape was a topic of considerable discussion at the end of the 19th century. Planck succeeded in developing a mathematical model for the black body. But, for the time being, Planck had to make an unusual assumption for electromagnetic oscillators inside the black body. He assumed that the energy that each oscillator could have was discrete with quantized energy differences. In the end, this unusual assumption led to the development of quantum mechanics about 28 years later. In quantum systems, the energy of a bound state is discrete, and the differences between these energy levels are given by the product of the Planck constant and the characteristic frequency of the system.

Since the Planck constant plays an essential role in quantum mechanics, one would think the best way to measure the Planck constant is via some quantum effect. However, simply considering its unit will provide the insight that for the measurement with smallest possible uncertainty, a mechanical apparatus is needed. In the SI, the Planck constant has the unit J s, which expressed in base units is kg m^2 s^{-1}. Previously, mass could be realized with the smallest uncertainty at the kilogram level, the point where the IPK resides. Hence, a macroscopic apparatus that uses a test mass with a mass of 1 kg is required to measure h with the smallest uncertainty and link mechanics to quantum mechanics.

In recent years, two methods have been used to determine the Planck constant: The Kibble balance and the X-ray Crystal Density method. Both ways are explained in more detail in the following sections.

The Kibble Balance

The Kibble balance was invented by Bryan Kibble in 1975 [6]. A balancing mechanism compares the weight of a mass mg to an electromagnetic force produced by a coil in a magnetic field—very similar to an ampere balance. The force is given by $F = BLI$ where I is the current in the wire coil of length L immersed in a magnetic flux density B. Usually the product BL is hard to determine precisely. But Kibble had an insight that the same geometric factor that is between force and current in a motor is also between induced voltage and velocity in a generator. So, by moving the coil in the magnetic field, the induced voltage is given by $V = BLv$ where v is the vertical velocity of the coil. Combining both equations leads to the watt equation $mgv = VI$ that has mechanical power on the left side and electrical power on the right side. Note that both power terms are virtual since the factors are not measured simultaneously but in two different modes. The electrical power is measured by routing the current through a resistor and measuring a second voltage drop, $VI = VU / R$. Both voltages can be measured via the Josephson effect, $V = n_1 hf / \left(2e\right)$ and $U = n_2 hf / \left(2e\right)$, and the resistor can be measured against the quantum Hall effect, $R = h / \left(ie^2\right)$, where i is a known integer. Combining all of the equations yields:

$$h = \frac{4}{n_1 n_2 i}\frac{gv}{f^2}m \quad \text{or} \quad m = \frac{n_1 n_2 i}{4}\frac{f^2}{gv}h.$$

The left equation shows how the Planck constant could be obtained from the mass before May 20, 2019, and the right equation shows how a mass can be measured from the fixed value of the Planck constant after that [7].

The XRCD Method

The theory of the hydrogen spectrum allows the calculation of the mass of the electron from other fundamental constants, $m_e = 2hR_\infty / \left(\alpha^2 c\right)$. Here R_∞ is the Rydberg constant and α the fine structure constant. Both constants are known with much smaller relative uncertainties than h, well below 1 part in 10^9. So, if we knew the mass of the electron in kg, the Planck constant could be determined. Unfortunately, it is challenging to measure the mass of the electron in kilograms. It is, however, possible to measure the relative mass between the electron and any other atom, for example, silicon-28. The idea of the XRCD method is to make a single crystal silicon sphere and weigh its mass, about 1 kg. The mass of the silicon atom can be inferred by dividing the macroscopic mass by the number of silicon atoms in the sphere. The number of silicon atoms is found by dividing the volume of the sphere $4/3\, r^3\pi$ by the volume $a_0^3/8$, where a_0 is the length of the unit cell of the silicon crystal, which is a cube containing eight silicon atoms. The length of the unit cell is obtained by X-ray diffraction. In fact, the X-ray diffraction measures the distances between different parallel planes in the silicon lattice, but a_0 can be inferred from it by geometry. The remaining problem is that natural silicon has three different isotopes, and it is impossible to measure the isotopic fraction with the required uncertainty. This problem is solved by using isotopically enriched silicon.

In the end, the mass of the silicon sphere can be written as:

$$m = \frac{\frac{4}{3} r^3 \pi}{a_0^3/8} \times \left(f_{28} r_{28} + f_{29} r_{29} + f_{30} r_{30} \right) \times \frac{2R_\infty}{\alpha^2 c} h$$

where r_{28}, r_{29}, and r_{30} denote the ratios of the masses of the isotopes ^{28}Si, ^{29}Si, and ^{30}Si to the mass of the electron. The respective isotopic abundances, which must be determined, are given by f_{28}, f_{29}, and f_{30} whose sum is 1. The equation above is solved for m. This is how the mass of the silicon sphere is obtained in the current SI. Before May 20, 2019, the equation would have been solved for h to give an experimental value for the Planck constant [8].

Implications of the Current SI

Before the revision of the SI, there existed one mass in the world, whose mass was known in kilograms with zero uncertainty. This mass was the international prototype of the kilogram. Since May 20, 2019, every mass measured in kilograms has an uncertainty. At the day of the revision, the revered 1889 IPK incurred an uncertainty of 10 µg. This uncertainty corresponds to a relative uncertainty of 10^{-8}. Before the revision our best knowledge of the Planck constant had exactly this same relative uncertainty. At the revision the relative uncertainty of the Planck constant was transferred to the IPK, and the IPK's relative uncertainty (0) was transferred to the Planck constant. We can assume that h has greater stability and can be called upon anywhere in the universe to give a result that is "for all times, for all people."

The additional uncertainty component for the IPK will not negatively impact mass metrology. Before the revision, the IPK had zero uncertainty but was not accessible. So, the BIPM used the working standards to calibrate national prototypes. The uncertainties assigned to the working standards depended on the elapsed time since the working standards had been calibrated against the IPK. In 2014, shortly before the extraordinary calibration campaign, the calibration certificates of the BIPM showed relative uncertainties of 7 µg, only slightly smaller than the 10 µg. Furthermore, for the old artifact-based system the uncertainty would have increased as more time passes. In the new system, the uncertainty starts out at 10 µg, but as the Kibble balances and the XRCD methods are further developed, the uncertainty will decrease.

The idea behind the current SI is that the units can be realized at any time and at any place from the seven defining constants. However, for mass, the international metrology community proceeds with caution and the dissemination from individual realizations of the mass unit will come after three phases [9]. In the first phase, the unit of mass will still be disseminated from the IPK but with an added uncertainty of 10 µg (relative uncertainty of 10^{-8}). In phase two, a consensus value compiled from all primary realizations (Kibble balances and XRCD methods) will be disseminated. The second phase ensures that a worldwide uniform mass scale is disseminated until enough trust has been gained to transition to phase three, a sovereign realization for each country that has a method or primary realization.

The more interesting change for mass metrology is that in the current SI the unit of mass can be realized at any arbitrary magnitude. Before, it was only possible by starting at 1 kg. Smaller mass values were obtained by subdivision, a process that is time consuming and has led to an increase in relative uncertainties for smaller mass ranges (see Fig. 3 and [10]). Now, in principle, this is no longer necessary. Different Kibble balances can be built to cover smaller ranges. Unlike a silicon sphere, which still realizes mass at one point, a Kibble balance is capable of operating over a wide range of mass values. For

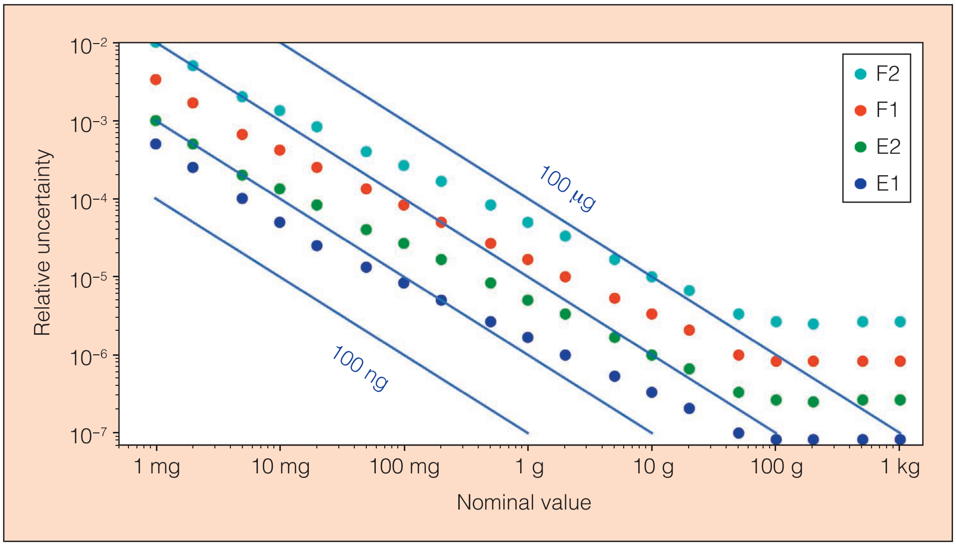

Fig. 3. Relative uncertainty of mass as a function of its nominal values for four types of calibration weights, described in OIML R111-1 [10]. The solid lines indicate lines of constant absolute uncertainty. Clearly the points are aligned along these lines.

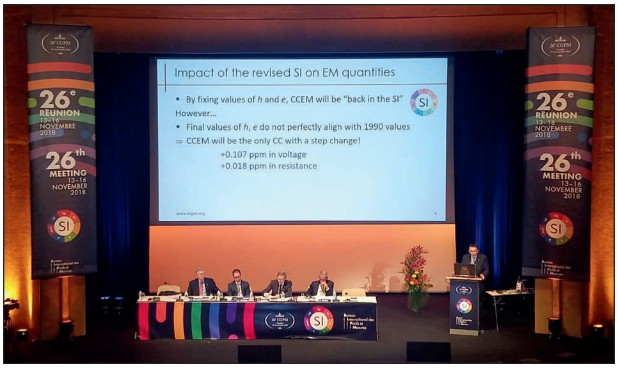

Fig. 4. Gert Rietveld, President of the Consultative Committee for Electricity and Magnetism (CCEM), speaks at the 26th meeting of the General Conference of Weights and Measures (CGPM) shortly before the vote on the revision of the international system of units. Photo courtesy of NIST.

very small masses, sub milligram electrostatic balances can be used [11]. Scientists at NIST have built an electrostatic balance that can measure masses at 1 mg with relative uncertainty of 7.3×10^{-6} which is smaller than the best that can be achieved by dividing down from the kilogram, about 1.2×10^{-4} [12].

In the same vein, the atomic masses are known with smaller uncertainty in the current SI. Before, the atomic mass unit had a relative uncertainty of 12×10^{-9}. In the present SI, it is possible to know the SI mass of the electron with uncertainties smaller than 1 part in 10^9.

For electrical measurements, there occurred a small step change on May 20, 2019. After that, however, the SI electrical units are firmly rooted in the quantum mechanical effects. The same measurement principles will be used as before, but instead of K_{J-90} and R_{K-90} the values of K_J = 483597.848416984 GHz/V and R_K = 25812.8074593045 Ω are used. The new values of R_K and K_J caused small steps in the relative unit values of ohm and volt, 1.07×10^{-7} in the voltage and 1.8×10^{-8} in the ohm. These changes were only detected by laboratories that have a primary realization of the ohm and volt. Fig. 4 shows a picture of the President of the consultative committee on electricity and magnetism discussing these changes at the 26th general conference of weights and measures. One disadvantage of the current SI is that the magnetic constant is no longer exact. The magnetic permeability of vacuum can be derived from the fine structure constant

$$\mu_0 = \frac{2\alpha h}{e^2 c}.$$

Since the elementary charge, the Planck constant, and the speed of light are all fixed, a measurement of the fine structure constant determines μ_0. Hence, the relative uncertainty of α will become the relative uncertainty of μ_0. But this uncertainty is well below 1 part in 10^9. After every CODATA recommendation for the values of the fundamental constant, there will be a new value for μ_0 and its uncertainty. The same relative uncertainty applies for the electric constant which, from an equation shown above, is simply given by $\varepsilon_0 = \mu_0^{-1} c^{-2}$. An exact value of c was adopted in 1983 to redefine the meter.

What is the consequence of the magnetic and electric constants no longer being exact? It is a minor inconvenience, in that the numerical value of the magnetic constant is no longer $4\pi \times 10^{-7}$ which was easy to remember. This number can still be used if the result of the calculation must only be precise within a 1 part in 10^9. If a better uncertainty of the calculation is required, the current recommended value must be used. One experiment where this has an effect is the Thompson-Lampard calculable capacitor [13], [14], which is used in several laboratories to realize the farad, the unit of capacitance. In the calculable capacitor, the capacitance per unit length is given by $C/L = (\varepsilon_0/\pi) \ln 2$, which is subject to a small change in ε_0 at every new CODATA recommendation. This looks very similar to the electrical units before the 1990 conventional unit system was established. However, the present situation is much better. First, it is believed that the relative change in the electric constant is very small, and second, the calculable capacitor is only one of two possibilities to realize the farad. The other possibility utilizes the AC quantum Hall effect, which relies on the fixed value of R_K.

Single electron tunneling offers a path to realize the ampere [15]. Here, a known number of electrons N are transported with a frequency f across a junction, resulting in a current Nfe. At present, the count rates are too low to produce practical currents. However, this research field is growing

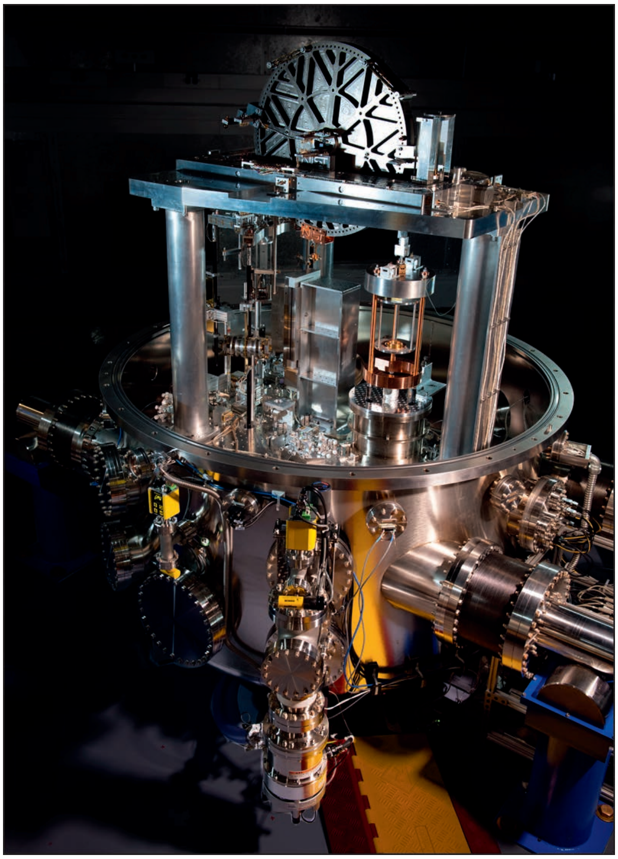

Fig. 5. The Kibble balance at NIST. This instrument can measure a mass of 1 kg with an uncertainty of 13 µg. Photo courtesy of NIST.

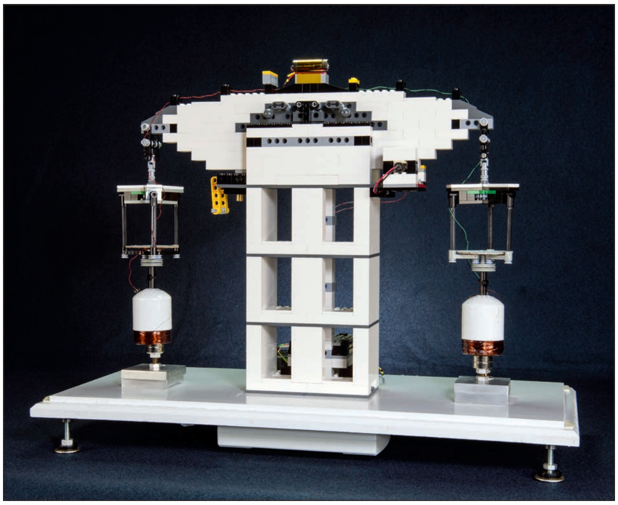

Fig. 6. A Kibble balance made from LEGO bricks [16]. This balance can measure masses up to 20 g with an uncertainty of 0.2 g. Photo courtesy of NIST.

fast. We are optimistic that in the future, single electron tunneling will be able to realize the ampere for small currents. Stay tuned.

In summary, the current SI embodies the ideal "for all times, for all people." The system is based on seven defining constants. Five of these defining constants are fundamental constants of nature. As such they are stable in time and space. But also, since these constants are woven into the fabric of the universe, and they can, in principle, be accessed by every human. They are not owned, and they do not have to be locked away in a safe. In this article, we discuss the consequences of the change from the previous version of the SI for the unit of mass and the electrical units. Guests visiting the Kibble balance at NIST are overwhelmed by the complexity of the instrument (Fig. 5) and doubt that building such an instrument would be truly for all people. We would like to point out that, while it is a considerable investment to build a Kibble balance with a relative uncertainty of 10^{-8}, it is possible to build one from LEGO™ bricks with a relative uncertainty of 10^{-2}(see Fig. 6 and [16]).

Authors' note: Certain commercial equipment, instruments, or materials (or suppliers, or software, etc.) are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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