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Universal Units Reflect Their Earthly Origins

By Michel J. Van Camp, Philippe Richard, and Olivier de Viron

For the past 2 centuries, scientists, surgeons, shipping companies, and shoppers have relied on a common system of measurements: the metric system. The basic units of this system have their origins in Earth's spatial dimensions, timescales, and material masses. As our ability to make measurements became ever more precise, these units were redefined, one by one, in terms of fundamental physical constants rather than material objects—except for the kilogram.

This basic unit of mass remained tethered to a 139-year-old metal cylinder about the size of a plum that sits in air under three bell jars in France. But on 16 November 2018, that tie was severed when the kilogram's new physics-based definition was officially adopted (see bit.ly/SI-units).

Scientists around the world rely on the International System of Units as a common basis on which to record and report their findings. The units used in this system are based on the meter, kilogram, second, kelvin, ampere, mole, and candela. Even though all scientific fields, including the geosciences, use these units every day, many geoscientists may not realize how important Earth's properties were in developing these units and how the new definition maintains its ties to terrestrial dimensions.

The change in definition shows that in an era when units are increasingly defined by the properties of atomic physics, Earth's properties remain important in metrology, the science of measurement.

Measuring the Earth

Earth, which at the time was thought to represent imperishability and stability, was the initial base for the International System of Units (Système International d'Unités; SI) of length, time, and, indirectly, mass. Geodesy, the science of the shape of the Earth, its orientation in space, and its gravity field, was key in the definition of the metric system during the French Revolution.

In 1791, the French Academy of Sciences defined the meter as 1/10,000,000 the length of a quadrant of Earth's meridian. However, since 1983, the meter has been defined as the length of the path traveled by light in a vacuum during an interval of 1/299,792,458 of a second. Hence, *c*, the speed of light in a vacuum, was fixed to a given value, and the definition of the meter now derives from that of the second.

Translating this concept into practical measurements requires some method that is both precise and repeatable. Several methods compete for the practical realization of the definition of the meter (also called mise en pratique). Today the SI meter is often derived from the wavelength of an iodine-stabilized red helium-neon laser.

The SI unit of time, the second, was originally defined as 1/86,400 of the mean solar day. Subsequently, clocks reached a precision that allowed monitoring irregularities in the Earth's rotation and revolution. In 1967, the General Conference on Weights and Measures (Conférence Générale des Poids et Mesures; CGPM) changed the definition of the second to "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom" [*International Bureau of Weights and Measures*, 2006].

By this definition, the above frequency (abbreviated in metrology to $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$) is exactly equal to 9,192,631,770 transitions per second, and the second is defined accordingly.

This 3-D rendering shows the International Prototype Kilogram with two of its three protective glass bells. Credit: iStock.com/AlexLMX

The Drifting Kilogram

In 1799, the kilogram was defined as the mass of 1 cubic decimeter of water at a temperature of 4°C. Until last November, this unit was unique in that the standard was based on a manufactured object rather than on a physical constant. The prototype kilogram from 1799 (the "kilogram of the archives") and the present artifact from 1875 (the international prototype kilogram, or IPK) were manufactured to be consistent with this definition. The IPK is a cylinder of 39-millimeter height and diameter, made of 90% platinum and 10% iridium. At present, the IPK is kept at the Bureau International des Poids et Mesures in Sèvres, France.

Forty replicas of the IPK were manufactured in 1884, and 34 of them were distributed to the signatories of the Meter Convention. The United States was allocated prototype numbers 4 and 20; Belgium received numbers 28 and 37; and Switzerland got number 38 and, more recently, number 89. These replicas have been used as national standards ever since.

The kilogram joined the other SI units, and its prototypes became museum items when the kilogram was officially redefined in terms of the Planck constant (see bit.ly/kilogram-redefined). This change in definition was necessary because the use of the IPK, a physical artifact, posed various problems. There was no way to ensure its long-term stability, it could have been destroyed or damaged, and it posed logistical problems when it had to be compared with copies at other national metrology institutes (NMIs).

Comparisons of the mass of the IPK to those of official copies and the national prototypes in 1889, 1948, 1989, and 2014 indicated that the IPK seems to have lost about 50 micrograms over 100 years (five parts in 100 million). It is also possible that all the prototypes show a common mass drift, which cannot be detected by intercomparisons. We thus faced a strange situation: By definition, the mass of the IPK is invariant, but there is no means to check its stability using an absolute reference.

The instability of the IPK propagated to other base units that are tied to the kilogram, such as the candela (luminous intensity), the mole (number of atoms in a mass of material), and the ampere (electric current). It also influenced the derived quantities such as force, density, and pressure. Consequently, for the past 25 years, several NMIs worked to replace the IPK with a definition based on a fundamental constant of nature [*Richard et al.*, 2016].

Based in Physics, Measured in Geodesy

Although Earth's properties are not stable enough to serve as a basis for the SI, geodesy has not said its last word. The new definitions of the second and the meter, previously derived from geodesy, now rely on laboratory physics experiments. The new definitions, however, must be consistent with the previous ones and are thus still related to Earth's shape and motion.

On 16 November 2018, the 26th CGPM (see bit.ly/CGPM-26) ratified the revised SI based on seven constants: the frequency of the ground state hyperfine splitting of the cesium-133 atom $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$, the speed of light in a vacuum c, Planck's constant h, the elementary charge e, Boltzmann's constant k, Avogadro's constant N_A, and the luminous efficacy K_{cd}. These constants exist independent of our ability to measure them, and thus, the definition and practical realization of the units will be decoupled.

The Smurfs try their hand at measuring gravitational acceleration (left), perhaps inspired by the FG5#202 absolute gravimeter at the Royal Observatory of Belgium's underground geophysical monitoring station near Membach (right). Credit: © Peyo – 2018, Lic. Lafig Belgium – www.smurf.com; Kris Vanneste, Royal Observatory of Belgium

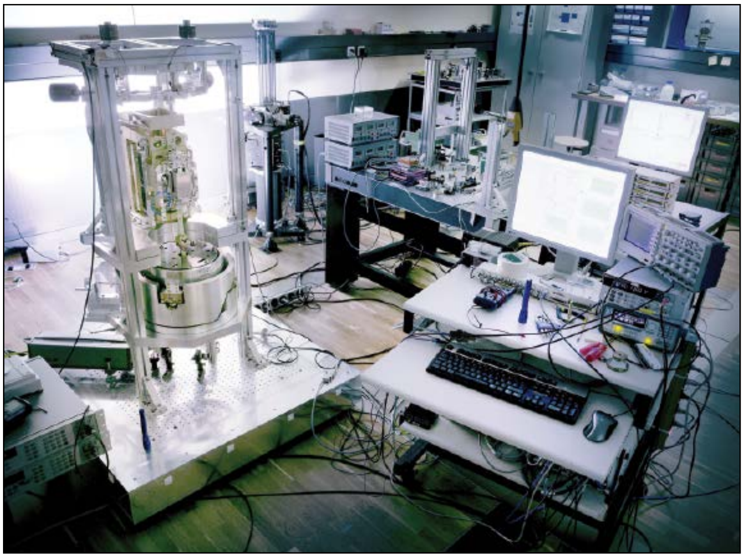
In short, this means that the practical derivations of mass can be established and replicated by different experiments with ever-increasing accuracy, while the definitions remain unchanged.

Henceforth, the magnitude of the kilogram (kg), the unit of mass, will be derived from the value of Planck's constant ($h = 6.62607015 \times 10^{-34}$ joule-seconds; see *Fischer and Ullrich* [2016]), used in Einstein's energy formula $E = mc^2 = h\nu$. Because a joule is a kilogram meter squared per second squared (kg m²/s²), the kilogram standard will now rely on SI units of length and time, which were already previously standardized.

A New Balance

Just how do we derive the kilogram from those known quantities?

After the redefinition, a first route to standardizing the kilogram consists of counting the number of atoms in a silicon-28



The new definition of the kilogram lends itself to measurements using a Kibble balance (at left) and an absolute gravimeter (in the background, with the black tripod and the transparent, cylindric dropping chamber), like these instruments at the Federal Institute of Metrology (METAS) in Switzerland. Credit: André Roth, Roth und Schmid Fotografie for Mettler Toledo

(^{28}Si) single-crystal sphere using the X-ray crystal density approach. This is also known as the Avogadro experiment because it was originally used to yield an accurate value for Avogadro's constant, the number of carbon-12 atoms that amass to exactly 12 grams. (Avogadro's number of hydrogen atoms, the lightest element, would weigh 1 gram, but carbon is much easier to weigh than hydrogen.)

Another route to the kilogram is based on the Kibble balance [*Robinson and Schlamminger,* 2016]. In this scheme, the mechanical power of a mass in a gravitational field is balanced by the electrical power of the balance. The kilogram depends on Planck's constant, which appears in the quantum phenomena used to determine the balance's current and voltage.

Knowing the current, voltage, length, and time to measure the velocity of the coil moving within a magnetic field and the local acceleration of gravity, one defines the mass as the amount of matter required to balance a given amount of electrical power. To allow this derivation of the kilogram, the gravity acceleration must be determined at the 10^{-8} level by absolute gravimetry, tracking the free fall of an object or cold atoms repeatedly dropped inside a vacuum chamber [*Van Camp et al.,* 2017].

From the Conceptual to the Practical

Since 1967, geodetic metrology is no longer required for the definition of the meter and the second. However, gravity will still be key in the new realization of the kilogram. A measurement of Avogadro's constant could be converted to a measurement of Planck's constant h (and vice versa) through Rydberg's constant, which links the atomic and macroscopic properties of matter.

The new constants are not completely divorced from their historical ties. The number chosen for the numerical value of h is such that at the time the definition was adopted, the redefined kilogram was equal to the mass of the IPK within the uncertainty of the combined best estimates of the value of Planck's constant. The same holds true for c and $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$, which, like h, remain historically related to the Earth's dimension and rotation.

The accurate gravity measurements required to determine the kilogram using the Kibble balance would not have been possible without research to measure and monitor gravitational acceleration and to understand its variations in time and space [*Van Camp et al.,* 2017]. Geoscientists have worked on this problem since Galileo Galilei investigated the motion of falling masses in the 16th century and showed that acceleration due to Earth's gravitational field is the same for all masses (and thus cannot be used to define any specific mass, including the kilogram).

However, using the Kibble balance method requires dropping objects, not to measure their mass but to determine an accurate value for gravitational acceleration. Thus, monitoring the free fall of an object or cold atoms, as achieved in absolute gravimeters, is still a fundamental tool in geosciences and metrology.

Since last November, our meters, kilograms, and seconds are now defined by the motions and energy of electrons, atoms, and photons. However, the benchmarks by which we bring these definitions into everyday use remain rooted in measurements derived from our home planet.

Acknowledgments

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