Universal Units Reflect Their Earthly Origins

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

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 $E = mc^2 = hv$. Because a joule is a kilogram meter squared per second squared (kg m$^2$/s$^2$), 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 will consist of counting the number of atoms in a silicon-28 ($^{28}\text{Si}$) 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 will not be completely divorced from their historical ties. The number chosen for the numerical value of $h$ will be such that at the time the definition is adopted, the redefined kilogram will be 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 $\Delta v^{(133\text{Cs})}\text{hfs}$, 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.
After November, our meters, kilograms, and seconds will be 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.

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