A ampere | cd candela | K kelvin | kg kilogram | m metre | mol mole | s second

Quantum leap

Redefining SI

BY **DAVE SAMMUT**

Several units in the *Système international d'unités*, including the kilogram, are under review in the lead-up to the proposed 'new SI' in 2018.

The arcane science of metrology is on the cusp of a quantum leap, a bold redefinition of four of the seven SI base units, in the aftermath of which we will find our lives radically unchanged.

The *Système international d'unités* (SI) has its roots in imperial France. In the late 1700s, King Louis XVI ordered investigations into a new, standardised system of weights and measures to crack down on rampant fraud. Louis' expert committee proposed measures based on nature – such as the triple point of water for temperature, and a fixed volume of water for mass. Before the revolution, the 'grave' was proposed as the mass of litre of water, but in 1799 this was updated to the 'gramme' – the mass of 1 cm^3 of water at 4°C.

However, a pea-sized volume of water (for extremely large values of 'pea') was not a practical unit, so the kilogram gained traction as a standard unit, embodied as a physical object.

Following the Metre Convention of 1875, 17 member countries agreed to a standardised system, and the modern SI system was born. Since 1889, the International Prototype of the Kilogram (IPK) has been stored at the *Bureau International des Poids et Mesures* (BIPM) near Paris, under the auspices of the *Conférence Générale des Poids et Mesures* (CGPM).

One of 40 identical artefacts carefully manufactured by British firm Johnson Matthey as a 39 mm cylinder (approximate length and diameter) of platinum (90%) and iridium (10%) and then selected by lot, this IPK is periodically brought out and checked against the national prototypes that have been distributed to member states around the world. Of the original 40 manufactured, there remain six national prototypes, eight working standards and two additional copies for special units.

And here lies the key problem with physical constants. More than just the logistical problems of access, transport and measurement, by definition a physical constant should be both universal in nature and constant in time. But successive measurements have shown a drift in some of the national prototype kilograms against the IPK of up to 50–60 μg (6×10^{-8} relative uncertainty).

Either the IPK is losing mass (possibly through the diffusion of gas encapsulated during manufacture, or loss of atoms on handling), or the national prototypes are gaining mass (such as through mercury vapour adsorption or carbonaceous contamination). Either way, the IPK is by definition a kilogram, so the rest of the world is getting heavier, and that can't be allowed to continue (see box, p. 31).

At its 23rd meeting in 2007, the CGPM mandated a committee of 18 eminent scientists, the *Comité International des Poids et Mesures* (CIPM) to investigate the use of natural constants to replace the IPK. The CGPM has eliminated the International Prototype Metre (1960) and the definition of the second based on the period of rotation of the Earth (1956, 1967), leaving the kilogram as the only base SI unit still anchored to a physical artefact.

Two alternative methods of defining the kilogram in terms of natural constants have been proposed. CIPM's preferred method (amidst strenuous ongoing debate) is to define the kilogram in terms of Planck's constant (see box), specifically by setting the numerical value of h to exactly $6.62606x \times 10^{-34}$ joule second (where the numbers making x have yet to be determined).

The science of the arguments gets complex pretty quickly, but to paraphrase BIPM's very cogent explanation: the natural constant h is composed as the product of two components, its numerical value $\{h\}$ and its unit $[h]$, so that in this case:

$h = \{h\}[h] = 6.62606 \ldots \times 10^{-34}\,\mathrm{kg\,m^2/s}$

The factors $\{h\}$ and $[h]$ can be chosen in different ways such that the constant itself, h, remains unchanged. Until now, the unit $[h]$ has been dependent on the fixed definition of the kilogram, making the numerical value $\{h\}$ a measured variable. Under CIPM's preferred approach, the numerical value $\{h\}$ will be fixed, in turn yielding the definition of the unit $[h]$. The metre and second are both defined by natural constants, and this in turn yields a new definition for the kilogram.

The current definition fixes the mass of the IPK at 1 kg with zero uncertainty, which in turn means that the current best measurements of Planck's constant have a relative uncertainty of 4.4×10^{-8}. By fixing the value of Planck's constant (with zero uncertainty), the IPK itself may no longer have a mass of 1 kg, but will assume the relative error of 4.4×10^{-8}.

In practice this means that the kilogram can be experimentally measured on a watt balance, which compares electrical power and mechanical power. In simple terms, a conducting wire carrying an electric current (I) perpendicular to a magnetic field of known strength will experience a force of known strength. In a watt balance, the current is varied to precisely counteract the weight (at known local gravity, g) of a standard mass (m).

By moving the wire through the magnetic field at known speed (in a separate 'calibration mode'), a potential difference (U) is generated across the ends of the wire, which can be used to remove the effect of the magnetic field strength and the length of wire, such that:

$UI = mgv$

Planck's constant

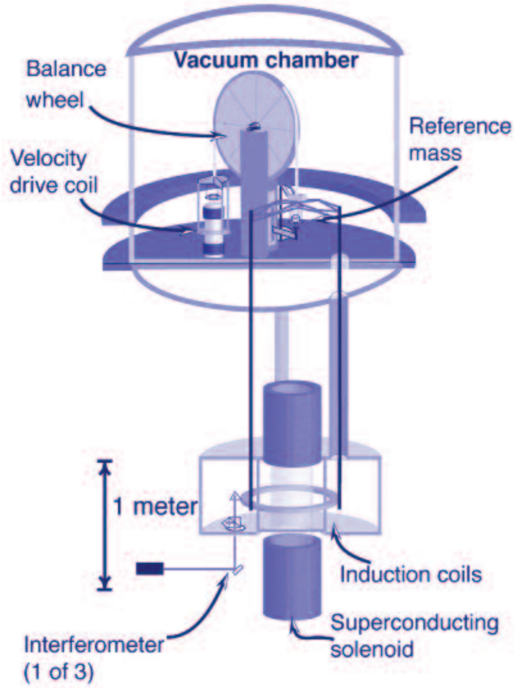
The duality of light has been an enduring paradox for physics. As early as 1801, Young's two-slit experiment demonstrated that light is a wave. Maxwell's equations and Faraday's discoveries reinforced this view. But then came Max Planck and Albert Einstein.

In 1900, Planck – using only mathematical foundations – showed that light must be emitted and absorbed in discrete amounts if it is to correctly describe black body radiation (the fact that hot objects emit light at different wavelengths depending on temperature). Einstein followed this in 1905, using Planck's initial equations to explain the photoelectric effect, and thereby clearly showing that light was composed of discrete particles – photons. Einstein showed that the energy of a photon was related to its frequency by Planck's constant:

$$E = h\upsilon = \frac{hc}{\lambda}$$

In 1954, Einstein said of Planck's work: 'This discovery became the basis of all twentieth-century research in physics and has almost entirely conditioned its development ever since. Without this discovery it would not have been possible to establish a workable theory of molecules and atoms and the energy processes that govern their transformations.'

With extremely accurate measurements available for U, I, g and v, it is expected that the watt balance can be used to generate extremely accurate measurements of the kilogram. As example, the US's National Institute of Standards and Technology's (NIST) newest prototype watt balance, NIST-4, was commissioned in 2015, and is expected to measure the kilogram/Planck's constant with an



In the NIST watt balance experiment, a kilogram test mass is placed on a balance pan that is connected to a coil of copper wire, which surrounds a superconducting electromagnet. If electric current is sent through the coil, then just as in an electric motor, electromagnetic forces are produced to balance the weight of the test mass. The apparatus measures this current and force. The apparatus also can move the coil vertically, and, like an electric generator, that induces a voltage. The velocity and voltage of the coil also are measured. These four measurements determine the relationship between mechanical and electrical power, which can be combined with other basic properties of nature to redefine the kilogram.
R. Steiner/NIST

Crystals of silicon-28 can be machined into spheres with a defined mass of 1 kilogram. Using this, the spatial parameters of the silicon's crystal lattice and the mass of an individual silicon atom, Avogadro's number can be determined. NIST

The Avogadro Project ... uses perfectly spherical balls of ultra-pure (99.9995%) silicon-28.

uncertainty of 3×10^{-8} – half the current uncertainty from the IPK.

The alternative method for measurement has included CSIRO and the National Measurement Institute facility at Lindfield, Sydney. The Avogadro Project, as it has come to be known, uses perfectly spherical balls of ultra-pure (99.9995%) silicon-28. Each 'super sphere' costs about US$3.2 million, and is handcrafted by a master lens-maker. CSIRO's Australian Centre for Precision Optics has claimed that the spheres have total out-of-roundness' of only 35 nanometres.

The crystalline balls have a predictable pattern of atomic spacing that can be measured by X-ray crystallography. With only one dimension to be measured (via highly precise optical interferometers), and with nanometre precision in the milling (so that if the approximately 94 mm spheres were blown up to the size of the Earth, the difference between the highest peak and the lowest trough would be 3–5 metres), the number of atoms in the spheres can be determined with extremely high precision.

According to NIST, the best measurement to date has the same level of uncertainty as the best watt balance measurements: 3×10^{-8}. This then provides an excellent second method of verifying the measurements from the watt balance approach. As stated by NIST: 'The watt balance and Avogadro Project measurements are not so much competing with as complementing each other to define the kilogram. In fact, metrologists are counting on a large amount of agreement between the two experiments for a first-shot redefinition. The two strategies can act as checks against one another, which would give scientists more confidence that each new definition is a reliable replacement for "the big K" [the affectionate term for the IPK].'

One of the consequences of the Avogadro Project approach is that it would link the definition of the kilogram to the mole, which is also under CGPM review. The current definition of the mole is the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12.

The proposed revision fixes the value of Avogadro's constant at $6.02214x \times 10^{23}$ mol^{-1}, which would in turn affect the definition of the dalton and the atomic mass unit (which would be dropped as an SI unit altogether), with minor differences emerging between the last two.

CIPM has advised that the criteria for acceptance of kilogram measurements should be that three separate experiments using the watt balance and silicon sphere should yield values having uncertainty of no more than 5×10^{-8}, with at least one value better than 2×10^{-8}.

Master optician Achim Leistner measuring the roundness of a precision silicon sphere that was manufactured at CSIRO. CSIRO

Redefining the kilogram in terms of a fundamental natural constant will ensure its long-term stability and reliability. After years of detailed argument, it is now proposed that a new approach will be adopted at the 25th CGPM meeting in 2018. This is to be termed the 'new SI'.

And at the end of all of that effort, what will have changed in our laboratories and day-to-day lives? Well … nothing, actually. While the changes will affect certain high-precision industries such as telecommunications, and will become more important as our technologies develop, the methods used now to calibrate 'at the coal face' will remain unchanged.

From my limited perspective, the kilogram will no longer be an object that I will never see outside a photo, and instead will be derived from a concept based on an arcane theory by a bloke who had something against cats. Call it a quantum leap in my lack of understanding.

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Matters of substance

As I dolefully contemplate my bathroom scales of a morning, I find that the subject of mass is of fundamental importance to me. The problem started when our son was born. Did you know how you weigh less in the morning than when you go to bed at night? After staying up all night with a screaming baby, this stopped happening for me. I started to get fatter. So I went on my first diet ever. Like a good scientist, I applied the scientific method to my experiment:

Aim: To avoid having to purchase new pants.

Method: Measurements taken at $t = 0$. Ingest nothing but healthy food for several weeks. Measurements repeated.

Results: System changes observed and recorded.

Conclusion: Judging by what I lost during the test, the 'will to live' weighs approximately 2 kg.

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