The Kilogram, redefined: the weight is over

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The Kilogram, Redefined

The Weight Is Over

By Andrew Oldershaw and Kevin McClure

Q Does the redefinition of the kilogram really mean that it will be possible to realize the International System of Units (SI) unit of mass at any place, at any time, and by anyone?

A The world of measurement is changing. Fundamental constants of nature are replacing artefacts as the basis for defining units of measure. On World Metrology Day, May 20, the last artefact, the international prototype kilogram (IPK), or "the grand k," was replaced by Planck's constant in defining the unit of mass, the kilogram. The redefinition does not change the numbers much, and few labs will notice any difference. In the grocery store, apples will still be apples and the price, whether by kilogram or by pound, certainly will not change as a result of the redefinition.

WHY CHANGE?

Since 1889, calibrations of national standards (copies of the IPK) show a change in stability of about 50 µg.[1] Now that has been fixed and the Planck's constant will never change. Benefits of the new stability will be seen much more broadly than in just mass measurements. Mass influences the ampere, the mole, and the candela as well.

Accessibility is another strong motivator. Once the revised definition of the kilogram comes into force, "It will be possible to realize the SI unit of mass at any place, at any time, and by anyone."[2]

"The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be 6.626 070 15 × 10^{-34} *when expressed in the unit J s, which is equal to kg m*^{2} *s*$^{-1}$*, where the metre and the second are defined by exact values of the hyperfine transition frequency of the caesium 133 atom* $\Delta\nu_{Cs}$ *and the speed of light in vacuum c.*[2]

To add context, the realization — and its possibility as described above — has to be in accordance with the *mise en pratique* for the kilogram, the standard instructions published by the International Bureau of Weights and Measures (BIPM). The *mise en pratique* for the kilogram gives two options: realization of a mass by comparing electrical power to mechanical power and realization of a mass by the X-ray crystal density method.[2]

Here we explore two quests to define the kilogram. Both are accomplished by comparing electrical power to mechanical power using a watt balance, also known as a Kibble balance, in recognition of physicist Bryan Kibble, D.Phil. First, the development of the National Research Council Canada (NRC) Kibble balance, and second, as a contrast, the experiences of this column's co-author, Kevin McClure, a metrologist, developing his own Kibble balance at home.

In the NRC Kibble balance experiment, the gravitational force on a mass is balanced against the electromagnetic force generated by passing a current through a coil suspended in a magnetic field. The current is calibrated using quantum standards of voltage and resistance, providing the link between Planck's constant and mass. Besides the electrical measurements, alignment of the balance must be adjusted to very fine tolerances, gravitational forces on the mass must be known precisely, and the motion and position of the coil must be controlled interferometrically within fractions of the wavelength of light.[3]

In what we will call "the McClure basement balance," the principal operation is the same but on a different scale. It is modeled on the U.S. National Institute of Standards and Technology's (NIST) LEGO balance and uses the NIST free software in its operation.[4] The coils are hand wound with a wooden base and arm. The voltage and current measurements use a National Instruments USB data acquisition unit. The critical distance measurements (for speed) are done with a shadow sensor that is a line laser and a photodetector. This is calibrated with tape measures, rulers, and a dot laser on the arm projecting on a ruler on the wall. This allows a relatively accurate electronic detection of the pan. This is also the largest source of error in the uncertainty budget. Currently, this setup has a total uncertainty of about 1%. All of the components are readily available and traceable.

The NRC's motivation stems from the global challenge to redefine the kilogram, in particular, the condition that Kibble balance experiments yield consistent values of the Planck constant with relative standard uncertainties not larger than five parts in 10^8.[5] The NRC Kibble balance is a world-class experiment, measuring a value for Planck's constant with measurement uncertainties at nine parts in 10^9. It is the culmination of more than a decade of research at the forefront of measurement science at the NRC and, prior to that, the National Physical Laboratory in the United Kingdom. The coincidence of Kevin's birthday and World Metrology Day and the momentous event of the redefinition make it seem predestined that Kevin's passion for metrology would motivate him to build the McClure basement balance.

MEETING THE TECHNICAL CHALLENGE

Both balances follow Kibble's original concept of two modes, to cancel out the magnetic field strength and length of conductor from the measurement equation, which are difficult to measure. This leaves mass, gravity, voltage, current, and velocity.

Carlos Sanchez, Ph.D., National Research Council Canada, makes adjustments to the NRC Kibble balance.

The McClure basement balance uses guidance on setup from the U.S. National Institute of Standards and Technology.

The scale of challenge differs, but common measurement challenges for both balances are:

- Achieving a constant velocity at the right point in the rocking motion of the balance;
- Timing of the measurements and data collection; and
- Isolating the balance and all the measurements from noise, interference, and vibration.

To build on and surpass state-of-the-art measurement capabilities and meet the challenges for redefinition of the SI, novel techniques were necessary. These are just a few examples of the approaches with both balances (See "The Two Balances" on following page.)

METROLOGICAL TRACEABILITY

There is no metrological traceability without measurement uncertainty, but no limits on uncertainty as long as it is fit for the application of the measurements. The NRC Kibble balance played a pivotal role in the redefinition of the kilogram and will be used to provide traceability to the SI. Measurement helps our understanding of the world around us. It is fundamental to the advancement of science and to our ability to build new technology.

There is always a need to push the barrier and make better and better measurements. Sometimes better is greater precision and accuracy, but for the vast majority of everyday measurements, better can mean easier, more reliable,