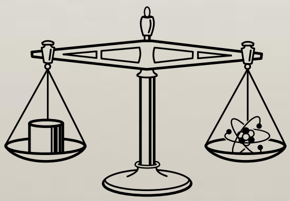
Weighty Matters

THE CENTURY-OLD ARTIFACT THAT DEFINES THE KILOGRAM, THE FUNDAMENTAL UNIT OF MASS, IS TO BE REPLACED BY A MORE ACCURATE STANDARD BASED ON AN INVARIANT PROPERTY OF NATURE



BY IAN ROBINSON

In an age when technologies typically grow obsolete in a few years, it is ironic that almost all the world's measurements of mass (and related phenomena such as energy) depend on a 117-year-old object stored in the vaults of a small laboratory outside Paris, the International Bureau of Weights and Measures. According to the International System of Units (SI), often referred to as the metric system, the kilogram is equal to the mass of this "international prototype of the kilogram" (or IPK)—a precision-fabricated cylinder of platinum-iridium alloy that stands 39 millimeters high and is the same in diameter.

The SI is administered by the General Conference on Weights and Measures and the International Committee for Weights and Measures. During the past several decades the conference has redefined other base SI units (those set by convention and from which all other quantities are derived) to vastly improve their accuracy and thus keep them in step with the advancement of scientific and technological understanding. The standards for the meter and the second, for example, are now founded on natural phenomena. The meter is tied to the speed of light, whereas the second has been related to the frequency of microwaves emitted by a specific element during a certain transition between energy states.

Today the kilogram is the last remaining SI unit still based on a unique man-made object. Reliance on such an artifact poses problems for science as measurement techniques become more precise. Metrologists (specialists in measurement) are therefore striving to define mass using techniques depending only on unchanging properties of nature. Two approaches seem most promising—one based on the concept underlying the Avogadro con-

METAL CYLINDER (*right*), weighing one kilogram, is the precision-manufactured mass standard used to calibrate all the mass scales in Italy. Like all other national mass standards worldwide, it is itself calibrated against an identical master artifact in France.

FROM A SILICON SPHERE TO A KILOGRAM STANDARD

One approach to redefining the kilogram is based on accurately quantifying the number of atoms in a silicon sphere weighing one kilogram.

1 The method starts with native silicon (a mixture of three isotopes—^{28}Si, ^{29}Si and ^{30}Si), which is reacted with fluorine to create gaseous silicon fluoride (SiF_4).

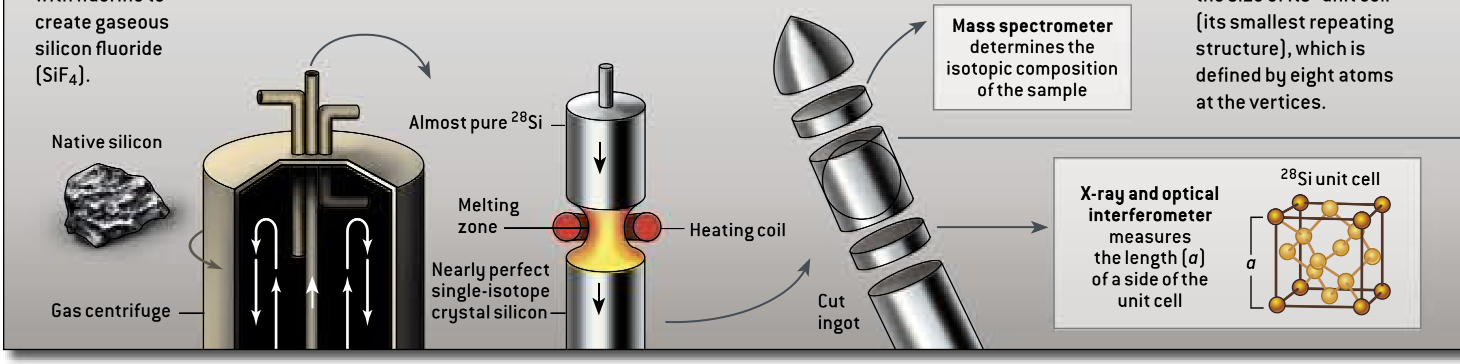
2 Researchers place the SiF_4 in centrifuges, which spin rapidly to separate the lightest isotope, ^{28}Si, from the others.

3 The resulting solidified material has a ^{28}Si concentration of around 99.99 percent. Workers then melt the refined silicon and make an ingot of nearly perfect crystalline silicon.

4 They next slice the recrystallized ingot into a large cylindrical work piece and several smaller samples for analysis.

5 Researchers place one sample in a mass spectrometer to ascertain the material's purity and thus its average molar mass (*m*), its mass per mole.

6 The other sample is analyzed using interferometry to measure the distance between the crystal's atomic planes. From this length, researchers find the size of its "unit cell" (its smallest repeating structure), which is defined by eight atoms at the vertices.



stant, the number of atoms in 12 grams of carbon 12, and the other involving Planck's constant, the fundamental value physicists use, for example, to calculate a photon's energy from its frequency. Because scientists measure constants in SI units (including the kilogram), any drift in the IPK's real mass will give rise to a drift in the value of a measured constant—a seeming paradox for what is commonly considered an immutable phenomenon. In the process of more accurately redefining the kilogram independently of the IPK, however, scientists will choose a best estimate of the constant's value and thus "fix" it.

Web of Measurements

THE PRESENT DEFINITION of the kilogram requires that all SI mass measurements carried out in the world be related to the mass of the IPK. ("Mass" is commonly equated with "weight," but technically the "mass" of an object refers to the amount of matter in it, whereas its "weight" is caused by the gravitational attraction between the object and the earth.) To forge this link, metrologists remove the IPK from its sanctuary every 40 years or so to calibrate the copies of the IPK that are sent to the International Bureau of Weights and Measures by the 51 national signatories of the "Meter Convention"—the treaty that governs the SI. Once equilibrated, these copies are used to calibrate all other mass standards of the member states in a long, unbroken sequence that propagates down to the weighing scales and other instruments employed in laboratories and factories around the globe.

It makes economic sense to have a stable, unchanging standard of mass, but evidence indicates that the mass of the IPK drifts with time. By observing relative changes of the other mass standards fabricated at the same time as the IPK and by analyzing old and new measurements of mass-related fundamental constants (which are thought not to change significantly over time), scientists have shown that the mass of the IPK could have grown or shrunk by 50 micrograms or more over the past 100 years. The drift could have been caused by such things as accumulated contamination from the air or loss from abrasion. Because the base units of the SI underpin worldwide science and industry (via the national standard calibration chains), ensuring that they do not vary with time is critical.

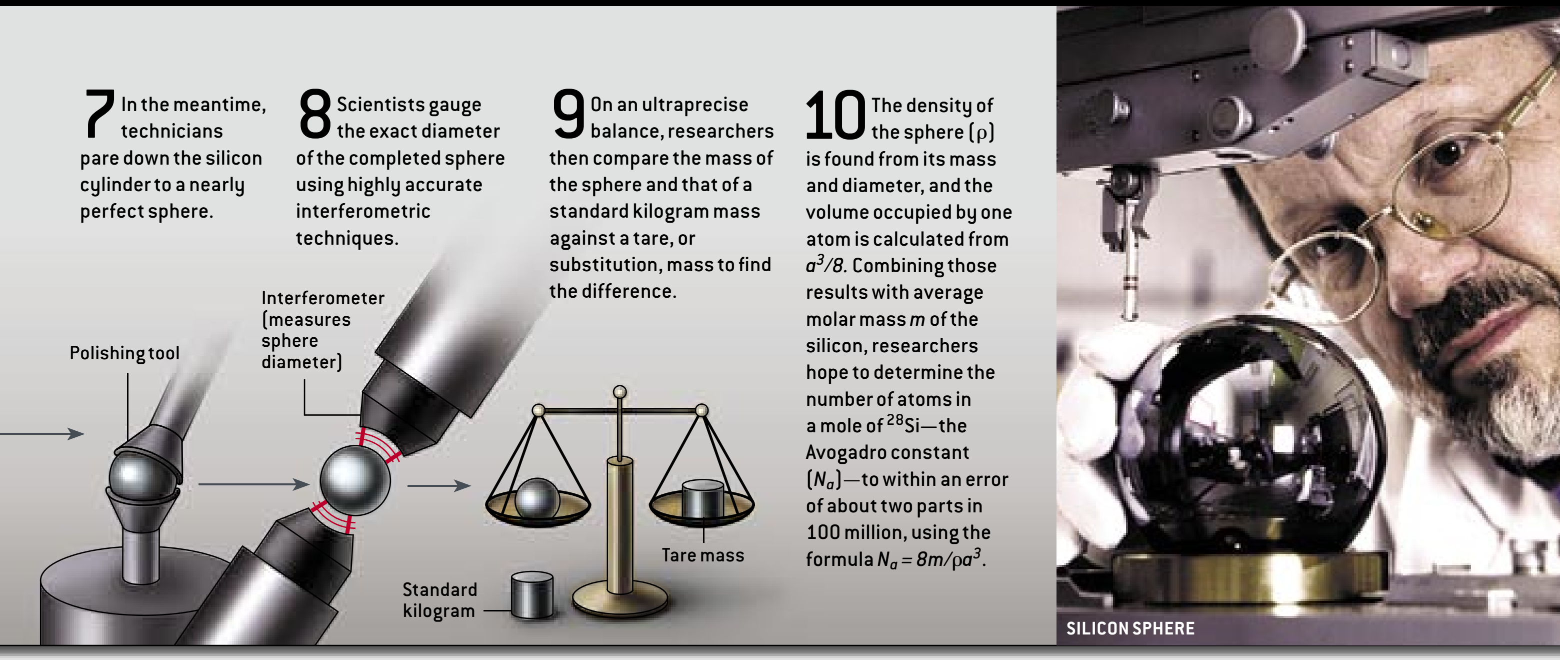
Based on Nature

THE SAME INCONSTANCY that plagues the definition of the kilogram previously affected the second and the meter. Scientists once defined the second in terms of the rate of rotation of the earth. In 1967, however, they redefined it to be "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." Metrologists introduced this change because the rotation rate of our planet is not constant, whereas the wavelength of the radiation

Overview/*Kilogram Redefined*

- For more than a century, metrologists have relied on a metal cylinder the size of a plum to standardize for the world the basic unit of mass, the kilogram. Continued technological progress requires that a new definition be developed, one based on a fundamental property of nature.
- Two methods are being pursued. One approach meticulously calculates the number of silicon atoms in a kilogram of pure silicon. The other effort employs an indirect comparison of mechanical and electrical power to measure the kilogram using length, time and quantum-mechanical effects.

RICK JONES (*scale on page 102*); COURTESY OF NATIONAL INSTITUTE OF METROLOGICAL RESEARCH, TORINO, ITALY (*preceding page*); JEN CHRISTIANSEN (*illustrations above and opposite page*)



CSIRO AUSTRALIAN CENTER FOR PRECISION OPTICS (*photograph*)

emitted by cesium 133 during a specific transition—that is, the ticking of an atomic clock—does not alter with time and the measurement can be reproduced anywhere in the world.

Although the definition of the second is not based on an artifact, it suffers from its dependence on a particular transition of a specific atom, which unfortunately turns out to be more sensitive to electromagnetic fields than is desirable. The definition may need to be changed in the future to accommodate the even more precise optical clocks that physicists are now developing.

The definition of the meter, on the other hand, is firmer. The SI originally based the meter on an artifact—the distance between two lines inscribed on a highly stable platinum-iridium bar. In 1983 the meter definition was switched to "the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second." This definition should also be resilient because it fixed the value of a key physical constant, the speed of light, at exactly 299,792,458 meters a second. Thus, progress in the control and measurement of the frequency of electromagnetic radiation (the number of sinusoidal vibrations a second) will merely improve the accuracy with which scientists can measure the meter—with no change in the unit's definition required.

Atomic Accounting

TO REDEFINE THE KILOGRAM in terms of a physical constant, metrologists measure the value of the constant as accurately as possible using the existing definition of the mass unit. This number can then be incorporated into the new definition to ensure a seamless transition between the old and new ones. Researchers can then employ the measurement method, in conjunction with the now fixed value of the constant, to determine mass according to the new definition.

One promising approach relates the kilogram to the mass of an atom by quantifying the kilogram as the mass of a certain number of atoms of a selected element. This route would fix the value of the Avogadro constant, which is defined as the number of atoms of a specific element in a mole—about 6.02×10^{23} atoms. (A mole is the amount of an element that has a mass in grams equal to the element's atomic weight; a mole of carbon 12 has a mass of 12 grams.) The problem with this strategy, however, is that it requires one to count enough atoms to make a weighable quantity of material for comparison with a kilogram mass. Because several physical effects limit the accuracy and resolution of balances to around 100 nanograms, a minimum of five grams of material would be needed to approach the target accuracy of approximately two parts in 100 million. Sadly, physicists cannot count out atoms rapidly enough; even if a counter capable of tallying individual atoms at a rate of one trillion a second could be produced, the device would take about seven millennia to tally enough carbon 12 atoms.

Scientists could, however, determine the number of atoms in a perfect crystal by dividing the volume of the crystal by the volume occupied by a single atom. If the crystal is then weighed and the mass of the atomic species that makes up the crystal is known relative to that of carbon 12, they can calculate the Avogadro constant from these data, thereby providing a path to the redefinition of the kilogram.

This more practical method, which is now being pursued, first measures the volume occupied by an atom by determining the regular spacing of atoms within a nearly perfect crystal (with a known number of atoms per unit cell) of known weight, close to one kilogram. Then, by determining the dimensions of the crystal, scientists can find the total volume, from which the mass of an atom in the sample can be calculated. The Avogadro constant, which is calculated from the ratio of the molar mass of an element to the mass of an atom, could then be derived from the results.

Although this plan is simple in concept, researchers have difficulty implementing it because of the extreme degree of precision it entails. Indeed, the high complexity and cost of this project mean that no one facility can hope to carry it out alone. Consequently, the load is being shared among a consortium of laboratories in Australia, Belgium, Germany, Italy, Japan, the U.K. and the U.S.—the International Avogadro Coordination. For this technique to work, the crystal must have an almost perfect structure; it must contain few voids or impurities. Project scientists chose to make the crystal out of silicon because the semiconductor industry has studied it closely and has developed procedures to grow large, practically perfect, single crystals. Once researchers had completed all the measurements of the crystal, they could relate the results to the carbon 12 definition of the mole using the extremely precise relative atomic masses of silicon and carbon obtained from mass spectrometers.

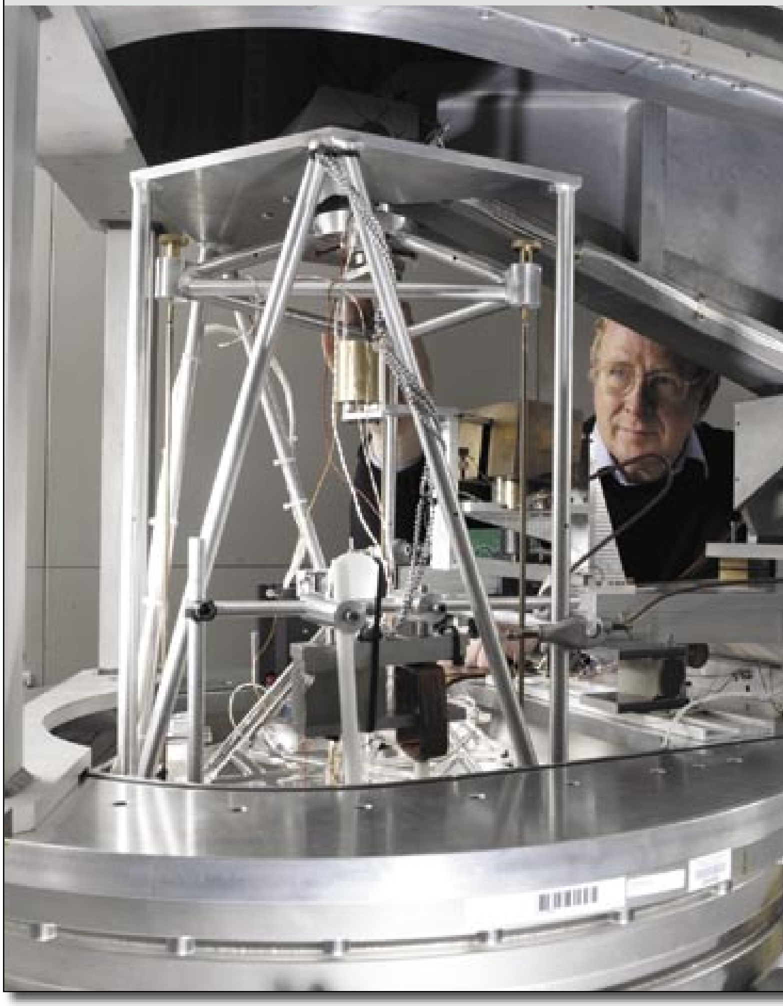
To begin the procedure, they cut several samples from a raw crystal. One was polished to form a one-kilogram sphere to measure [*see box on preceding two pages*]. Planners selected a rounded shape because a ball has no corners that could get knocked off and because craftsmen already knew how to hone silicon into a close approximation of a perfect sphere. Australian technicians fabricated a sphere with a diameter of 93.6 millimeters that departs from the ideal by no more than 50 nanometers. If each silicon atom were the size of a large marble (about 20 millimeters across), the sphere would equal the approximate size of the earth, and the distance between the highest and lowest “altitude” on its surface would be about seven meters (about 350 marbles in length).

To find the volume of the silicon sphere, researchers had to determine its average diameter to within the diameter of an atom. They first carefully reflected laser light of a known frequency off opposite sides of the sphere in a vacuum and gauged the difference in light paths (in wavelengths) with the sphere present and absent. This step enabled them to find its diameter in meters, as the wavelength of the light is equal to the (fixed) speed of light divided by the known laser frequency. Scientists then calculated the volume from the diameter, together with a few small corrections related to the slightly imperfect shape of the crystal and the optical properties of the surfaces.

Researchers obtained the volume occupied by one atom using combined x-ray and optical interferometry to find the distance between atomic planes in a sample cut from the raw crystal. Technicians machined several slots into the sample so that one part of the crystal could be moved reproducibly with respect to the rest of it while maintaining the angular alignment of the atomic planes. The sample was placed in a vacuum and illuminated with x-rays having a wavelength small enough to reflect easily from the atomic planes in the crystal. They then used the strength of this reflection, which varies according to the relative position of the atomic planes in the moving and stationary parts of the crystal, to count the number of plane spacings the repositioned part of the crystal had shifted. Scientists simultaneously measured the translation distance using a laser interferometer that used light of a known frequency. This technique determined the interplane spacing in meters. Using

FROM A WATT BALANCE TO A KILOGRAM STANDARD

Another approach to redefining the kilogram quantifies a mass in terms of its energy equivalent. It relies on adjusting the force produced when a current passes through a wire in a magnetic field to balance exactly the weight of a mass. The procedure makes use of a sophisticated scale called a watt balance (*below*). On one side of the scale sits a simple counterweight (*diagrams*). On the other, a standard kilogram of mass *m* dangles above a horizontal coil of wire. The weight of the standard is the product of *m* times the acceleration caused by gravity *g*.



COURTESY OF NATIONAL PHYSICAL LABORATORY, U.K., © CROWN, 2005

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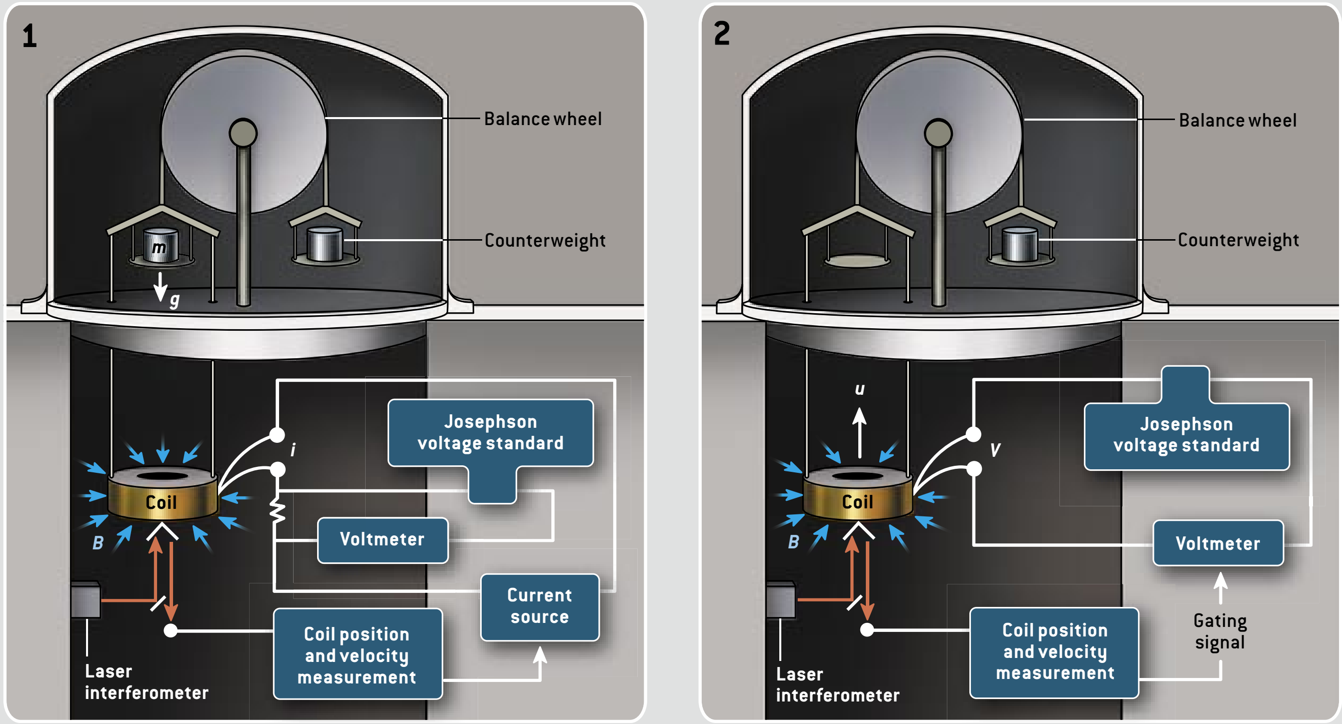

1 WEIGHING PHASE

In the first step, the coil dips into a radial magnetic field and an electric current passes through it. An induced electromagnetic force then acts on the coil, oriented opposite the force of gravity. If this electromagnetic force precisely balances the weight of the standard, one can calculate the standard's mass *m* as:

$$m = BLi/g$$

where *B* is the magnetic field strength, *L* is the length of wire in the coil, and *i* is the electric current. Unfortunately, in practice the product *BL* is almost impossible to gauge directly with sufficient accuracy.

2 MOVING PHASE

If, however, the coil moves at a constant velocity *u* at right angles to the magnetic field, the entire coil generates a voltage *V* that is equal to *BLu*. (This process is equivalent to the operation of an electric generator.) Voltage and velocity can both be measured very precisely. One can then eliminate the problematic product *BL* from the equation above:

$$m = Vi/gu$$

The final result equates mechanical and electrical power. The mechanical power measured is equivalent to that obtained if the mass is moved vertically with velocity *u*, whereas the electrical power is equivalent to that dissipated in an ideal resistor with voltage *V* across it and the current *i* passing through it. Because the two measurement phases are separated in time, however, the power is not real (scientists call it "virtual power"). These "virtual" measurements allow the technique to ignore the real power that is generated or dissipated in both phases of the experiment, which makes it possible to achieve the low uncertainties that are required.

During the experiment, several high-accuracy measuring systems monitor the watt balance. A laser interferometer measures the coil's movement, which is timed against an ultraprecise reference signal. A sensitive gravimeter (*not shown*) monitors the local pull of the earth's gravitational field. Other devices based on the Josephson effect and the quantum Hall effect [*see box on next page*] measure the voltage and current with extraordinary precision. Scientists can therefore link the mass of a kilogram to the Planck constant of quantum theory, the meter and the second with an extremely high degree of precision.

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knowledge of the crystal structure, they then found the volume occupied by an atom.

Metrologists ascertained the mass of the crystal sphere by "substitution weighing" using a conventional balance and a "tare mass," whose mass must be stable but need not be known. They placed the sphere on a balance and compared it against a separate one-kilogram tare mass sitting on the other arm of the balance. They then substituted the sphere with a mass known in terms of the IPK mass standard and repeated the weighing process. Because the substitution was carried out so that the balance remained unaffected by the switch, the difference in the two readings gave the difference in mass between the sphere and the mass standard, which revealed the mass of the sphere. This method eliminated error arising from factors such as unequal lengths of the balance arms.

The researchers also analyzed other samples of the silicon material to establish the relative abundance of the various isotopes to account for their differing contributions to the molar mass of the sphere. To accomplish this task, they had to determine the proportion of the three isotopes—silicon 28, silicon 29 and silicon 30—present in the natural silicon crystal. For this step they used mass spectroscopy, which separates charged isotopes according to their different charge-to-mass ratios.

The IAC has nearly completed work on the natural silicon spheres, having thus determined the number of atoms in a one-kilogram sphere with an accuracy close to three parts in 10 million. But this accuracy is not good enough. To achieve higher levels, the group is producing a sphere that consists almost entirely of a single isotope, silicon 28. Making such an object will cost between $1.25 million and $2.5 million. Gas centrifuges in Russia that were once employed to refine weapons-grade uranium are purifying the material for the new sphere. The consortium is aiming for an uncertainty in the final result of about two parts in 100 million before 2010.

Weighing Equivalent Energy

THE OTHER PATH to redefining the kilogram is based on the concept of measuring mass in terms of its equivalent energy, a principle that Albert Einstein explained using his famous equation $E = mc^2$, which relates mass and energy at the most fundamental level. Investigators would thus define mass in terms of the amount of energy into which it could (potentially) be converted. As is true of counting atoms, though, the techniques involved have considerable disadvantages. For example, large releases of atomic energy result when mass is converted into energy directly. Luckily, easier methods that compare conventional electrical and mechanical energy or power are feasible, provided that researchers can overcome problems associated with energy losses.

To get a sense of the obstacles to this type of approach, imagine using an electric motor to lift an object having mass m (against gravity). In an ideal situation, all the energy supplied to the motor would go into increasing the potential energy of the object. The mass could then be calculated from the electrical energy E supplied to the motor, the vertical distance d traveled by the object and the acceleration from gravity g, using the formula $m = E/gd$. (The acceleration caused by gravity would have to be gauged very accurately using a precision gravimeter.) In the real world, however, energy losses in the motor and other parts of the system would make an accurate measurement almost impossible. Although researchers have attempted similar experiments using superconducting levitated masses, accuracies better than one part in a million are hard to achieve.

About 30 years ago Bryan Kibble of the U.K.'s National Physical Laboratory (NPL) devised the method now known as the watt balance, which avoids energy-loss problems by measuring "virtual power" [*see box on preceding two pages*]. In other words, by designing a sufficiently clever, two-part procedure, scientists can sidestep the inevitable losses. The method links the standard kilogram, the meter and the second to highly accurate practical realizations of electrical resistance (in ohms) and electric potential (in volts) derived from two quantum-mechanical phenomena—the Josephson effect and the quantum Hall effect, both of which incorporate Planck's constant [*see box at right*]. In the process, the technique allows the value of the Planck constant to be measured very accurately.

In the watt balance, an object having mass m is weighed by suspending it from the arm of a conventional balance to which a coil of wire is also attached with a total length L hanging in a strong magnetic field B. A current i is passed through the coil to generate a force BLi, which is adjusted to exactly balance the weight mg of the mass (that is, $mg = BLi$). The mass and current are then removed, and in a second part of the experiment, the coil is moved through the field at a measured velocity u while the induced voltage V ($V = BLu$) is monitored. This second phase finds the value of the BL product, which is difficult to determine in any other way. If the magnet and coil are sufficiently stable, so that the BL product is the same in both parts

QUANTUM EFFECTS MEET CLASSICAL PHYSICS

Although the principles of the watt balance would be familiar to a 19th-century physicist, its ability to measure mass in terms of fundamental constants arises from two quantum effects discovered only within the past 45 years: the Josephson effect and the quantum Hall effect. Both phenomena occur at the temperature of liquid helium (4.2 kelvins) or below.

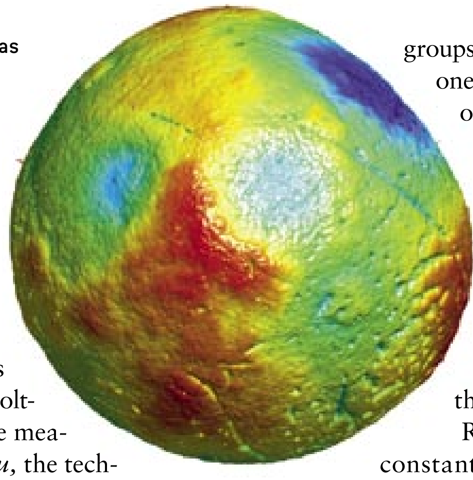
JOSEPHSON EFFECT

A Josephson junction consists of two superconductors separated by a small insulating gap that electron pairs can traverse in a process called quantum tunneling. If such a junction is illuminated with microwaves, the pairs of electrons in the superconductor absorb photons from the microwaves and jump the gap. Under these conditions, the voltage across the gap will be a small multiple of $hf/2e$, where h is Planck's constant, f is the frequency of the microwave radiation and e is the elementary charge. This relation is believed to be exact and provides a voltage standard of unparalleled accuracy.

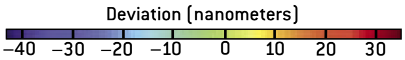
QUANTUM HALL EFFECT

The standard Hall effect occurs in all conductors. The phenomenon occurs when an electric current is passed through a material that is in a magnetic field. The magnetic field generates a force on the charge carriers in a direction perpendicular to both the field and the current. These conditions cause electric charge to build up on the sides of the device, producing both a voltage and a corresponding electric field that opposes the magnetic force on the carriers. This voltage is proportional both to the applied current and the magnetic field, so the effect can be thought of as a resistance to electric flow (the Hall resistance), which is proportional to the magnetic field.

In specially fabricated semiconductors that are subjected to low temperatures (in the range of 1.2 to 0.03 kelvin) and high magnetic fields, the quantum-mechanical version of the Hall effect can be observed. Under these conditions, and over small ranges of magnetic field, the quantum Hall resistance becomes independent of both the magnetic field and the semiconductor material; it is equal to h/ne^2, where n is a small integer. This equation provides scientists with a quantum-based standard for measuring electrical resistance.



SILICON SPHERE, 100 millimeters in diameter, was measured with an x-ray optics calibration interferometer. The colors in this digital image show the deviations from sphericity.



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of the procedure, the results can be combined to give $mgu = Vi$, which states the equality of mechanical power (force times velocity, mg times u) to electrical power (voltage V times current i). By separating the measurements of V and i as well as mg and u, the technique yields a result that is not sensitive to the loss of real power in either part of the experiment (that is, heat dissipated in the coil during weighing or frictional losses during moving), so the apparatus can be said to have measured "virtual" power.

Scientists determine the electric current in the weighing phase of the watt balance procedure by passing it through a resistor. This resistance is specially gauged using the quantum Hall effect, which permits it to be described in quantum-mechanical terms. The voltage across the resistor and the coil voltage are measured in terms of quantum mechanics using the Josephson effect. This last result allows researchers to express the electrical power in terms of Planck's constant and frequency. Because the other terms in the equation depend only on time and length, researchers can then quantify the mass m in terms of Planck's constant plus the meter and the second, both of which are based on constants of nature.

The method's principle is relatively straightforward, but to achieve the desired accuracy of approximately one part in 100 million, scientists must determine the major contributing quantities with an accuracy at the limit of many of the best available techniques. Besides measuring g very accurately, they have to perform all the procedures in a vacuum to eliminate the effects of both air buoyancy during the weighing process and the air's refractive index during the velocity measurement (which uses a laser interferometer). Researchers must also precisely align the force from the coil to the vertical direction and perform angular and linear alignments of the apparatus to a precision of at least 50 microradians and 10 microns, respectively. Finally, the magnetic field has to be predictable between the two modes of the watt balance, a condition requiring that the temperature of the permanent magnet vary slowly and smoothly.

Three laboratories have developed watt balances: the Swiss Federal Office of Metrology, the National Institute of Standards and Technology (NIST) in the U.S., and the NPL. Meanwhile the staff of the French National Bureau of Metrology is assembling prototype equipment, and that of the International Bureau of Weights and Measures is designing an apparatus. Ultimately these efforts will yield five independent instruments with varying designs, so the extent to which their results agree will indicate how well researchers have identified and eliminated systematic errors in each case. The long-term goal of these groups is to measure Planck's constant to around one part in 100 million, with the possibility of approaching five parts in a billion.

Weighty Future

THE LATEST RESULTS from the work on the Avogadro constant and those from the NPL and NIST watt balances differ by more than one part in a million. Researchers must reconcile this discrepancy before a redefinition of the kilogram will be possible.

Redefinition in terms of the Avogadro constant or Planck's constant will have widespread effects, reducing reported uncertainties associated with those constants. Moreover, if Planck's constant and the elementary electric charge are fixed (by combining, for example, watt balance and calculable capacitor measurements), many other important constants would also be fixed.

The International Committee for Weights and Measures has recommended that national measurement laboratories continue their efforts aimed at measuring the fundamental constants that support the redefinition process. Researchers hope that these steps will lead to new standards not only for the kilogram but the ampere, the kelvin and the mole by 2011.

Once the redefinition is complete, a few nations will build or maintain the equipment necessary for implementing the definition directly. Those that do not will have their standards calibrated using a consensus value for the kilogram derived from the laboratory work. Still, fears of damaging or contaminating a single master reference standard should fall away because comparisons between national standards and a working standard based on the new definition could be performed as needed. The new definition would allow authorities to adjust the world mass scale in tiny steps every so often to keep it free of drift and fully locked to the best—the latest consensus and independently confirmed—value of the SI unit of mass. Such a system would be robust and stable, allowing scientific and technological progress to continue unabated. SA

MORE TO EXPLORE

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