Recipe for a Kilogram

By counting atoms and generating standard forces, physicists are closing in on an absolute standard for the kilogram, the one fundamental unit still tied to an artifact

Richard Deslattes has a problem with the kilogram: It's a *thing*. Although the meter, the second, and the other four "base units" are all defined in terms of universal constants such as the speed of light or the quantum ticks of an atom, the official kilogram is just a hunk of platinum-iridium locked in a safe in France. It could be lost or damaged. It is probably gaining weight. It is definitely provincial. "If we wanted to communicate our knowledge of the world to some extraterrestrial group, we could encode everything in binary, except the kilogram," says Deslattes. As for the mass standard, "we'd have to throw it."

So partly as a matter of principle, and partly to stay a step ahead of the world's requirements for a stable measure of mass, Deslattes wants to change the standard. The physicist at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, and his colleagues in the standards community are trying to replace the lump of metal with a simple number that would specify exactly the same mass. They hope to define the kilogram as the mass of a specific number of atoms—say, 10^{25}-odd atoms of silicon—or as a weight equivalent to the force generated by a wire carrying a standard current wrapped around a magnet. The result would be a universal kilogram standard that could be recreated anywhere and that would be guaranteed by the laws of physics.

Beating out the original won't be easy. Any replacement will have to vary by less than one part in 10^8, a level of precision that will force scientists to worry about effects as small as missing atoms and the gravitational tug of the tides. But at the upcoming Conference on Precision Electromagnetic Measurements (CPEM) in Washington, D.C., this July, physicists plan to announce that they are on the verge of breaking into that last decimal place. If they can push a little further, the old artifact may be headed for the scrap heap.

By any standards, the kilogram (also known as "Le Grand K") has held up remarkably well during its 100 years at the International Bureau of Weights and Measures (BIPM) in Sèvres, France. In 1989 scientists at the BIPM removed the kilogram from its triple bell jar for only the third time, weighed it against some copies, and concluded that its mass was drifting by less than 5 millionths of a gram per year. The metal artifact sits in "the ordinary humid air of the suburbs of Paris," which has all kinds of contaminants that could build up on its surface, explains BIPM director Terry Quinn. Official policy is to clean the kilogram before using it to calibrate any copies (*Science*, 12 May 1995, p. 804), but its weight still wanders. "It's amazing it's as stable as it is," Quinn says.

The standards community could have an absolute guarantee of stability, however, if it could peg the macroscopic kilogram to unchanging microscopic quantities. There are two camps: The "atom counters" (as Deslattes calls them) would link it to the unchanging atomic mass of a specific element (times a very large number). The "force measurers" would rely on electrical units of voltage and resistance, which ultimately rest on immutable numbers such as Planck's constant, which describes the spacing of the electron orbitals in an atom. Both techniques confront weighty problems. "The standards racket is tough," says Deslattes, who is widely regarded as the first atom counter.

CSIRO, AUSTRALIA

One plan for a new kilogram. A sphere of crystalline silicon, ready to have its atoms counted.

Atom by atom

Establishing a standard based on atom counting sounds simple: Just figure out how many atoms are in a known mass of a particular material. Atom counters approach the problem roughly like a geometry student estimating how many gum balls are in a gumball machine. From the size of the gum balls and of the glass sphere that houses them, it's possible to get a rough idea of how many fit inside. In the atomic version, the sphere is solid and made of crystal silicon whose atoms are arranged in a regular rectangular lattice. Scientists measure the size of the sphere and the distance between the atoms in the lattice.

That's enough information to count the atoms in the sphere but not enough to give a cookbook recipe for constructing another one that will have exactly the same mass. Silicon comes in various isotopes, which have slightly different masses, so to completely describe one of these spheres from the atom up, scientists also have to know its exact isotope concentrations—the proportion of its atoms that have 15 neutrons instead of the usual 14, for instance.

Subtle details like that have made atom counting an international enterprise, as each step requires equipment and expertise available in only a few places. The spheres begin as ultrapure silicon rods manufactured by companies in Germany or Japan. Then Australia's National Measurement Laboratory in Sydney polishes the rods into 93-millimeter-diameter spheres, perfectly round to one part per million. Standards labs in Germany, Italy, and Japan each take a sphere home and measure its mass relative to the kilogram, its volume, and, using x-rays, the distance between atoms. Bits of silicon also go to the Institute for Reference Materials and Measurement (IRMM) in Geel, Belgium, where researchers vaporize them and sift out the isotope concentrations by mass spectrometry. Each component "requires an absolute, deep, exquisite knowledge of measurement science," says IRMM's Paul De Bièvre.

Over the years that understanding deepened, and the error bars shrank. But in 1994 the field hit a wall. Researchers from the labs in Japan, Germany, and Italy came together at an international conference to compare their results. The labs converted their silicon atom counts into a common currency—the Avogadro constant, or the number of carbon-12 atoms in 0.012 kilograms. Their values were miles apart. "The Japanese number was very different from the two Italian and German numbers," recalls Giovanni Mana of Italy's metrology lab, the IMGC in Torino. The difference was some 10^{18} atoms, or three parts in

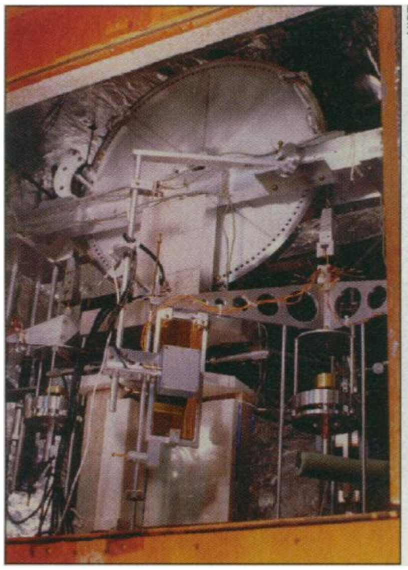
10^6—10 times what the estimated uncertainties would allow.

So the groups retraced their steps, looking for something that could have tripped them up. They swapped bits of silicon to compare lattice spacings, rechecked the isotope measurements, and reweighed their spheres, but couldn't find a hitch. "It was torturous," Deslattes recalls. Last year the researchers gave up and tried a different tack. Maybe, they thought, the problem lay not with the scales or mass spectrometers, but inside the lattice itself. Maybe the lattice had holes.

Deslattes tested the hole hypothesis recently, using a high-resolution x-ray technique to see inside the silicon. To his delight, he found what appeared to be small voids a few micrometers wide in some of the rods, where trillions upon trillions of atoms were missing. "It's as if someone had taken a bite out of the crystal and closed it up," he says. Deslattes thinks the voids could have been formed by gas bubbles trapped in the silicon during the manufacturing process. The density of voids in the Japanese silicon, Deslattes says, is enough to explain the discrepancy. "It's premature to declare victory," he says, "but when I saw those images, I actually let out a little whoop! For a very old man, that's really something."

Mana is also excited by the news: "If Deslattes's results are correct, we will be put on solid ground and we can [explain] the anomalous results." Michael Gläser at the German standards lab, the PTB in Braunschweig, agrees. "If you could measure the density of holes," he says, then that might bring the accuracy of the method to four parts in 10^7, just a factor of 10 away from mounting a challenge to the kilogram artifact.

Deslattes thinks it might be possible to measure the hole density by diffusing copper into the holes and then separating out and weighing the copper. Peter Becker, who leads the atom-counting effort at the PTB, is also looking into a technique that would use neutrons to probe and gauge the size of the holes. If the holes can be conquered, the next step would be to improve the measurement of the isotope abundances. "It's the [next] bottleneck," says Kan Nakayama, a researcher at Japan's National Research Lab of Metrology (NRLM).



NIST

Another plan for a kilogram. An electromagnetic Watt balance.

Force field

Although the atom counters appear to be back on track, the force measurers are also inching forward. Their goal is to find a way to reliably manufacture an electromagnetic force that exactly balances the force of gravity on a kilogram. Then that electromagnetic force could be used instead of the metal standard. Bryan Kibble, a physicist at the National Physics Laboratory (NPL) in Teddington, U.K., first proposed the modern "Watt balance" in the mid-1970s. "It's been a rock on my back for the past 15 years," he confides. "The work is very slow and painstaking."

Fortunately, Kibble's group has some company. At NIST, a group led by Edwin Williams recently finished new measurements with its own Watt balance. The device is a full two stories tall and sits in an isolated wooden building to minimize vibrations and electromagnetic disturbances. Like a conventional scale, the balance has two pans and tips toward the one with the heavier contents. But instead of being hung from either end of a beam, the pans are essentially suspended from the ends of a flat cable running over a half-meter pulley. The pulley allows the pans to move up and down without moving sideways as well, as they do in a conventional balance.

Hanging below each pan from rigid rods is a wire coil, which fits around a cylindrical magnet that is fixed to the base. Running a current through a coil generates an electromagnetic force, which drives it up or down the magnet, pulling the pan along with it. When a kilogram of gold (a copy of the official one) is placed on one of the pans, the currents are adjusted to keep it from tipping. Because gravity—and hence the weight of the gold kilogram—changes with the tides, the researchers have a state-of-the-art gravimeter nearby to measure the local gravitational tug. Folding all these numbers together, the researchers can measure the kilogram's mass in terms of standard units of voltage and current.

Understanding the nuances of the balance has taken years. Just recently the group realized that the kilogram sat in a cold spot and was probably gaining a bit of weight from moisture condensing from the air. They solved that problem, but last September the kilogram weighed in a little on the heavy side for a couple of months before returning to its old value. "We still don't know exactly what fixed it," Williams says, shrugging. "Time seemed to help."

After years of tinkering, the NIST group now thinks its balance could be used to monitor fluctuations in an object's mass at the level of 1.5 parts in 10^7, a two-fold improvement over Kibble's earlier work. The real test is to compare their definition of the kilogram with the NPL experiment. The NIST group won't release final numbers until the CPEM conference, but Williams says the news is good—the two experiments agree. His team is now building a new balance that will sit in a vacuum, which they hope will eliminate convection currents that could disturb the balance and should also keep variations in air pressure from throwing off the laser interferometer that measures the position of the balance pans. In England, Kibble is already running his balance in a vacuum chamber and thinks he can attain an accuracy twice as good as NIST's.

Indeed, physicists from both camps think they may reach an accuracy of one in 10^8 in the next decade, which would put them within shooting range of the kilogram artifact. And several variations of the two approaches are in the works. The Swiss Federal Office of Metrology is currently working on a scaled-down version of the Watt balance that would be easy to transport, and a group at the NRLM is hoping to replace the Watt balance with a magnetic levitation system.

On the atom-counting front, Gläser is also working on a new method that would send a stream of gold atoms into a box, counting them like beans as they pile up. By giving the atoms an electric charge and monitoring the current they carry, he says, it's possible to get a good head count. After a week or so 10 grams would accumulate—enough to weigh. Gläser thinks his approach could rival the others in a decade or so. Other scientists are less optimistic, but encouraging. "It's going to be very challenging," says the IRMM's De Bièvre, "but probably fruitful."

"Ideally," says Williams, "we would like to have both methods work." That way they could have a new kilogram and something to double-check it with. Terry Quinn, the keeper of Le Grand K, says that the new method would probably serve first for monitoring the old standard to see how its weight wanders. And when the BIPM does change the definition for the kilogram, he says, it won't be handing out Watt balances or silicon spheres. Even if Le Grand K is dethroned, metal kilograms will still set the standard for laboratory balances and supermarket scales.

–David Kestenbaum