The kilogram is the only unit of measure still defined by a physical object. Now, a marathon effort to tie the kilo to a constant of nature is nearing the finish line

A Most Unbearable Weight

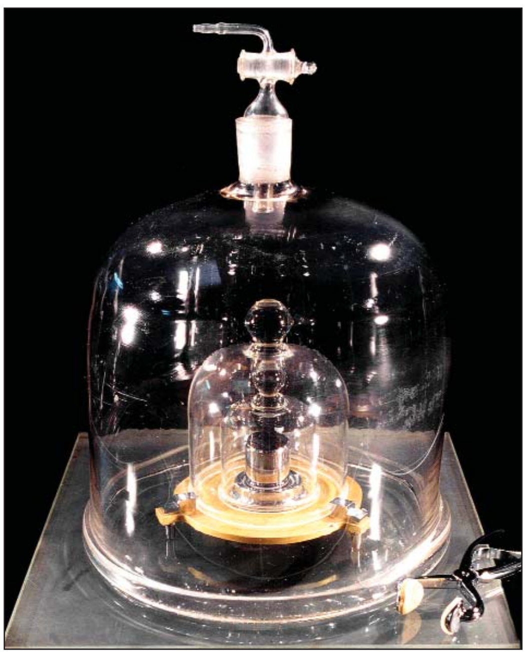
London—"You're in luck!" says Stephen Downes. An unlikely looking treasure is making a rare foray into open air. Perched on the pan of a balance in the U.K.'s National Physical Laboratory is a squat cylinder of metal, some 4 centimeters tall, with a faint number 18 engraved on its dull gray side. This unprepossessing lump is so precious that it spends most of its life locked away in a bombproof subterranean vault.

That's because "kilogram-18," as it is known, is the ultimate arbiter of every weighing scale in Britain. Like its clutch of siblings around the world (the U.S. equivalent, kilogram-20, is converted into pounds), number 18 is ruled over by a chunk of metal in Paris. Dubbed "Le Grand K," this is the granddaddy of weights the world over, the literal embodiment of the kilogram, and it has been removed from its heavily guarded chamber just three times in 120 years.

The care with which these objects must be handled is a constant exasperation to physicists. "It's a dinosaur of a process," says Downes. Whereas other units of measurement are defined by constants of nature such as light speed or atomic vibrations, the kilogram alone in the scientific lexicon is still tied to a physical object. "The kilogram is a black spot on the white jacket of the entire measuring system," says Peter Becker of Germany's national metrology institute, the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig.

Researchers around the world have been trying to eradicate this spot for decades, using approaches ranging from counting the number of atoms in a kilogram to converting the mass into a kind of electric force. Now at last the electric approach is pulling ahead of its rivals, and results due later this year or early next year could finally set in motion the redefining of the kilogram. The atom counters, however, have not yet given up hope. Last month an international consortium began a last-ditch attempt to bring its troubled project back into play.

The problem is more than aesthetic: Unlike physical constants, an artifact can change over time. Although kilogram-18 and the other national standards have differed very little from the one true kilogram in Paris over the past century, they could still be changing in unison. All were forged in the 1880s in a heavily polluted London, and if molecules of pollutants have been slipping back out of the metal matrix, the standards may have been losing mass ever since. Or they may have gained mass. The atmosphere contains more mercury than it did 100 years ago, and the kilograms are made from an alloy containing platinum, which soaks up mercury.



One kilogram, précisément. Standard kilograms, including Le Grand K (shown here in its glass cage), may have changed mass since they were forged in the 19th century.

"That's the scary part," says Richard Steiner of the U.S. National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. "We believe that they're not changing very badly or noticeably, but because there's no absolute way to measure we don't know for sure."

A fine balancing act

Elsewhere in the National Physical Laboratory, Downes's colleague Ian Robinson is tweaking the apparatus that he hopes will put kilogram-18 and kin out of business. Known as a "Watt balance" after the unit of electrical power, it stands some 2 meters tall in an air-conditioned inner sanctum. It looks at first like a sophisticated version of any standard set of weighing scales, its centerpiece a hefty aluminum arm bearing metal balance plates on either end. But the right side is simply a counterweight. On the left, the action end, a standard gold-plated kilogram (a copy of the original) dangles above a spiderlike Pyrex cage wrapped with copper coils. The cage dips into a magnet so strong that even the stray field outside its casing can stop analog watches in their tracks, and any wrenches in the room must be carefully hooked on bolts to prevent them from crashing into its walls.

As the wire coil sits in its magnetic field, a current passing through it generates an upward electromagnetic force. Robinson adjusts the current until this force exactly balances gravity's downward pull on the kilogram. Next, he removes the kilogram and measures the strength of the magnetic field by moving the coil down through the magnet and monitoring the voltage generated. A laser pointing up through the barrel of the magnet measures the coil's movement, and the time it takes is judged against an ultraprecise reference signal piped in by cable.

Elsewhere in the room, machines are busily measuring other parts of the equation. A six-legged gravimeter monitors the pull of Earth's gravitational field, and a large stainless steel Dewar contains devices that measure the wire's voltage with extraordinary precision, thanks to quantum effects that force electrons to adopt exact energy levels, like rungs on a ladder.

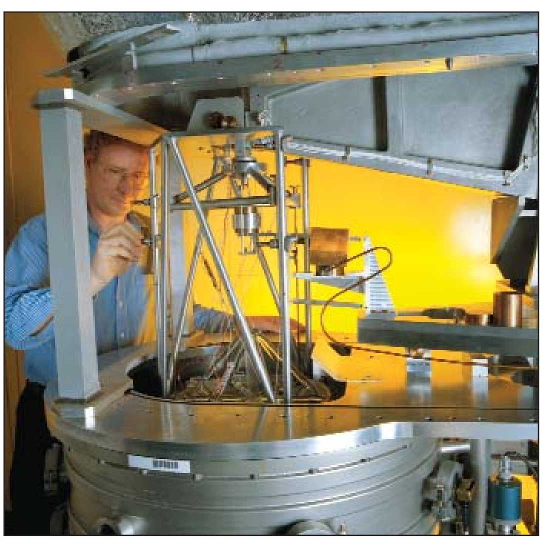
Robinson's goal is to tie the kilogram to fundamental constants of nature with an accuracy of one part in 100 million, which is a little less than the amount by which Le Grand K and its siblings have drifted apart over the past century. If he succeeds, he will be able to redefine the unit of mass in terms of length, time, gravity, and a number called Planck's constant, which is related to the spacing of energy levels in the quantum ladder.

To achieve this, the machine must be staggeringly sensitive. Even a faint thumbprint on the test mass would send the results way out of whack, as would any stray vibrations. Experiments are run at night when the building is otherwise unoccupied; during runs, a red tube on the wall lights up, advising researchers to "MOVE GENTLY."

Robinson has flirted with measurements at a level of parts per 10^8, but he has been chary of publishing because the values drift frustratingly after just a few weeks. He thinks he knows where the problem lies. The measurements must all be made under vacuum to eliminate the buoyancy of air, and Robinson suspects that when he pumps out the air, the delicate machinery's alignment shifts slightly. He is now exploring how to realign the machine after the air is removed.

Meanwhile, a Watt balance at NIST also looks promising. In 1998 Steiner and his colleagues published results accurate to one part in 10 million. With a revamped machine, they are obtaining values at a few parts in 10^8, although they too are plagued by drift. Steiner thinks that electrical noise is skewing the results: "The smaller the effect, the more causes you possibly have, and that's what makes it hard."

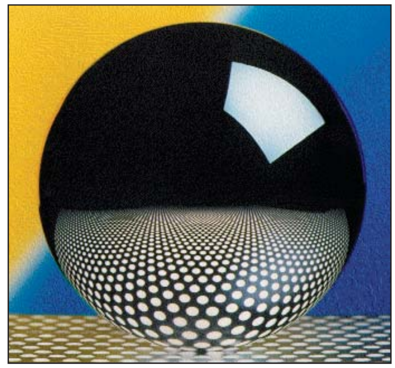
Still, the success of these two Watt balances has brought new machines springing up like mayflowers. The Swiss have a prototype in operation, and one is being built in Paris. "It's a very powerful technique," Robinson says. "Though they all use the same basic approach, this machine, the one at NIST, and the Swiss one are physically completely different. If they all produced the same value independently, it would be a very strong indication that the technique is working. And that's the sort of assurance you need before you can start talking about redefining."



Metrological alchemy. The U.K. National Physical Laboratory's Watt balance is one of several striving to convert a kilogram mass into constants of nature.

Atomic number crunching

Just as things are looking good for the Watt balance teams, their chief rivals, the atom counters, have hit a severe problem. This approach is more intuitive than the complex Watt balance method is: It simply involves counting the number of atoms in a known mass. Adding up something like 10^{23} atoms individually would take far too long, so several groups have been trying to find clever ways of speeding up the process. Michael Gläser of Germany's PTB has been sending a beam of gold ions into a collector and using the current they carry to tally them as they accumulate. The trouble is that ions can bounce. Any ions that deliver their charge but then spring back out of the box send the counting hopelessly askew.



Silicon sister. The Avogadro project aims to peg the standard to the number of silicon atoms in a 1-kg sphere.

More promising is an international collaboration named after the Avogadro constant, the total number of carbon-12 atoms in 0.012 kilograms. The Avogadro project involves grapefruit-sized, ultrapure silicon spheres, manufactured so that each is a single crystal with no internal voids. Measuring the diameter of the spheres and the spacing between their atoms should reveal exactly how many atoms they contain.

The problem is that even the purest silicon from the semiconductor industry comes in an array of isotopes, each with a slightly different mass. So the Avogadro researchers must know the precise combination of isotopes in any one sample. And it is in measuring these ratios that they have hit a roadblock. Nearly a decade ago, they came up with an answer to a few parts in 10 million, but try as they might, they have gone no further.

Hoping to get back on open road, the PTB last month signed a contract with former nuclear technologists in Russia to make highly enriched silicon in which 99.99% of the atoms are Si-28. Labs around the world are eagerly awaiting this material, which should be ready in 2006.

However, because the material for a single 1-kilogram sphere will cost more than €1 million, there will be only one to go around. "The game's not over, but it's taken an expensive turn for the Avogadro project," says Downes. And even that single, pristine sphere may contain hidden blemishes. Downes has discovered that a surface film of silicon oxide or organic contaminants could distort the diameter measurement. He acknowledges that these complications put the Avogadro project on the back foot. "The Watt balance does seem to be getting more of an edge," he says.

Other researchers are murmuring that the enriched sphere is beginning to sound like tying the kilogram to yet another physical object. "You can make and measure one perfect silicon sphere, but then that's it," says NIST's Steiner. "You're basically creating a new absolute artifact." Becker disagrees but concedes that, given the astronomical expense involved, this is likely to be a one-off experiment rather than a reliable new recipe for the kilogram. Even so, he says, the enriched silicon should provide a vital test of the Watt balance results. "When you want to change the definition of the kilogram, you need at least two independent methods," says Becker. "If we provide a check on the Watt balance method, we'll have done our job."

And even though confidence is building in the Watt balance labs, researchers there all declare that they and the Avogadro labs are engaged in a collaboration rather than a race. "Nobody will act on one lab's results," says Robinson. "It's going to take a lot of results from a lot of places before anyone is prepared to move away from the kilogram. Even if you come in with your results first, you still have to wait around for everybody else to arrive with theirs."

The verdict from the Watt balances should arrive within the next few years. The final step will be persuading the General Conference on Weights and Measures, the international committee that serves as the guardian of measurement systems, to take the new definition on board.

The Watt and Avogadro scientists, at least, can't wait to consign kilogram-18 and its compatriots to the scrap heap. "We've been doing this the same way since the 18th century, and it would be nice to move on," says Robinson. "A system based on nature will always be better than one based on artifacts, because it's likely that nature will last a little longer."

–GABRIELLE WALKER

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