Why the World is Losing Weight

The world's most exact reference for a kilogramme is getting lighter – and no one knows exactly why

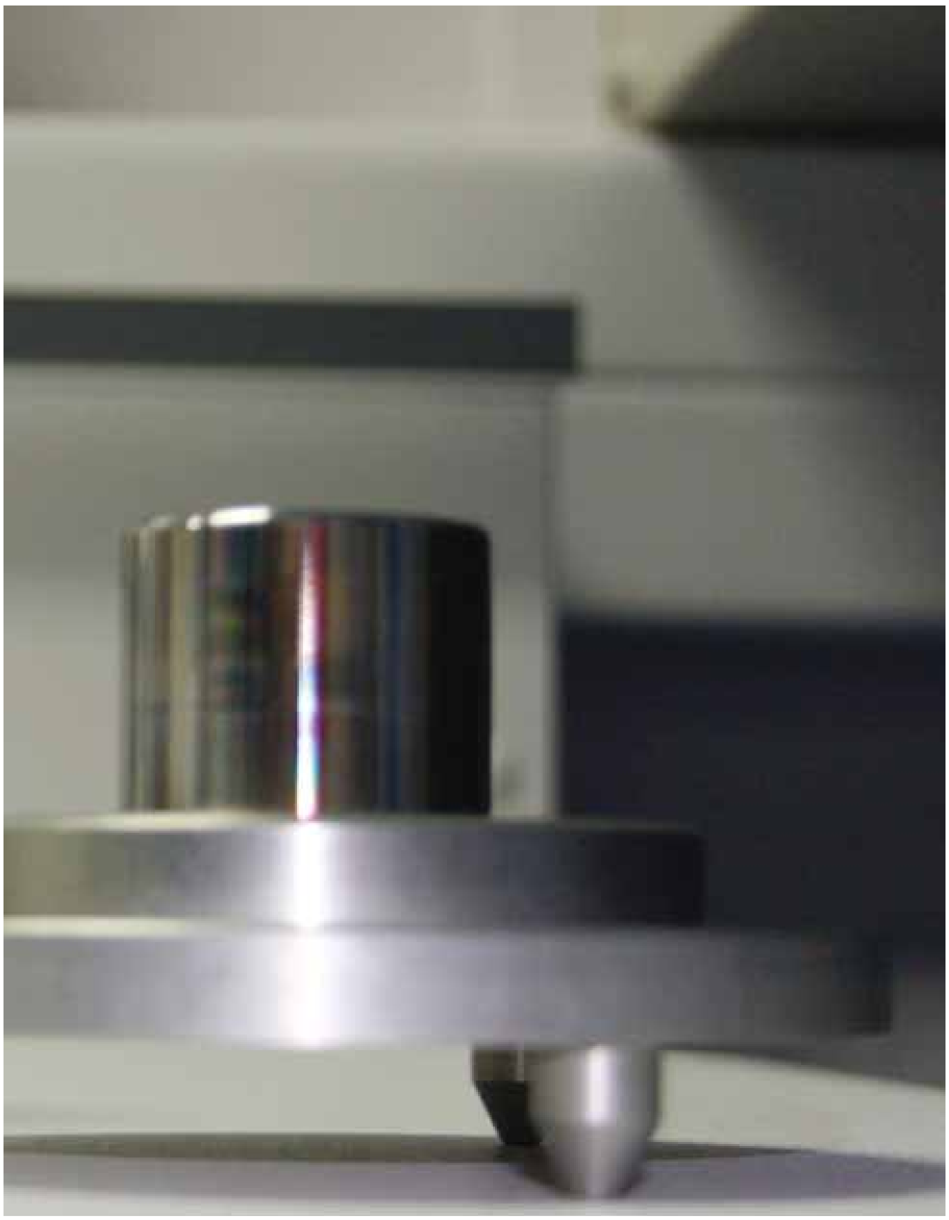
Mary Bowers

A Kilogram prototype is displayed part way through the polishing process. Underground laboratory, BIPM Serves

On a warm summer lunchtime in the Parc de St Cloud in Sèvres on the outskirts of Paris, office workers sit basking in the sun. A circus tent is being set up just beside the River Seine. A gaggle of schoolchildren crocodile their way to the National Ceramics Museum. They are unaware that behind them, a large copse of trees conceals one of they city's best kept secrets, and buried in a vault beneath it, a phenomenon that has been puzzling the international scientific community for more than half a century.

The International Bureau of Weights and Measures (BIPM, or Bureau International de Poids et Mesures) is based here at the picturesque Pavillon de Breteuil, in what was part of a château built for Louis XIV's brother, and damaged by fire in 1870. The land is designated international territory: the cars have special number plates, and even French government officials must obtain permission before entering. Most scientists here have joined the city's traditional August exodus, leaving behind Dr Richard Davis, an American physicist.

Davis is guardian of a small piece of metal, kept in high security and controlled conditions in a vault beneath the building. 'Le Gran K', as it is fondly known, is a 120-year-old cylinder of platinum-iridium alloy. It is the International Prototype for the Kilogramme; the mass of this humble object, at any one time, dictates the measurement of scales worldwide. The only trouble is that 'le Gran K' is shrinking, and with it the world's value for the kilogramme. No one is quite sure why.



According to Davis, there are no credible answers. "There could be hydrogen gas inside because of production methods, which is slowly evolving out," he says. Others blame the cleaning process, which has not been changed in over a century and still involves wiping the object manually with alcohol and a soft cloth. Others say oxidisation is responsible.

The object itself is unassuming. It is surprisingly shiny for its age, but then it is only removed once a year by an international committee which troops down to the vault to ensure that it is being kept under the correct conditions. At 39mm tall – hardly bigger than an apricot – 'le Gran K' offers tenacious resistance when picked up, as if it might be stuck to the table.

The kilogramme has been measured three times: once after its manufacture, once again in the 1940s – a process interrupted by war – and most recently in 1989. It is calibrated against the average mass of its sister prototypes, six of which are kept in the same safe and others in laboratories throughout the world. In comparison to these references, 'le Gran K' is becoming smaller.

"The rate is very hard to study because it is so minute," says Davis. "It is something in the region of 50 microgrammes [50 millionths of a gramme] in 100 years – that's half a microgramme a year."

Whatever the reason and the rate for the decline in weight, it is a source of concern for international scientists.

In 1999, the International Convention of Weights and Measures

(CGPM), a smaller group of country representatives from the BIPM, decided that a new definition for the kilogramme was needed. A broad consensus specified a deadline: at the 2011 Convention, a new definition would be chosen from a number of projects worldwide. Instead of a human-made object, which is subject to change over time, the new definition would be calculated from a permanent physical constant that could be measured in a laboratory anywhere in the world. Applications in the form of published papers would need to be received by New Year's Eve 2010. Some projects were already underway. Others began in earnest. A global race had begun.

Over 200 years earlier, in 1791, French astronomers Jean-Baptiste-Joseph Delambre and Pierre-Francoise-André Méchain set off from Paris, also on a metrological mission. Accompanied by trained assistants, carriages and armed with highly accurate measuring instruments, their task was to return with the first metre stick. They climbed every clock tower between Dunkirk, on the north coast of France, and Barcelona, using methods of triangulation to measure the ground distance. Using astronomical observations, the distance would be scaled up to calculate the distance between the North Pole and the equator, passing through Paris. The metre would be defined as this number divided by 10 million, and then marked as two scratches on a cylinder of platinum-iridium. After seven years of work, hampered by revolutionary wars, they returned triumphant.

The escapade had been commanded by a committee decreed by Louis XVI of France earlier that year. A conference of some of the greatest chemists, mathematicians and astronomers of the day was formed to decide a system of units for the world. The project was stalled by the ensuing bloody revolution: many of the committee's great heads, including that of Louis himself, were lost to the guillotine's blade. After the bloodshed, the idea was rekindled. Napoleon was determined that his empire should author such a system. Although a new decimal calendar failed to stick, the earlier prototype of the metre was endorsed.

The kilogramme was also fixed and the first metal prototype was made. It was originally intended to replicate the mass of $10cm^3$ of water at 4˚C, when it attained its maximum density.

The BIPM was set up in the following century by countries who signed an international treaty known as the Convention of the Metre. There are now 52 tithing members, including India. As its first task, the metre was officially put into service. The committee's second task was to remake the kilogramme. The original calibration turned out to be a hash job, so it was decided instead to fix the definition not on the universal value of water but solely on the new prototype: a lot of responsibility for one small object to carry.

Platinum was stable, and a 10 percent iridium mix made it easier to melt and shape. A company in London, Johnson Matthey, manufactured the material and 'le Gran K' was born, along with 40 other prototypes. (The BIPM still order the alloy from London to make the kilogramme, as member countries require: each unit carries a price tag of around €40,000).

But the kilogramme's sister measurements have all since evolved, leaving the 'le Gran K' sitting unadventurously in its safe. In 1960, the metre stick was replaced by a calculation of krypton radiation. In 1983, it was fixed to a slicker discovery: the distance that light travels in a vacuum in 1/299,792,458 of a second.

The second was originally defined as $1/86{,}400^{th}$ of a solar day in the tropical year 1900. But it was soon discovered that Earth's revolution was slowing down due to energy lost through tides. Days, and thus seconds, were growing slightly longer. In 1967, the Committee decided that the unit would be linked to the radiation emitted by a specific Caesium atom. The development of atomic clocks of increasing accuracy has further sharpened that definition. The most modern atomic clocks are so precise that if two were started simultaneously, it would be 13 million years before they deviated from each other by a single second.

There are five other major measurements now under the jurisdiction of the BIPM: Kelvin (thermodynamic temperature), ampere (electric current), mole (amount of substance) and candela (intensity of light). The ampere was redefined in 1972 by a constant known as the Josephson Effect; the candela by quantifying monochromatic radiation; the mole by a specific number of atoms in a specific amount of substance, and the Kelvin by the thermodynamic state of water. More accurate definitions are expected to be introduced, without controversy, at the 2011 convention.

The kilogramme is the last major measurement to be determined by a human-made object. While it heaves its last gaseous sighs, scientists continue to debate over its successor.

Professor Ian Mills is the man who may have the most leverage in the decision over the kilogramme's reconstitution. He is at the head of the Consultative Committee on Units (CCU), an advisory group to the International Committee of the BIPM. He is also Professor Emeritus at Reading University Faculty of Chemistry.

On a deserted campus one July afternoon, after the end of the academic year, the few remaining students mill through the car park. Their feet appear across the top of the window of Mills' basement office, which is reached by a snaking passage of heating pipes and low doorways. Like Davis, Mills is still hard at work as his colleagues play. At 78 years old, with hair flecked wisdom-white, he is still passionate

Biplab Muzibar Rahaman

Kilogram cases being prepared to ship kilograms off to their home countries. Each of the 52 members is invited to buy one for their national laboratory

about his subject. His office is littered with ancient hardback volumes on quantum physics and old scales, dials and measures.

"They'll throw anything away," he says. He gestures to one particular set of scales acting as a bookend. "These are worth quite a lot of money. I don't know what I'll do – show them to my grandchildren?" His screensaver displays a sailing boat, which he keeps in a dock near Chichester and took out only last weekend. Even Mills' leisure time is spent with compasses and charts.

His mission to redefine the kilogramme is not as fustily scientific as his surroundings might suggest. Mills insists that the time is not only ripe, but urgent. He says that new standards, which are accurate to minute levels of detail, are needed at the forefront of electronics. Experiments are becoming increasingly specific, requiring high levels of metrological accuracy. The difference between a couple of microgrammes might not affect the number of tomatoes bought for a fixed price at the market (it would represent a fraction of a grain of sugar in a kilogramme bag), but it will have other practical uses.

"When we redefined the metre, no one had a use for it. But after 10 or 15 years, they could use it to put a satellite into orbit around the earth and create GPS," he says. "We find applications in 10 to 20 years' time that follow scientific experiments. Look at the discovery of the laser. At the time it was a phenomenal discovery, but of what use? Now they're on every checkout counter of every supermarket. Give it time, and a use will turn up.

"It grows in importance every day," he says. "We have to have a set of units for the world and agree on them."

Measurements have been recognised as intrinsic to the workings of society for centuries: the Magna Carta lays out regulations for international trade. All aspects of daily life depend on it. Medicines must be carefully calibrated. Trading items must be weighed and checked for quality controls. Communications satellites, Internet searches and global positioning systems rely on minutely accurate measurements of the second and the metre.

Mills co-authored a paper published in the scientific journal *Meterologia* in 2006. In it, he set out several recommendations to the committee of 2011 that will decide on the fate of the kilogramme.

"Changing the definition has to be done," he says. One of the greatest problems with the kilogramme, he says, is that when there's only one, it is only used by an elite group. These are egalitarian principles.

"They only unlock it once a year and it's not available to everyone," he says, and moves closer, flapping his arms excitedly, and insisting his words be written down. "A good definition is available to anyone, anywhere, at any time. You shouldn't have to get hold of one. That's what we're trying to achieve, and we're well on our way!"

The process is accelerating in several different corners of the globe. According to recommendations by Mills and his committee, there are two major methods that should be investigated. They would fix a number for either of two physical values: Planck's constant, or Avogadro's number. The former is one of the fundamental "quanta"or quantum physics: the proportion of the energy of a photon particle to the frequency of light. The latter represents the number of carbon atoms in exactly 12 grams of carbon-12. From either of these, an equation would be made to calculate a value for the kilogramme.

No physical method is ever exact. But in order to be accepted by the committee, the chosen method must fix the value of the mass of the kilogramme with a greater accuracy than that of the shrinking prototype, a matter of many millionths of a gramme.

The first procedure recommended by the committee, the watt balance method, would be used to fix Planck's constant, the fundamental constant of quantum mechanics.

Five watt balances currently exist in the world, and of those three are still under construction. One is at the BIPM. Davis waves at what at first appears to be a large piece of Meccano, attended by two technicians with frowns of deep concentration. They are surrounded by nuts, bolts, and wires. Arms of steel, about two metres tall, stretch from a small platform in the middle. It looks like it might bring small creatures back to life in a science fiction movie.

The watt balance measures weight (the force of gravity upon a mass) against an electromagnetic force. It is similar to an electric generator and an electric motor combined and requires a strong magnetic field about 5,000 times that of Earth. Simply put, the watt balance measures the force required to balance the kilogramme with Earth's gravity. Combined with some other calculations, a figure for Planck's constant would be produced.

The technique sounds complicated, but most scientists, including Mills, believe that it is the forerunner of accuracy.

Aside from at the BIPM, watt balances are under construction in Switzerland and at the national laboratory in France. Two more are already running: at the National Physics Laboratory (NPL) in Teddington, just outside London, and at the National Institute of Standards and Technology (NIST) on the outskirts of Washington DC.

The latter project, at NIST, is headed by Dr Richard Steiner, who says that using a measurement of force to define the kilogramme would have other practical uses.

"Measuring force is closely related to measuring mass, since weight is the force on a mass," says Steiner. "Measuring very small forces comes into play in building things like hard disk drives for computers." Steiner also insists that watt balances could eventually be made for commercial use.

But watt balances don't come cheap; hence their rare status. The balance at NIST cost over US$1.5 million to set up, and with a team of between three and five eminent scientists working on the project at any one time, and the considerable use of expensive liquid helium, there aren't many countries – let alone factory floors – that can afford such a piece of equipment. Neither are there many scientists with the expertise to build and run one.

Dr Ian Robinson is one of the few. He was involved in the creation of the first watt balance, at the NPL in Teddington. He has seen it go through two evolutions since the idea was conceptualised by British physicist Brian Kibble in 1978.

"It's a long and difficult project," Robinson says. "Most people find it quite difficult. The equipment is very sensitive to changes, and it's difficult to debug it quickly and easily."

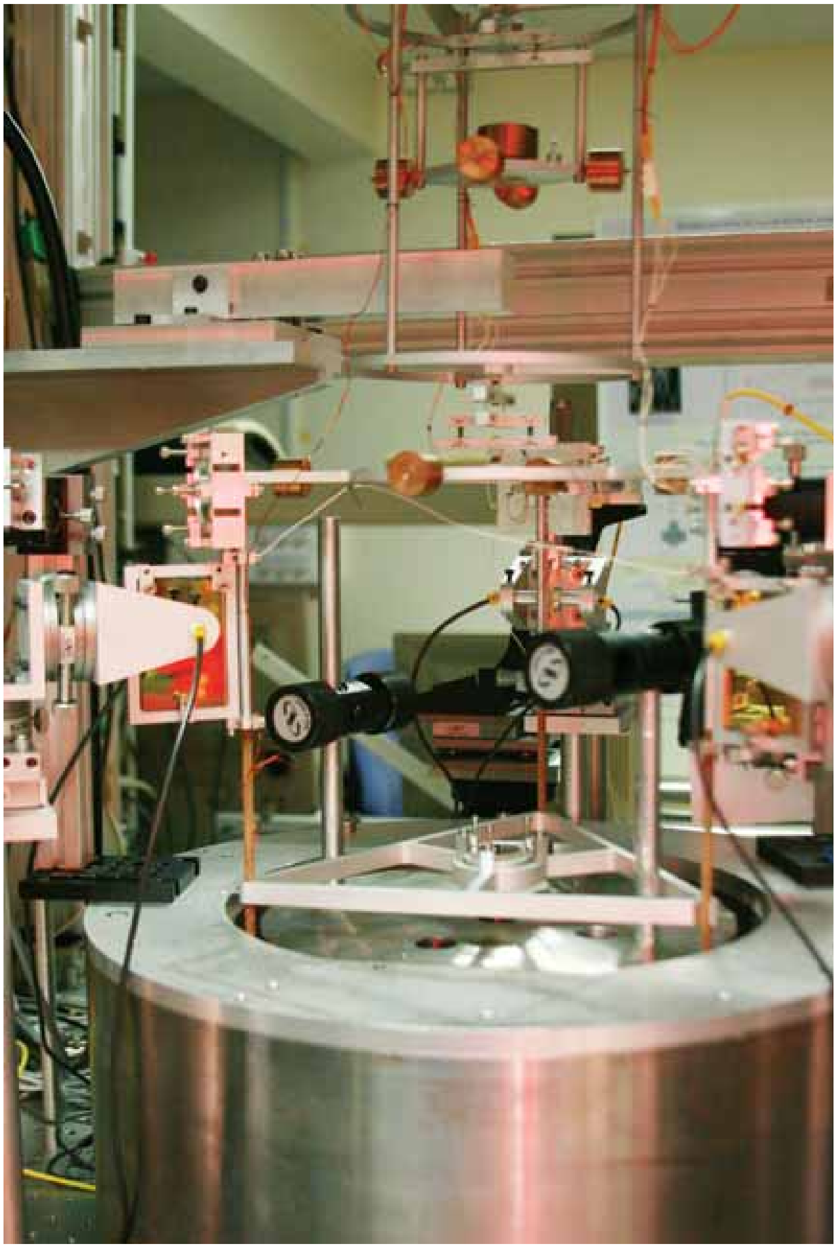
Robinson typically sets the watt balance to run overnight, beginning at five o'clock when his colleagues have gone home and most ground vibrations cease. By the morning, he will have taken several readings. He has run the process several hundred times, he says, and has in excess of 1,000 measurements. A handful has been accurate enough to publish.

"It's an extremely powerful technique," he says. "A lot of interesting physics is being discovered."

Across the world, at the National Measurement Institute of Australia, the answer to the kilogramme conundrum lies not in a mass of metal and wires but in a palm-sized, near-perfect sphere. It holds the secrets of another constant: Avogadro's number. Polished to a deviation from perfection of around one nanometre (one millionth of a millimetre), the sphere is so accurate that, were it scaled up the size of Earth, the tallest mountain would be six metres high, with its foothills beginning here in New South Wales and ending in Beijing. Under magnification, it is impossible to see where the surface of the sphere stops and the air begins. It is believed to be the roundest object in the world.

Two such spheres have been made, both from huge crystals of silicon of exceptional purity, manufactured in the same Russian factories that purified uranium for the atomic bomb. They are 93 millimetres in diameter; it they were to get much smaller, the same level of perfection would be hard to achieve.

The spheres are part of a worldwide project known as the International Avogadro Collaboration. Begun in the late 1990s, participants include Germany, Italy, Belgium, Japan and the USA. To find the number of atoms in 12



The Watt Balance machine at BIPM is currently under construction. It is one of the five in the world

grammes of carbon-12 the Avogadro scientists use silicon, which is more readily available and easily interchangeable with carbon, as the ratio is commonly known. By creating a kilogramme sphere and counting the atoms inside it, a simple division will find Avogadro's number. Placed in an equation, a new definition for the kilogramme would be calculated.

Senior Physicist Walter Giardini at the Institute in Australia is one of the scientists heading the project. "Between ourselves, the Germans and the Japanese, in the last five years we have reached unprecedented levels of accuracy," he says.

"You can hold it in one hand," says Dr Bruce Warrington, who, together with Dr Peter Manson and Dr Malcolm Gray, completes the current Australian team. "There's something instinctively right about that size. There's a beauty to this perfect sphere that's very polished on the outside so that you can see a reflection of the entire world around you. When you look at it, you see yourself, and you're right in the centre. And there's nothing you can do about it." He laughs. "You're always there."

Few on the watt balance side wax as poetic about the Avogadro method. Planck scientists believe that the Avogadro experiments have not yet reached a watt balance level of accuracy.

Since Avogadro's number is linked to Planck's constant, one can be checked by the other. Dr Davis says that the Avogadro project might be accurate enough to verify the watt balance results, but could not replace it. It could only play an auxiliary role in the redefinition of the kilogramme.

"The forerunner is the watt balance method because it could be done in future by a single lab," he says. "It wouldn't have to get an international group together. The use of the Avogadro method is a check. It could be that silicon spheres turn out to be useful artefacts in themselves."

"The first results were published in 2004 and differed from the results of the watt balance effort by one part per million, a huge amount in physical terms," says Steiner. "More recent figures have closed the gap, but many believe this is still not enough."

Another technique was developed in Germany, which involved collecting a stream of metal ions in a cup and counting them. But each measurement took months to measure, and the results were too erratic to be credible in the international effort.

Professor Ron Fox and Ted Hill, two mathematicians from Georgia Institute of Technology, have an alternative suggestion to ions, spheres and super-strength magnets. Their answer is to simply pick a logical number for the Avogadro constant – the cube root of the currently accepted value of Avogadro's number. It would be much the same as the process used to fix the speed of light and the second, for which, Hill says, "everyone just shook hands and decided what concrete numbers they would be".

"It was Ted's question to me – 'Is Avogadro's number even or odd?' – that got this started," says Fox.

"The current definition is actually somewhat humorous, at least to a mathematician," continues Hill. "A kilogramme is the mass of one particular 119-year-old platinum-iridium artefact stored in a vault in Paris, as measured shortly after cleaning by the approved method." He emphasises these last few words. "The current definition seems illogical. Are you telling me that modern science cannot tell me what a kilogramme is without a trip to Paris?"

Hill and Fox approach the problem from a mathematical standpoint, and as such find themselves no-nonsense outsiders in an international community of physicists ever in search of elusive perfection.

"To me, as a mathematician, the watt balance method seems impossibly complex. Even after I've read about it time and time again, quite frankly, I cannot tell you what a watt balance is," says Hill. He says that both the watt balance method and the silicon sphere method would leave the scientific community constantly dissatisfied. "It would require fine-tuning forever."

He also says that the silicon spheres themselves will never be accurate enough. "You can't simply construct a 'perfect sphere' out of silicon atoms, or ping pong balls, or tadpoles, or any other physical object. So it will always be just an approximation."

However, Fox and Hill say that their method is unpopular and has been the victim of sabotage by other scientists in the community, notably NIST.

"We found that the people at NIST were not being open with us about certain facts," says Hill. "They clearly want to use the watt balance approach and even changed the official value for Avogadro's number without telling us while in correspondence with us about these ideas. I corresponded with the head of the German team and he allowed that he too was not informed about how his values were used by NIST."

Hill suggests that because NIST's watt balance results are still inaccurate, dirty machinations were occurring behind the scenes. After the BIPM received NIST's public results in 2006, the BIPM agreed that the "current incoherence between two classes of experiment is a cause for concern".

"In order to eliminate this perceived inconsistency," Hill says, "NIST simply made an ad hoc adjustment." This adjustment reduced the results to an acceptable level of accuracy. "Fundamental physics by committee? There is obviously a lot of politics in the professional kilogramme business, and a simple out-of-the-box solution by outsiders is not warmly embraced. Ron and I do not have careers and laboratories that depend on whose definition is accepted."

In Britain, Robinson is all too aware of this: his career has become a casualty of funding cuts, and his watt balance was sold: the product of over two decades of nurture left home for a new life without him in Canada.

"There was a decision made by NPL, who no longer wish to do this kind of work," he mourns. "Canadians thought it was extremely important for the world of metrology, so they stepped in."

In Australia, Warrington is more optimistic about the state of play. "Rivalry is just human nature," he says. "It means you keep developing all the time."

Mills seems oblivious to any tension, either within the BIPM or outside it. "We all respect each other because we are all working towards the same goal," he says. "National politics don't exist. There are science politics, of course...the 'old boys' who hang on to their kilogrammes."

Professor Richard Davis, despite his support for the new projects, may still be hanging on to his. Framed pictures of 'le Gran K' hang on corridor and laboratory walls. Davis backtracks. He is not entirely convinced by the idea that the kilogramme is losing mass. It could be that the prototypes weighed against it are getting larger instead.

"You can say, 'I bet my own money that it is getting less massive'," he says. "But it would be hard to collect on that bet. No one is really sure what to change it to, even though people would like to."

Davis is cautious about the 2011 deadline. "It's not yet urgent," he insists. "It's not causing aeroplanes to drop out of the sky. People have been living with this for years."

Meanwhile, Mills is keen to counter the nay-sayers – he will, after all, be heavily involved in the debate's outcome.

"There's a lot of caution about," he says. "But I am convinced we've got it right. I shall be 81 when we get all of this done and then I shall have to retire if I succeed. I seem to have landed on my feet in old age."

Steiner, too, believes that 2011 will the kilogramme's year, although he is aware that human fallibility can sink science's insatiable appetite for accuracy. He recalls a particular experiment from his high school physics class.

"We were supposed to weigh a candle, burn it for a few minutes, and weigh it again," he recalls. While waiting for the candle to burn, he noticed, with an innocent eye for accuracy, that the lab scales weren't zeroed, and adjusted them.

"My lab partner and I were the only group whose candle weighed more after burning. And here I am putting together the most accurate absolute mass scale in the world," he says.

"I hope I get it right this time." □