continued from page 15
order of 10 μg (that is, 0.01 ppm). Even after cleaning, the national prototypes have exhibited continual increases in mass on the order of about 1 μg/year that are presumably the result of surface contamination. In the various national bureaus, the national prototypes are compared with the *primary standards*, which are made of steel or brass. The primary standards are then used to calibrate the *reference standards*, also made of steel and used for checking scientific and industrial mass standards. That all of these mass comparisons are made in air introduces errors from surface contamination and, most importantly, from buoyancy corrections, since platinum–iridium differs from steel and brass in density, leading to errors of about 30 μg (0.03 ppm) resulting from air temperature and density uncertainties. For determinations of large masses, a number of multiples of 1 kilogram must be constructed, usually of steel, to bootstrap the comparison masses to large values.[2]

It is exceedingly unlikely that the international prototype kilogram has the same mass as when it was first adopted as the unit in 1889, or even from one comparison to the next. That the mass comparisons are all made in air effectively limits the accuracy of macroscopic mass determinations to about 10 ppm; more commonly the masses are determined to about 100 ppm. These accuracies are adequate for most commercial purposes and also for determination of Newton's gravitational constant, G, which is known only to about 128 ppm.[1] However, all of the other constants of nature and fundamental units are known or defined to much greater accuracy, and Alvin J. Sanders and I have recently proposed an experiment[3] to determine G to about 1 ppm, with the greatest uncertainty arising from the comparison of the interacting masses (essentially *in vacuo*) with the mass of the international prototype kilogram (measured in air).

Since scientific metrology has made great progress since 1889, and all other constants of nature have now been defined in terms of more reproducible and presumably more invariant atomic quantities, it seems reasonable to redefine the kilogram, probably in terms of the mass of some reasonably fundamental particle, such as the proton or some other stable nucleus, *in vacuo*. Doing so would not make any change necessary in everyday determinations of macroscopic commercial masses, but it would put the measurement of scientific quantities, which can and should be measured with much greater accuracy, on a much more secure basis. It would also facilitate reference to primary standards in various scientific laboratories, which are the only places where the additional precision is possible and needed. Measurement of macroscopic masses could continue as at present, at least until the technology to compare them with the atomic standards becomes widely available.

The choice of which "atomic" mass is to be used to define the kilogram should be decided by international consensus, perhaps using such criteria as permanence, convenience and adaptability. The present state of our knowledge of the kilogram has recently been described by T. J. Quinn.[4] The simplest possibility would be to define the kilogram as a certain number of unified atomic mass units, simply inverting the present best value of the conversion ratio. To get a more up-to-date figure there could be considerable research on redetermining Avogadro's constant, counting atoms in pure single crystals (such as diamonds or silicon), measuring the mass of a counted number of large molecules such as $^{12}C_{60}$ "buckyballs" or fullerenes, measuring the electron charge–mass ratio and evaluating various electromagnetic devices used for making "mass" measurements. There have also been suggestions[5] that the kilogram and ampere should both become secondary units, derived from the volt (defined using Josephson junctions) and the ohm (defined using the quantum Hall effect) via the joule and newton. Perhaps it is time to reconsider the dimensionally attractive system of units based on length, time, electric charge and magnetic flux, in which all physical quantities have very simple dimensions. From the standpoint of fundamentality, the obvious physical bases seem to be c, e, $\hbar$ and one other quantity, such as magnetic flux.

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The Truth about Feynman's Father

Freeman Dyson's review of James Gleick's book *Genius: The Life and Science of Richard Feynman* appeared in the November 1992 issue of PHYSICS TODAY (page 87). Richard Feynman was my brother, and I would like to comment on the review.

Dyson says that he found the book enlightening in that it gave him a deeper understanding of some aspects of Feynman's character. In particular he says he discovered that our father did not, as my brother had written, impart a philosophy of science to my brother. Instead, our father was "a harassed and unsuccessful businessman who was forced to travel to earn a living and had little time left over for his children." Dyson remarks that "the fact that Feynman could create a legend of the philosopher–father out of such a meager reality is an important clue to understanding his character."

Dyson is in error. Our father was as my brother described him. It is particularly ironic that this debunking of the legend should appear under the headline "Doubt as the Essence of Knowing: The Genius of Richard Feynman." The importance of doubt as the first step to knowledge was one of the principles our father taught us both. It was due to his love and appreciation of nature that we both became scientists.

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Dyson replies: I am grateful to Joan Feynman for correcting my mistake. I should have consulted her before publishing an unwarranted speculation about her father. As she says in her letter, the mistake was mine. James Gleick is not responsible for it.

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Solar Cycle's Effect on How High Hubble Flies

A letter by John G. Kepros in your October 1992 issue (page 142) appears to be confused about the effect of the solar cycle on the orbit of the Hubble Space Telescope and NASA's plan for accommodating this natural orbital phenomenon.

Solar activity cycles between peaks every 11 years. During peak activity, the temperature of the atmosphere rises, and thus the density of the