

A PASSION FOR PRECISION

Daniel Kleppner



"Thought and action," "mind and hand," *mens et manus*—this theme of contemplation and activity is familiar among the mottos of academe. At the Massachusetts Institute of Technology *Mens et Manus* is both our motto and our logo. *Mens*, stalwart and fashionably dressed, contemplates a book of wisdom. The size of the tome suggests, perhaps, the *Science Citation Index*. *Manus*, more stalwart but less fashionably dressed than *Mens*, leans with a slight hint of fatigue upon a sledgehammer. His job appears to lie somewhere between railway laborer and clock maker. Not much imagination is required to picture *Mens* and *Manus* as metaphors for theoretical and experimental physics. It is their postures that give them away, for they gaze steadfastly in *opposite* directions. When one considers the joys they could share, one can only mourn their apparent indifference.

The estrangement of theoretical and experimental physics is often exaggerated, but there is some reality to the charge. For example, the joys of experimental discovery are difficult to describe and essentially impossible to share. Among these is the intensely pleasurable sensation that comes from measuring something useful to umpteen significant figures. To unearth the next link in the chain of digits that constitutes one of nature's constants is to experience the sudden glee of discovering a gem; it is to undergo a passion of pride with overtones of greed, lust and possibly gluttony. Sadly, intense passions are likely to be short-lived. Sooner or later somebody—perhaps you yourself—will unearth the next digit, and your victory will evaporate as your gem transmutes to dross. Every new digit demands a tenfold increase in accuracy, however, and so every ad-

vance is fraught with peril. The game is all the more heady because it is dangerous.

My own particular delight in the precision measurement game was inherited from my teacher Norman Ramsey, who is sharing this year's Nobel Prize in Physics for advancing the art of high-precision measurements. If you too have an urge to play the game, be prepared for high opening stakes. Today the game begins at an accuracy of roughly 3 parts in 10^7 . This is the accuracy with which most of your all-around, everyday fundamental constants are known: the electron's charge, Planck's constant, the Bohr magneton, Avogadro's constant and so on.¹ (Incidentally, purists carefully distinguish precision—the number of significant digits—from accuracy—the number of *correct* significant digits. Also, precision and accuracy should not be confused with resolution. For example, the fractional gravitational redshift of the Earth is only about 1 part in 10^9 . Nevertheless, the redshift has been measured to about 1 part in 10^4 using atomic clocks stable to 1 part in 10^{14} . The resolution is fabulous, but the accuracy is a mere 70 ppm.) The opening stakes for fundamental constants have increased by a factor of ten over the last two decades—an extraordinary achievement, roughly comparable to boosting one's scientific standard of living by an order of magnitude.

The push continues, with the most dramatic advances taking place at the frontiers of measurement, where the battle is waged in hand-to-hand combat. No matter how sophisticated the experiment, the research eventually comes down to twiddling knobs, tinkering with levers, leaning on some special spot while holding one's breath, or practicing any of the other magic arts of experimental physics. It also comes down to painful arguments on how to interpret the results: when to throw out data (practically never), when to throw out the whole experiment (occasionally), when to increase the estimate of error (more



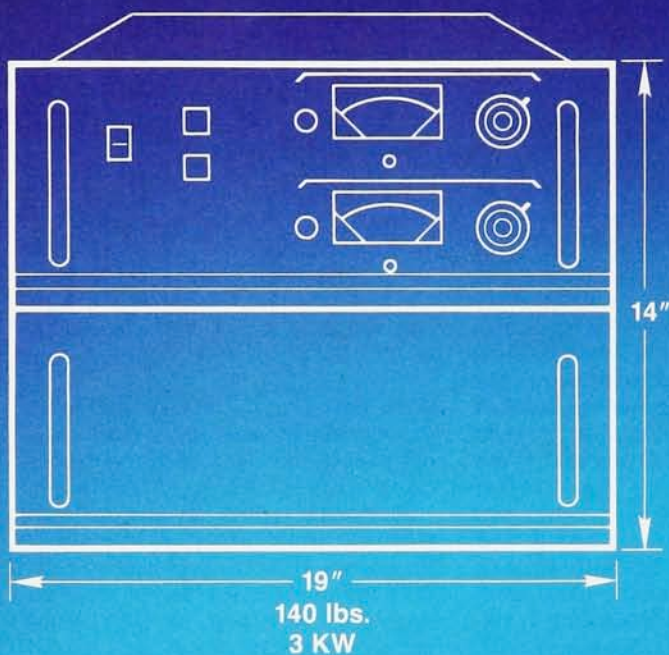
often than one would like) and when to decrease it (also more often than one would like—forgoing the protection of large error bars takes courage).

A notable recent advance in precision measurement comes from determinations by three separate groups² of the Rydberg constant, R_∞ , to accuracies of 2 or 3 parts in 10^{10} . These achievements represent a hundred-fold improvement since the early 1970s. What makes the advance really remarkable is that the results of the three groups agreed beautifully: Usually independent measurements disagree—not by too much, one hopes, but by enough to raise important questions. For three groups to agree suggests that something is amiss.

R_∞ is a unit of length (more precisely, inverse length): It is the atomic unit of length expressed in meters. (Recall that the wavelength of a transition between states of hydrogen with principal quantum numbers n and m is given by $\lambda_{nm}^{-1} = R_H(n^{-2} - m^{-2})$.) However, the meter itself is no longer defined in terms of length: It is defined as the distance light travels in a certain fraction of a second ($1/299\,792\,458$ of a second, to be exact). This unwieldy definition was introduced because nobody could devise a way to compare optical wavelengths to better than a few parts in 10^{10} . On the other hand, frequency and time intervals can be measured to parts in 10^{13} or better. The new definition of

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the meter is not as useful as one might wish, because the frequency of the best optical transition is known only to 1.6 parts in 10^{10} . So all three Rydberg measurements have come up against the same brick wall. That they agree so well suggests that each has precision to spare. What all this means is that new techniques for measuring the frequencies of optical transitions are desperately needed. Some ideas are in the air; if any come to fruition the precision measurement game should move to fields of unprecedented accuracy.

It is so easy to get carried away by the passion for precision that one must stop now and then to ask "Why?" The answer can't be squeezed into the rest of this column, but I will return to the question in some later essay. However, with respect to the Rydberg constant, it must be confessed that R_∞ is already so well known that it is technically classified as an "auxiliary" constant in the evaluation of the fundamental constants, which is to say that the approximately half-dozen less-well-known constants that depend directly on R_∞ will hardly be affected by any improvement in its accuracy.

Nevertheless, there are good reasons to push the precision of R_∞ . First, a constant that is auxiliary today may not be auxiliary tomorrow. The relative precisions of fundamental constants can jump in unexpected ways. Second, the Rydberg constant has always been a touchstone for spectroscopy; the advances in optical precision, including the fiendishly clever techniques of optical metrology (and this includes a fair fraction of all high-precision measurements), have been inspired by or somehow linked to spectroscopy. There is every reason to look forward to a new generation of optical metrology with precision of parts in 10^{15} or higher, and somehow or other the Rydberg constant will link this fabulous technology to the world of physics. Finally, there is the thrill of being the first to fill the Xs in the expression $R_\infty = 10\,973\,731.572\,XXX\,X(X)\,m^{-1}$.

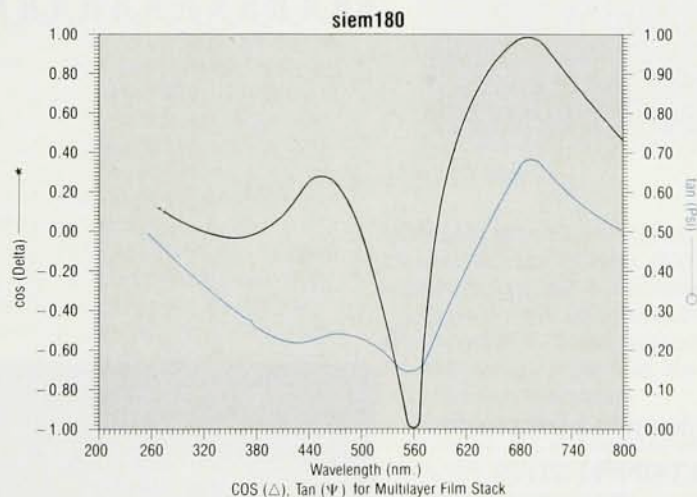
References

1. E. R. Cohen, P. Giacomo, *Physica (Utrecht)* **146A**, 1 (1987).
2. M. G. Boshier *et al.*, *Nature* **330**, 463 (1987); transition $1S \rightarrow 2S$ (two-photon). P. Zhao, W. Lichten, Z.-X. Zhou, H. P. Layer, J. C. Berquist, *Phys. Rev. A* **39**, 2888 (1989); transition $2S \rightarrow 4P$. M. Allegrini, F. Biraben, B. Cagnac, J. C. Garreau, L. Julien, *The Hydrogen Atom*, G. F. Bassani, M. Inguscio, T. W. Hänsch, eds., Springer-Verlag, New York (1989), p. 49; transition $2S \rightarrow 8D, 10D, 12D$ (two-photon). ■



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