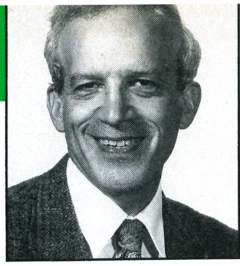

# A LESSON IN HUMILITY

Daniel Kleppner

If you should suddenly feel the need for a lesson in humility, try forecasting the future of physics. I acquired this little bit of wisdom rather painfully a few years ago when fate tossed me onto the Brinkman committee—one of those panels that is assembled in the US roughly once a decade to survey physics. To prepare for the task, I looked into the previous survey to see how well it had done in my pet field of atomic physics. The performance was unimpressive. Apparently nobody noticed that the laser was about to revolutionize atomic physics and propel optics into the mainstream of physical science. Single-particle traps, clusters, high-resolution scattering and lots of other advances were also missed. My gorge rising against the clods who did my field such an injustice, I looked up the list of members of the atomic physics panel. Smack in the middle was my own name.

When you get down to it, about the only thing scientists can forecast with much accuracy is an eclipse. Understanding this, veteran science forecasters invariably qualify their discussions with some cautionary statement to the effect that because the most exciting discoveries are unpredictable, their predictions cannot begin to do justice to the glorious potential of their particular fields. Such a disclaimer allows one to exaggerate while appearing to display a becoming humility. Nevertheless, scientific discoveries generally do exceed expectations. By way of evidence for this, note that although it is hardly more than five years since the last physics survey—the Brinkman report—there is already an impressive list of advances that we either underestimated or simply failed to foresee. One can view this as evidence that physicists are shortsighted or that nature is inexhaustible. Naturally I vote for the latter. To support my point, here is a list of some things that we missed.

*High-$T_c$ superconductivity.* The discovery of high-temperature superconductivity by two scientists with an apparently eccentric interest in a totally unfashionable material—the copper oxides—is already a legend. It confirms the great tradition of individual scientists' pursuing their own goals in their own way and demonstrates that miracles in science really occur now and then. It also demonstrates that apparently simple systems can be subtle and complex, for five years and 18 000 papers later, the basic physics of high-temperature superconductivity remains an enigma and the early visions of levitated trains and superconducting power lines remain unfulfilled. Nevertheless, recognition of the two-dimensional nature of the underlying superconducting structure has led to an understanding of thin film behavior, and this has opened the way to practical thin film devices. Achieving the large currents needed for more general applications requires overcoming the limitations of the underlying two-dimensional superconducting structure. One hopes for the best.

*Supernova 1987A.* Since supernovae light up in the Milky Way approximately once every 300 years, the occurrence in 1987 can be described as astounding but not miraculous. However, the detection of 15 of the roughly $10^{57}$ neutrinos that were ejected as the star's core collapsed, traveled for 170 000 years and arrived within a few seconds of one another approaches a miracle—a windfall from the search for proton decay in Japan and the US. The agreement between the neutrino signals and the theory for the supernova's explosive collapse is a triumph of neutrino physics. The supernova now glows with light powered from the radioactive decay of cobalt-57, though in its few short years its luminosity has dropped dramatically. Here again the measurements are in extraordinary agreement with the theoretical scenario, and this story is heading straight for the textbooks.

*Atom cooling and atom optics.* It is hardly news that light can push around atoms, but nobody seemed to recognize that the interplay of optical fields with the internal dynamics of an atom would make it possible to cool atoms to temperatures of a few microkelvin, suspend them in space, toss them around like tennis balls or let them collide in a new world of ultraslow motion. A fountain of such cold atoms has already produced a resonance signal 50 times sharper than that in the best atomic clock. Out of this line of research has grown the discipline of atom optics, loosely centered around the interaction of atomic waves with mechanical structures, optical fields or both. Mirrors made of light have reflected beams of atoms, and a new art of interferometry has been created based on coherent beams of atoms.

*Buckyballs.* The Brinkman report paid suitable homage to clusters—those small chunks of matter, somewhere between individual atoms and solid structures, that can be generated in supersonic beams—but the anomalous peak in the carbon spectrum at mass 60 had yet to be discovered. Observation of $C_{60}$ and identification of its soccer ball structure—the "buckyball"—led to a rumble of excitement, and when it was discovered that the material could be made in bulk, that in fact it has been around since time immemorial as a major component of soot, the rumble turned into a roar. Chemistry has a new building block, and the excitement is reminiscent of the excitement that followed the discovery of high-temperature superconductivity. $C_{60}$ is only one member of a novel class of molecules called the fullerenes. The

**Daniel Kleppner** is the Lester Wolfe Professor of Physics and associate director of the Research Laboratory of Electronics at MIT.

opportunities for chemistry and materials science created by the discovery of this new state of carbon are, for now, beyond comprehension.

*Complexity, chaos and nonlinear dynamics.* Given that physicists generally esteem simplicity, it is remarkable that the study of complexity has moved to center stage, but such are the ironies of nature. Complexity encompasses everything from the growth of crystals to the dynamics of neural systems. Its central theme—the elaboration of forms from the repetition of simple operations—is being recognized as a fundamental organizing principle of nature. Several commentators have used this column to spread the good tidings of complexity (Leo P. Kadanoff in March 1991, Philip W. Anderson in July, and I in August). But the term was not even mentioned in the last physics survey. Nonlinear dynamics has also moved to center stage. Its origins go back to Henri Poincaré's work at the turn of the century; the origins of chaos likewise go back for several decades. Only in the past few years, however, have nonlinear dynamics and chaos theory entered the mainstream of physics. The last physics survey hardly noticed that classical mechanics was on the threshold of a renaissance.

*Superdeformed nuclei.* Although their existence was anticipated by theory, until they were discovered experimentally it did not seem likely that nuclei really could be stable in sausage-like geometries while spinning so fast that they are on the verge of flying apart. However, when calcium-48 and palladium-108 ions collide they can fuse to form a dysprosium nucleus that boils off a few neutrons and settles down into such a state of $^{152}$Dy. The ratio of major to minor axes is approximately 2:1, and the angular momentum is extraordinary—approximately $60\hbar$. The $^{152}$Dy methodically emits a series of gamma rays, producing a spectrum so regular that it is almost picket fence. When the angular momentum is about $26\hbar$, the $^{152}$Dy suddenly flips its shape and behaves like a conventional nucleus. Similar behavior has now been discovered in many other nuclei, so the phenomenon is by no means isolated. On the contrary, superdeformed nuclei are now recognized as a new state of nuclei, an unexpected happy event in the nuclear family.

*Large-scale structure of the universe.* The uniformity of the early universe has been one of the more comforting thoughts of modern cosmology. Measurements by the Cosmic Background Explorer, for instance, gave spectacular confirmation of the blackbody spectrum and isotropy of the cosmic microwave radiation. Aside from a small correction due to local motion, the radiation was uniform across the sky to better than 1 part in $10^4$. In view of this uniformity, the recent discovery of large-scale structures of the universe—voids in the distribution of galaxies, sheets of galaxies and large, foam-like structures—was totally unexpected. Possibly the structures bear the signature of dark matter, or possibly the present scenario for the evolution of fluctuations in the early stages of the universe is completely wrong. In any case, our view of the universe has altered in the last few years.

*Mesoscopic physics.* A new world of physics has been discovered in mesoscopic systems, structures that are large on the atomic scale but so small on the laboratory scale that quantum effects are important. When the distance needed for an electron to exchange energy becomes large compared with the size of the system, electron transport turns into a coherent process, and the transmission coefficient that determines the conductance is determined by a sum of Feynman paths over all the random paths through the system. In this regime, any change in phase leads to a macroscopic change in conductance. If some parameter such as the magnetic field is changed, the conductance—no matter what its size—fluctuates by a universal value, $-e^2/h$. Such universal conductance fluctuations can generate $1/f$ electronic noise due to the migration of one atom. In the mesoscopic world, the charge of a single electron can alter the potential of an electrode enough to cause macroscopic changes in behavior. Out of this simple idea have already emerged a single-electron "transistor" and other single-electron devices.

This account hardly exhausts the list of surprises from physics in the last five years, but it should at least suggest Nature's abundance. The lesson is that scientific discoveries invariably exceed the power of our imaginations. Learning this over and over again should school us in humility, though it is more likely to leave us feeling exhilarated than humble. In either case, the lesson can help us to keep up our spirits in these times of deferred hopes and faltering institutions.

* * *

*I thank my numerous colleagues who helped me to prepare this column by sharing their wisdom and their excitement over these advances and discoveries.* ■