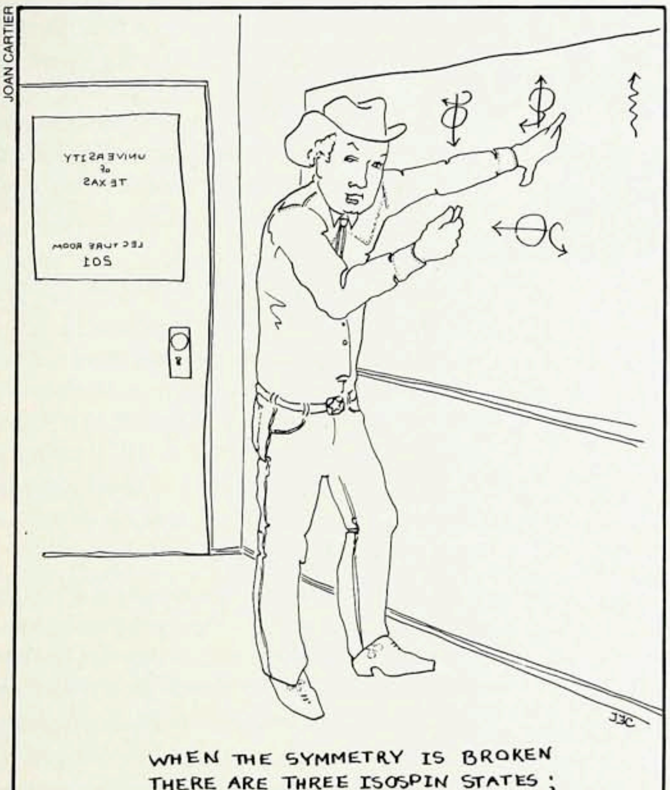
Holes and loose ends in particle physics

Steven Weinberg

Twenty years ago, the 13th International Conference on High Energy Physics met in Berkeley. Current algebra was the big news that year, although its success wasn't well understood. It wasn't generally realized that in doing current algebra we were exploiting the fact that the strong interactions had a symmetry, chiral $SU(2) \times SU(2)$, that was hidden from us by spontaneous symmetry breaking. The idea of spontaneous symmetry breaking was fairly new and not terribly popular. A lot of attention was given, as it had been for the previous few years, to the phenomenology of hadron resonances and diffraction scattering, and to their connection with each other through Regge pole theory. But we were terribly perplexed about what that had to do with the fundamentals of the strong interactions, in particular with the quark model. We had a good working phenomenological theory of the weak interactions, the famous $V-A$ Fermi interaction, but it was clear that it couldn't be applied beyond the lowest order of approximation. CP violation was a new mystery. Finally, I don't believe any of us talked about quantum gravity. Anyone who raised questions about quantum gravity would have been directed to another conference.

JOAN CARTIER



WHEN THE SYMMETRY IS BROKEN THERE ARE THREE ISOSPIN STATES; PARALLEL, ANTIPARALLEL AND LAID BACK.

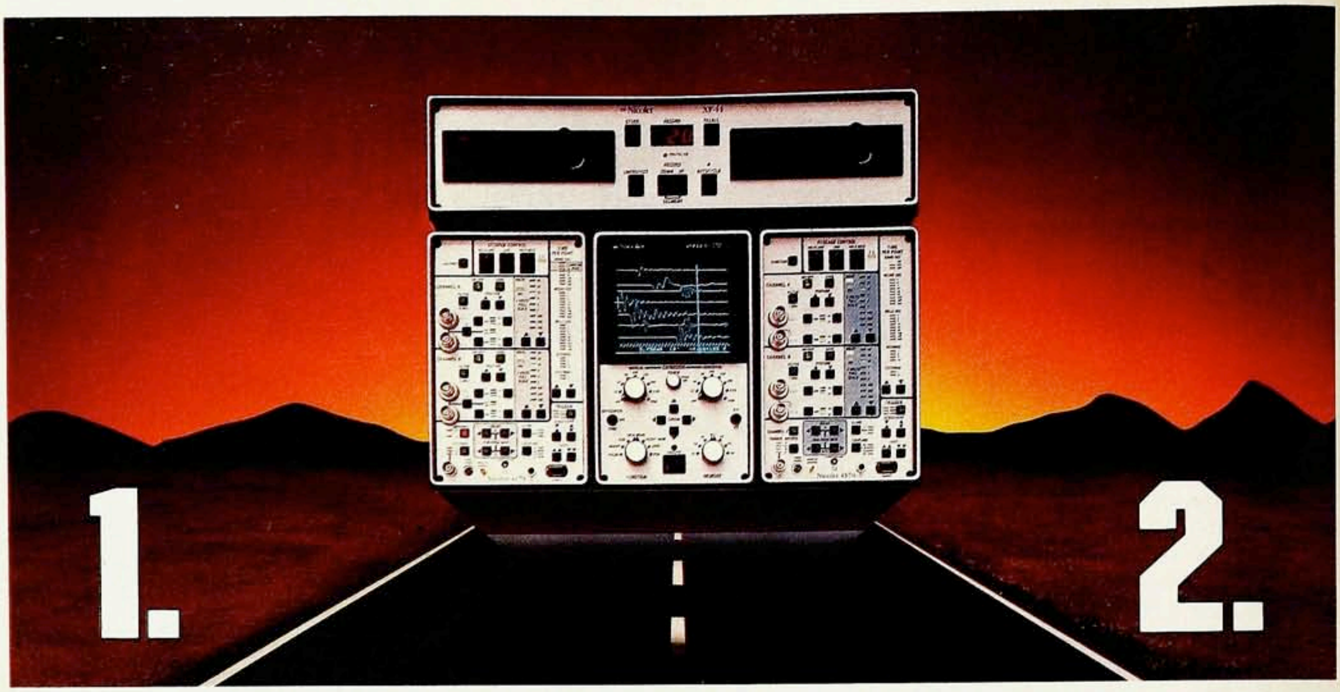
Recently the 23rd International Conference on High Energy Physics met again in Berkeley, giving me an occasion to review our progress over the intervening 20 years. It has been impressive. We now have a standard model, which provides a perfectly satisfactory description of all physics that is accessible to us at present accelerators. It's a renormalizable quantum field theory, very much like the quantum electrodynamics that was completed in the late 1940s. (That's an idea that would have seemed totally reactionary to the conference in 1966.) Instead of one photon we have 12; three of them have acquired masses from a spontaneous symmetry breaking, and eight of them are trapped. Instead of one electron, we have a whole menu of quarks and leptons defined by their representations with respect to the electroweak and strong gauge groups, and this menu is replicated three times: There are three generations.

As M. G. D. Gilchrist said at the 1986 Berkeley conference, "This standard model is now not seriously questioned as a description of acceptable physics." However, it has, we are all painfully aware, both holes and loose ends, much like a ball of string.

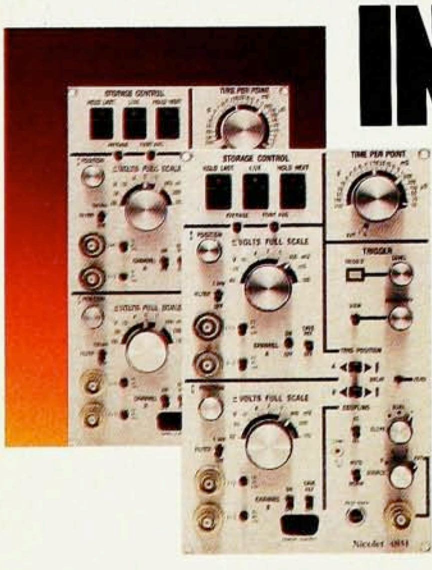
The least troublesome and most obvious hole is that we haven't yet found the top quark. Its mass is above 23 GeV, but we really don't know what it should be. I think the general expectation, if you have to bet, is that it would be somewhere around the W mass, because why should it be anything different? In fact, I would say the real

This month's columnist, Steven Weinberg, is a particle theorist. He is Josey Regental Professor of Science at the University of Texas in Austin. This column is adapted from the closing talk (which also reviewed recent progress in string theory and solar neutrino physics) given at the 23rd International Conference on High Energy Physics held in Berkeley in July.

THE FIRST NAME IN DIGITAL SCOPES



TWO DIGITAL SCOPES IN ONE.



The Acquisition.

With sweep speeds from days to nanoseconds and resolution up to 15 bits, the 4094 digital 'scope can capture the most elusive signals. Every plug-in has 16K of memory, viewable trigger set-up and independent pre- or post-trigger delay on each channel. Signal averaging is standard and our latest 10 MHz/12-bit plug-in even offers real time manipulation of the incoming signals. With two plug-ins the 4094 can record four channels simultaneously. Or even monitor two slow signals and capture high speed glitches at the same time. All under computer control or via manual operation: whatever your application demands.

The Analysis.

Expand and examine any waveform feature in detail. Use the dual cursors and numerics to measure the time or voltage of any point. Compare live or stored waveforms with each other or with pre-recorded references. Store signals on disk manually or automatically. Use pushbutton programs to manipulate the data or send it to your computer via GPIB or RS232 interface. Complete your report with a hardcopy plot using the XY/YT recorder or digital plotter outputs.

First Time, Everytime.

Don't miss important data because of set-up errors. From the World's first in 1973 to the latest models, Nicolet 'scopes are easy to use. Find out how they can be the quickest solution to your signal problems. For more information call 608/273-5008, or write Nicolet Test Instruments Division, P.O. Box 4288, 5225 Verona Road, Madison, WI 53711-0288.

Circle No. 7 for more information

NIC Nicolet

mystery is why all the other quarks and leptons are so much lighter than the W. So the fact that the top quark hasn't been pinned down is not in any way a worry yet.

Much more troublesome is that we don't really have a clear view of the Higgs sector: the mechanism for the spontaneous breaking of the electroweak symmetry. This Higgs mass could be anywhere between a TeV and a few GeV. There is a prejudice, now shared by many theorists, that there are probably just two doublets of Higgs. (The reason for this prejudice is that supersymmetry needs two; having more than two raises problems with flavor-changing neutral currents; and also opens up new possibilities of CP violation, which might raise problems for the ϵ'/ϵ ratio in neutral K decay.) We don't know where the Higgs is; we're not even really sure that we should regard the Higgs as an elementary particle, but we believe that something must show up by the time we get up to available energies of a TeV: a Higgs, or new kinds of strong interactions, or entirely new physics.

I am not listing here as a hole in our understanding of the standard model the fact that we can't solve quantum chromodynamics and predict all phenomena having to do with hadron physics. An analogy may be useful between quantum chromodynamics and another science that I think it will increasingly come to resemble, hydrodynamics. In both cases we think we know the underlying equation: the Navier–Stokes equations in hydrodynamics, the SU(3) Yang–Mills equations for quantum chromodynamics. In both cases fascinating, important hard problems have not been solved. In hydrodynamics there are problems involving flow at high Reynolds numbers—phenomena such as turbulence and chaos. In quantum chromodynamics there is everything having to do with low energies and long distances: glueballs, confinement, phase transitions. Turbulence is a fascinating subject, and will go on interesting physicists for many years, but we do not study turbulence to test the Navier–Stokes equations. In the same way I think that all the really interesting problems of quantum chromodynamics have nothing to do with testing quantum chromodynamics. Critical tests of quantum chromodynamics will come at high energy; my guess is that the critical tests will be found most beautifully in high-energy annihilation of electron–positron pairs into jets, where we will be able to avoid the "interesting" aspects of quantum chromodynamics.

The loose ends in the standard model are much more disturbing than the holes. Why $SU(3)\times SU(2)\times U(1)$? Why just the quark and lepton representations we know about? Why three generations? (Well, we don't really know there are just three generations, but it's looking increasingly as if that's the case. We heard evidence at the latest Berkeley conference that the number of neutrino species can't be much bigger than three, and the mass of any new charged lepton would have to be bigger than 41 GeV.) Finally, although $SU(3)\times SU(2)\times SU(1)$ does a very good job of pinning down the structure of the standard model in terms of a finite number of free parameters, that finite number is, embarrassingly, a large finite number: at least 17, and more if there are more than three quark–lepton generations or more than one Higgs doublet. There are the gauge couplings, the mixing angles, the Yukawa coupling of the quarks and leptons to the Higgs sector, the Higgs self-coupling, the mass of the Higgs and so on. We don't have any good idea of why these parameters have the values that they have. There are undoubtedly wonderful lessons to be learned in the values of these parameters that we've been looking at throughout our lives, but we haven't yet read the lessons.

To tie up these loose ends a number of ideas have been proposed over the last decade—ideas of technicolor, of quark and lepton substructure, supersymmetry, grand unification and so on. As I write that list, I feel a sense of tremendous frustration. We've been working on these ideas for more than a decade, since the mid-1970s, and we have almost nothing to show for it in terms of hard agreement between predictions and experiments. Only perhaps the prediction of $\sin^2\theta$ stands up as robust and verified.

I'm not going to survey all this, partly because it's too painful, but also because I think it's presumptuous. There are new facilities just about to come into operation: Tristan at Tsukuba, Japan (see the story on page 21) and the SLAC Linear Collider (both electron–positron machines), and the Tevatron proton–antiproton collider at Fermilab. These, I think, are going to make many of our speculations about loose ends obsolete. In particular, supersymmetry, if it exists at all as a low-energy approximate symmetry, should begin to show up at the Tevatron collider. In fact it may be that the two dijets with large missing momentum transfer that have been seen at the CERN UA1 detector not only give us a lower bound on the mass of the squark, but actually *are* squarks, though of course it's too early to say. □