

pany scientist of Intel Corp, has a similar perspective. He sees three obstacles to Moore's law: the fundamental thermodynamic property that limits the concentration of dopant atoms; thickness of the gate oxide insulating material (the oxide film has become so thin that there is already current leakage from the transistor gate); and the statistical fluctuation in the number and distribution of dopant atoms.²

The good news is that researchers at Bell Laboratories have developed ultrathin oxides that are only 5 atoms thick. The insulating layer of SiO₂ in today's chips is, on average, 25 atoms thick. The Bell Labs researchers believe their work may help to extend the life expectancy for silicon-based technology to 2012. The researchers also have proved that a 4-atom layer is the fundamental physical limit for silicon-dioxide-based insulators.³

Finally, Birnbaum and Williams mentioned Moore's second law and the costs of building a new fabrication facility. What they left out of this discussion are the costs of the chips themselves. As many people in the industry know, we are approaching a time when a chip plant will cost about \$20 billion, when each wafer will cost tens of thousands of dollars to process, when statistical dopant fluctuations and similar physical dielectric problems will cause huge yield losses, and where the resulting chip will cost about \$10 000 to manufacture, but be expected to sell for half that.

As the next generation of 64-bit processors, IA-64 "Merced," is a joint effort of Hewlett-Packard and Intel, it remains to be seen which of the two partners will be right.

As an aside, Hewlett-Packard's Teramac is not the only defect-tolerant computer. IBM is building a "self-healing" supercomputer that will run 500 times faster than any other. The company is spending \$100 million to develop "Blue Gene," a novel computer that will operate under rules described as "simple, many, and self-healing"—SMASH for short.⁴

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WILLIAMS REPLIES: I disagree with Igor Fodor that the future of computing and electronics is "... more a matter of practicable engineering and technology than it is of theoretical limits of the physical theory." This is exactly the type of thinking that prevented most of the major vacuum tube companies in the world from investing in semiconductor technology in the 1950s. Fodor makes several correct points, which are extensions of those we mentioned in our article, about the difficulty of scaling Si technology at its current rate of improvement for several decades into the future. That is the reason we need a new technology, and the scientific basis for that technology has to be established now to be available when the scaling of Si starts to slow down! Physical theory shows that we are far from any fundamental limits to computing, so physicists can be major players in the invention of new computing paradigms. Most of today's major electronics companies and associations, as well as government agencies, have recognized this and are working to create new types of computing machinery. Announcements of advances in such areas as quantum computing and molecular electronics appear regularly in the popular press. Our article was intended both to point out to a larger audience the exciting opportunities in computing research for physicists and to call for help in finding new approaches that are both powerful and affordable.

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Unseen Strangeness in the Proton

I read Bertram Schwarzschild's report on the strange-quark-in-proton experiments in the June 1999 issue of *PHYSICS TODAY* (page 21) with profit and pleasure. I would like to mention, as a reminder of an apparently forgotten point, a certain technical caveat to the interpretation of these experiments as pure strangeness measurements.

Even if clearly nonvanishing signals are seen at MIT's Bates Linear Accelerator Center and the continuous electron-beam accelerator (CEBAF) at Jefferson Lab, another, far more mundane physics is indistinguishable from the strangeness content as the source of those signals. This is the isospin SU(2) symmetry

breaking (SB) in the nucleon. This specific kind of SU(2) SB goes by the name of charge symmetry breaking (CSB). It is, of course, a part of the SU(3) SB, but the specific effects that are discussed in the article are different. An elaboration of these statements can be found in the article with Steve Pollock,¹ where the magnitudes of the effect for the electric, magnetic, and axial form factors have also been estimated in a constituent quark model. These results have been confirmed and refined in the same model,² and in chiral perturbation theory,³ with similar conclusions.

Perhaps we ought to expect a non-zero signal at CEBAF whether there is strangeness in the proton or not, as there is plenty of experimental evidence for CSB. More specifically, the puzzle posed by the data from the Indiana University Cyclotron Facility regarding the difference in the analyzing powers of neutrons vs. protons has been solved,⁴ using the same methods and assumptions we used. A complete absence of signal at CEBAF would thus indicate an accidental cancellation of strangeness and isospin SB effects. The one channel that seems to be free of substantial CSB effects is the axial one, but that is also the least interesting one, as the deep-inelastic scattering data tell us what we should expect there prior to measurement.

There is more to these experiments than the strange quarks in the nucleon. Our only hope of clearly separating the strangeness content effects from the CSB ones is if the former are substantially larger than the latter.

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Correction

February, page 19—In the figure, the labels for the two axes were switched. The horizontal axis should be labeled "Time of Flight (ns)" and the vertical axis, "Energy (MeV)." ■