lowed an entirely different and far less admirable tradition of using the names of politicians or famous historical figures whose relation to a facility or its purpose is far-fetched at best.

Jefferson's high regard for the sciences is hardly enough of a distinction to warrant affixing his name to a facility that, according to an account in PHYSICS TODAY (July 1996, page 49), is very much the achievement of a single scientist—Hermann Grunder.

I close with two questions: Is Fermilab about to become the Abraham Lincoln National Laboratory? Will Congress and the state legislatures ever set policy on the naming of publicly funded enterprises?

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Nambu's Importance Discussed: Pion-eer or Man of 'Color'?

In his review (October 1996, page 72) of *Broken Symmetry*, a compilation of Y. Nambu's papers, Roman Jackiw shows admirable collegiality but misses a point of scientific history.

One of Nambu's most consequential works was his paper on spontaneous symmetry breaking. Published in 1960, it subsequently revolutionized particle theory.[1] Jackiw remarks that Nambu "did not appreciate the generality" of the idea in particle theory. It seems to me that, on the contrary, Nambu not only fully understood the idea of vacuum degeneracy but also gave the first successful physical application to the case of chiral symmetry breaking and the pion. In his later paper, which cited Nambu, J. Goldstone gave a mathematical model that illustrated the idea of spontaneous symmetry breaking but stated in his opening paragraph that "the present work merely considers models and has no direct physical applications."[2]

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2. J. Goldstone, Nuovo Cimento **19**, 15 (1961).

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JACKIW REPLIES: Paul Frampton has misread my review. I wrote that Nambu "did not appreciate the generality *of a gapless mode* . . . accompanying vacuum degeneracy [emphasis added]." This point I inferred from Nambu's own recollection in *Broken Symmetry* (page xii): "[Goldstone] conjectured the generality of the existence of zero modes. As for [this] point, I had been debating . . . how to write a paper addressing it as a general phenomenon."

But I fully agree with Frampton that (as, in fact, I stated) Nambu gave us the present theory of the pion. On the other hand, I believe that Nambu's "most consequential" work was his early suggestion of the "color" degree of freedom, not only leading to a global symmetry, but also coupling to a new gauge field. With this he preceded later formulations of color quantum chromodynamics by seven years.

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A Fizz-sics Solution: Use Limestone to Cure Lake's CO_2 Problem

In discussing possible remedies for the occasional lethal eruptions of carbon dioxide from Lake Nyos and similar lakes (PHYSICS TODAY, May 1996, page 20), Ray Ladbury describes "the leading proposal for degassing the lakes" as being a plan, as reported by George Kling and associates,[1] to lay pipes at the deepest layers and pump the supersaturated water to the surface layer to be degassed.

I suggest another way of getting rid of the excess carbon dioxide accumulating at the bottom of such lakes: Dump limestone ($CaCO_3$) into the lake; the carbonate ions will react with the CO_2 to form bicarbonate, and the bicarbonate ions will remain in solution: $CO_3^{2-} + CO_2 + H_2O \rightleftarrows 2HCO_3^-$.

The limestone approach may be a more environmentally benign solution to the Lake Nyos problem than controlled degassing would be. The pH at the bottom of the lake would rise from 4 or 5 to 8.3, characteristic of the dissociation constant of bicarbonate,[2] and that could possibly lead to the restoration of the lake's aquatic life.

Possibly, the limestone approach could also prove cheaper than the degassing approach. Because of the large volume of water to be pumped to the surface, degassing would require several pipes of very large diameter or a bundling of many smaller pipes—the "Lake Nyos organ pipes." Installing such pipes and also pumps, as well as providing the pumping energy, would be a formidable and expensive engineering task.

How much limestone would be required? To soak up all of Lake Nyos's CO_2, one would need 1.25 million metric tons. However, the yearly accretion of CO_2 in the lake is only about 9000 metric tons.[1] That would require the dumping of only 20 000 metric tons of limestone a year—a not-outrageous amount that would fill about 200 railroad cars, or about 1000 trucks.

There are potential problems associated with the limestone dumping. The dissolving of $CaCO_3$ in the lake water may be slow, so that the limestone would have to be pulverized and pneumatically dispersed over a large area of the lake. Perhaps of greatest concern would be the fact that inserting 20 000 metric tons of limestone in Lake Nyos could possibly trigger a premature turnover of the lake and thereby bring about a repeat of the 1986 disaster. Limnologists should look into that issue.

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MAAD Scientists and Others Do Numerical Fracture Studies

In "How Things Break" (PHYSICS TODAY, September 1996, page 24), Mike Marder and Jay Fineberg present their recent studies on rapid brittle fracture (I use "their" to include the authors' collaborators). For their "crisis" phase, they describe the crack going beyond a critical speed and leaving "a thicket of small branches penetrating the surface behind [it]." This description follows from their fracture studies using a lattice model by Leonid Slepyan in which they first discovered this pattern. Later, their fracture experiments on Plexiglas showed an extensive network of microcracks radiating from the main crack, and the authors compare the results of their experiment and their simulations based on the Slepyan model. Their work and that of other researchers reflect the fact that brittle fracture is a truly rich phenomenon, and its numerical modeling is rapidly improving.

My colleagues and I have done two-dimensional molecular dynamics simulations of rapid fracture assuming Newtonian physics and a simple pair potential,[1] an *ab initio* approach in relation to the Slepyan two-dimensional lattice model. Our early simulations established the instability as an intrinsic property of the crack dynamics and not a consequence of material imperfections. Most important, our

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simulation results agreed with several experimental features generic to brittle fracture, not all of which are observed using the Slepyan model; they include the crack speed for the onset of the instability, the limiting crack speed and the scaling law for crack roughening. With this experimental validation, we then used our computational microscope to "see" what was happening dynamically at the atomic level and to understand the origin of these features. However, our simulations did not show the pattern found using the Slepyan model and later seen in the Plexiglas experiment. We observed two fracture patterns: an expanding zigzag pattern about the averaged forward direction[1] and a cascade of multicrack branching.[2] These patterns are consistent with many experiments on brittle fracture. I also conclude that the rich fracture pattern may be model-dependent as well as material-dependent.

In their conclusion, Marder and Fineberg state that "the computer can treat 100 million atoms for a few times 10^{-12} seconds, but we need to understand 10^{23} atoms on time scales of minutes or years." In collaboration with a team at the Cornell Theory Center,[3] I am now simulating three-dimensional fracture dynamics for 100 million atoms on the nanosecond time scale, or greater than two orders of magnitude longer than suggested. We have discovered an instability in the brittle fracture of certain face-centered cubic solids when the crack reaches one-third of the surface sound speed, giving rise to a "dynamic" brittle-to-ductile transition and the onset of a proliferation of loop dislocations. In addition, another group of researchers—known as the Macro–Atomistic–Ab initio–Dynamics, or MAAD, Coalition—is addressing the issue of reaching the time and space scales called for by Marder and Fineberg by developing techniques that bring together the continuum, atomistic and quantum descriptions in a seamless marriage. (The MAAD Coalition consists of F. Abraham, IBM; J. Broughton, Naval Research Laboratory; H. Gao, Stanford University; E. Kaxiras, Harvard University; R. Phillips, Brown University; and X. Xu, IBM). The continuum description, used successfully by the applied mechanics community for decades, is proper except in the region of failure, where an atomistic description is required. The atomistic level is being modeled by classical dynamics and

empirical interatomic force laws, except where bonds are breaking; in that case, a quantum description is being applied.

Multimedia versions of our two-dimensional and three-dimensional atomistic simulation studies of fracture are available on the World Wide Web at, respectively, (1) http://www.almaden. ibm.com/vis/fracture/prl.html and (2) http://www.tc.cornell.edu/~farid/fracture/100million.

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I believe that Marder and Fineberg have oversimplified the explanation for the strength of a cracked elastic solid—to the extent that their picture is fundamentally misleading.

Their argument is based on the idea that the stress at the crack tip determines crack growth, and they refer to the work of C. E. Inglis, who showed that very high stresses could be expected there. But this "stress-at-a-point" argument is exactly what fracture mechanics is not about.

The key advance that rested on Inglis's work was the calculation, by A. A. Griffith, of the change in elastic energy of a plate consequent upon the introduction of an elliptical cavity—for which, read "crack" in the limit of a long narrow ellipse. The important quantity that comes from this calculation is not the stress at the crack tip, but an imaginary force, the derivative of energy with respect to crack length, which acts in the direction of crack growth.

The notion that fracture of brittle bodies is caused by stress seems intuitively obvious, but it is false. The truth is more difficult to grasp, but it is more interesting, and I think the authors could have brought this out.

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MARDER AND FINEBERG REPLY: In our article, we did not describe the full range of numerical fracture experiments now being performed at IBM's Almaden Research Center, Los Alamos National Laboratory, Louisiana State University, Brown University and elsewhere. We thank Farid Abraham for bringing us up-to-date on the astounding scale these simulations now reach. We fully agree with all of his remarks. Our only addition would be that Slepyan potentials are not obviously less realistic for brittle fracture than Lennard–Jones potentials, but they have the advantage of allowing complete analytical solutions for moving fractures involving arbitrarily large numbers of atoms. The benefits to be had through comparison with these solutions have not been fully realized.

J. R. Griffiths raises an interesting subject—the two points of view on what makes a crack move. In the first, the effective force on a crack is the energy released by an infinitesimal extension. In the second, the effective force is given by singular stresses near the crack tip. The equivalence of these two points of view follows from the work of George Irwin that constitutes the foundation of fracture mechanics. Irwin showed that stresses near a static crack tip adopt a universal singular form, diverging as $1/\sqrt{r}$ where r is the distance to the tip, and with angular factors depending only upon the symmetry of external loads. Cracks begin to move when the coefficient of this singular term, the stress intensity factor, reaches a critical value. Jim Rice of Harvard University has used the basic conservation laws of continuum elasticity, in this context called the J integral, to show that this criterion for crack motion is identical to one that demands a critical energy release by virtual crack motion. When a crack is viewed at the atomic level, neither of these criteria for crack motion turns out to be entirely correct, but the errors are only on the order of 10%.

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Correction

January, page 88—The correct e-mail address for the contact for the HCIS-10 conference, which starts on 28 July, is hcisx@mbi-berlin.de. ■