toll: Myojin-sho killed nine researchers in 1952.

The reaction among volcanologists to the recent tragedies varies greatly, according to Tom Casadevall of the U.S. Geological Survey (USGS) in Denver, who is involved with international efforts to address the safety issue following Galeras. Those whose chosen line of work takes them into craters recognize the risks, and in fact, says Casadevall, they see the hazard as precisely the reason why scientists wish to monitor volcanoes. But he adds, "Folks whose work doesn't take them into craters have been very critical." One such volcanologist, who insisted on anonymity, told *Science*: "I don't think it was surprising; volcanoes explode. It's plain those guys didn't take the hazard seriously." As examples of their lack of seriousness, he cites the large size of the party in harm's way and the fact that only three of the 12 were wearing hard hats.

Others agree that hard hats might help. They're among the pieces of safety equipment recommended in a set of "Lessons Learned at Galeras Volcano" being circulated by Michael Conway of Florida International University, a Galeras survivor. Other recommended safety measures include flame-retardant clothing, powerful two-way radios for links to those outside who are monitoring the volcano, and a research plan that minimizes the number of field party members and the time they spend near open volcanic vents. The initial reaction to the suggested guidelines has been positive, says Conway, and they will probably figure in discussions on safety guidelines at a volcanological congress next September in Australia.

But while veteran volcano visitors don't object to such guidelines, many see a limited payoff. Stanley Williams of Arizona State University, who led the gas sampling group at Galeras and suffered a fractured skull, a crushed leg, and third-degree burns, is of this school. "I've seen drafts about safety rules, and so far I haven't seen any great new insights." While he wasn't wearing a hardhat that day, he adds, "it wouldn't have done me much good."

As to the larger question of whether some higher authority should be telling volcanologists when they can enter particular volcanoes, the answer so far is no. "I'm concerned there will be an overreaction" to Galeras, says Donald Swanson of the USGS at the University of Washington, a frequent visitor to Mount St. Helens. "We certainly want to minimize the risk, but we have to stop short of keeping people out of situations that would allow them to do some good." Casadevall adds: "The overwhelming consensus seems to be to not legislate behavior." Volcanologists' behavior may not be legislated, but recent losses have had a sobering effect. "I feel guilty having led groups into dangerous places when the payoff was marginal," says Rose. "I don't want to do that again."

–Richard A. Kerr

COMPUTER SCIENCE

Researchers Defy the Physical Limits to Computation

Each year's new computing technology, it seems, leaves the last year's in the dust. But physicists are now beginning to tell computer scientists that it can't go on this way. Sooner or later, as computers get smaller, faster, and more complex, the laws of physics will throw up roadblocks to further progress. There's only one way out of this bind: radically new strategies. And some of those strategies are starting to emerge.

Rolling Back the Costs of Computing

Strange as it may seem to computer users who have seen their machines effortlessly wipe out files, it takes energy to destroy information. And in current computer designs, the machines are destroying information every step of the way, even when they're working properly. Computer scientist William Athas and his group at the University of Southern California (USC) are working to end some of that waste—and thereby tremendously improve the efficiency of computers. Athas' group has realized a theoretical possibility proposed some 20 years ago and built a computer switch that, by preserving the information that goes into each computation, may ultimately lead to a new generation of energy-sparing computers.

For the moment, the switches designed by the Athas group are too cumbersome to make a dent in the real-world computer market, but there's a strong practical impetus for refining the idea further, says Xerox Corp. physicist Ralph Merkle. If computer circuits go on getting smaller and more powerful, by the year 2000 it will be possible to pack about 10^{17} logic gates into a cubic centimeter. And no matter how efficient those circuits are made, says Merkle, they will still have to dissipate megawatts of energy—enough to dry a thousand hairdos—simply to destroy information as the computation proceeds. If the information could somehow be spared, computers could be made as efficient—and as cool—as you like.

The idea that the destruction of information would place a fundamental limit on the efficiency of computing was proposed by theorists, including IBM's Rolf Landauer and Charles Bennett, in the 1970s. Bennett describes the problem this way: Imagine two memory elements in your computer. One (call it A) is set to 0; the other (B) is set to 3. If A is made equal to B during a computation, you've thrown away the information that A was equal to 0. Destroying that information consumes energy, explains Los Alamos researcher Wojciech Zurek, because by turning two values into one, it decreases entropy, which is a measure of the number of possible configurations of a system.

The theorists who identified this stumbling block thought they saw a way around it—at least in theory: Make every process in the computer reversible, so the information that goes into a computation can be recovered. Instead of setting A to equal B, for example, describe A's new value in terms of its old one—as A+B. Then you have enough information to retrieve the original A, by taking the new A and reversing the operation. Though performing such a reversible operation will still dissipate some energy, as electrons course through the circuits, the amount can be arbitrarily small. The slower you run the device, the less energy you use, says Landauer.

But this possibility remained speculative until recently because in conventional computers both the logic circuits and other components are set up to run in one direction only. Late last year, however, Merkle, Athas and his USC colleague Jeffrey Kollar, and several other groups realized that there was a way out of that bind. What they did was to take energy-efficient CMOS transistors, arrange them into reversible switches, and intersperse among them elements known as inductors, which harvest electrical energy that would have been lost as heat and feed it back into the power supply. The reversible circuits, the researchers say, are 7.7 times more efficient than conventional ones.

Yet, as always when researchers are approaching limits of computation, there's a catch: achieving those gains in efficiency requires slowing the computations by a thousand-fold. Even if the system could be sped up, Athas says he doesn't see his work leading to a completely reversible computer. The ideas are still too new. "I'm skeptical of whether anyone will use this in the near future," he says. Eventually, though, he thinks computers will use some reversible parts and some irreversible ones. "We will end up with a hybrid solution—that's what I see when I look into the crystal ball." Merkle is less cautious. As computer scientists push back the limits of miniaturization and efficiency, he thinks the attractions of these thrifty circuits will be irresistible. "My rash prediction," he says, "is that reversible logic will dominate in the 21st century."

The Next Transistor?

After several years of sharp cutbacks in the research staff at Bellcore in Red Bank, New Jersey, Mark Johnson is the only physicist left doing basic research. He may be lonely, but supporting his studies of how materials affect a property of electrons called spin could turn out to have been a lucky move for Bellcore. In this issue of *Science* (see p. 320), Johnson describes an invention that has emerged from those studies: a tiny electronic switch that some solid-state researchers say could serve as the nerve cells of tomorrow's computers. Johnson's switch, which uses the direction of a magnetic field to switch an electric current, could give rise to "a new class of electronics" says Naval Research Laboratory physicist Gary Prinz. "The next transistor," he calls it.

Ordinary semiconductor switches open or close a path for current by controlling the number of electrons in a "gate" layer. Circuits based on this kind of design have tremendous strengths, but they begin to falter when they are made very small. The "bipolar spin switch," on the other hand, a sandwich of two magnetic alloys and a film of gold, gets better as it gets smaller. As a result this new switch may be just what computer scientists need to push circuits toward the scale of atoms. "It's interesting that this came along just when we needed it," says Prinz.

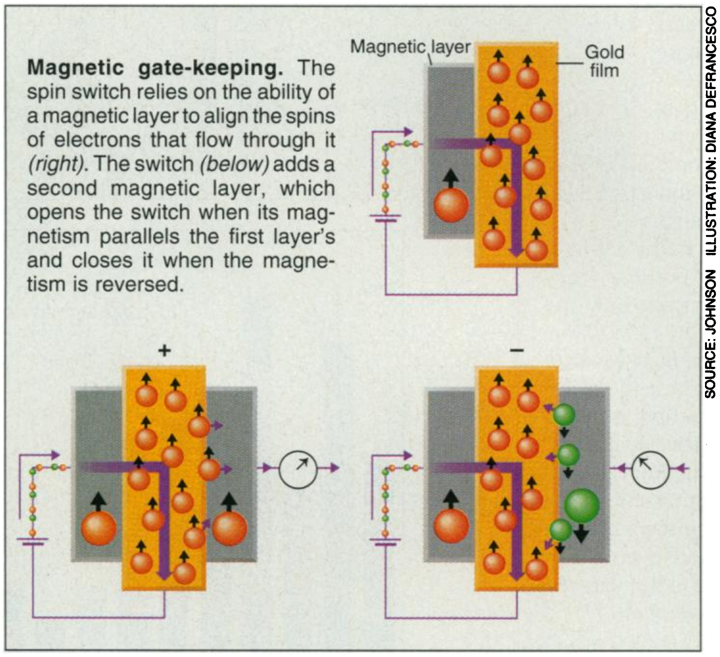
The key to the operation of the spin switch is the lingering effect that a magnetic material has on the spin of electrons passing through it. The spin of an electron is described as being in one or two quantum states —"up" or "down"—and ordinarily electrons spin up or down at random. But when a current flows through a magnetic material, the electrons get "polarized"—their spins are lined up in the direction of the magnetism. What is more, they tend to stay that way even after they leave the magnetic material.

Although there were early hints of this effect in the 1970s, it was only in 1988 that Johnson showed in his thesis project that the effect was large enough to harness for practical benefit. He does so in the new switch by sending a current through the first layer of magnetic material and into the gold film. The spins get lined up as the electrons pass through the magnetic layer, and, because the spins persist, a crowd of polarized electrons gathers in the gold.

The polarized electrons, combined with the magnetic properties of the third layer of the sandwich, turn the apparatus into a switch. If, for example, the spins in the gold layer are polarized in the "up" direction and magnetism in the final layer has the same orientation, the switch is open: The up electrons packed into the gold film by the current eagerly flow from the gold region into the third region and out, generating a new current.

But if the magnetization of the third layer is reversed—by applying a small electric pulse, for example—the up electrons in the gold layer will be penned in, unable to move into the third layer. Instead, because there's still plenty of room in the gold for down electrons, electrons are pulled in from the third layer. The current flows backwards, and the switch is closed.

Like ordinary transistors, the switch could be the building block of more complex circuits. There's one key advantage, explains Prinz: Shrink a conventional circuit, and eventually the semiconducting material can't muster enough electrons to make the device work. That happens at dimensions of about 1000 angstroms, he says; laboratory devices will soon approach that size. But because the spin switch is made entirely of metals, it should have electrons to spare.



Magnetic gate-keeping. The spin switch relies on the ability of a magnetic layer to align the spins of electrons that flow through it *(right)*. The switch *(below)* adds a second magnetic layer, which opens the switch when its magnetism parallels the first layer's and closes it when the magnetism is reversed.

Bellcore sees the possibilities in the device: It has applied for a patent. But Johnson himself isn't going on record with any predictions. "It's like asking the father of a newborn if his baby will grow up to be president."

Chemists Simulate Smart Beakers

Most researchers in the field of computing are straining to expand the limits of computation's current medium: electrons running through semiconductors. Stanford University chemist John Ross, however, is after something entirely different. He's trying to transfer computing to a new medium: liquid chemistry. On page 335 in this issue of *Science*, Ross and his colleagues A. Hjelmfelt and F.W. Schneider of the University of Würzburg in Germany show that a network of chemical-filled beakers can perform one of computing's hardest tasks—recognizing a pattern.

Ross and company's chemical computer wouldn't win any prizes for speed. In fact, it doesn't even exist yet—except as a simulation on a conventional computer. But the idea is within reach, says Ross, because the chemical reaction that would drive the computation is well understood. Ross isn't trying to corner the computer market with such devices. But he says there's evidence that macroscopic chemical reactions are going on in the brain, possibly doing some kind of information processing. His system shows one way it might work.

The model for Ross' effort was a neural network, a computer especially adept at pattern recognition. Neural networks are webs of processors linked by adjustable connections that strengthen or weaken as the system is programmed—as it "learns" various patterns. The chemical network replaces the processors with 36 vessels, each hosting a reaction that can yield either a low or a high concentration of product. The containers are joined so that reactants can flow between them, and the reaction flips between the "high" and "low" states depending on the concentration of reactants.

To store a pattern, the researchers adjust the connections between the vessels, altering the flow of reactants until the pattern of concentrations becomes a stable configuration—what Ross calls a stationary state. With the connections adjusted just right, the system can settle into any one of several different configurations of high and low concentrations. The system can "learn" as many as three patterns at once.

When this schooling is over, Ross and his colleagues expose the system to a new pattern by introducing some new combination of high and low product concentrations to the vessels. The computer simulation showed that if the new pattern is similar to one "stored" in the system, it responds by switching to the appropriate stationary state. Anything too far off, though, causes the system to revert to uniformly high or all low concentrations—in effect, throwing up its hands.

–Faye Flam