A magazine for Hewlett-Packard and Agilent people

March–April 2000

MEASURE

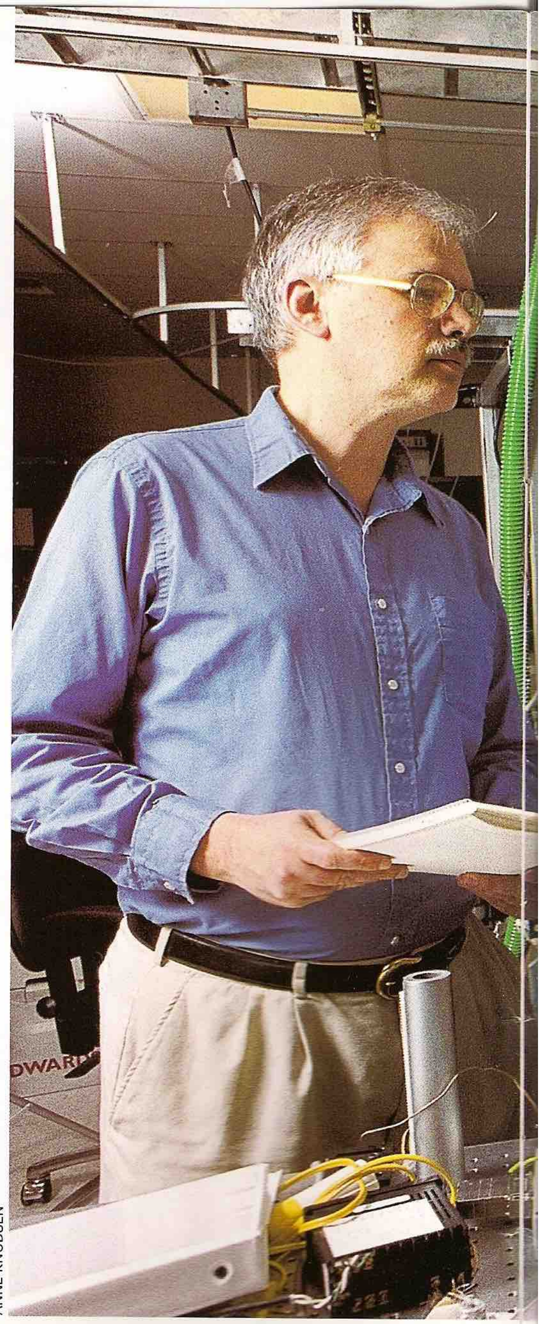
Hey, we're shrinking the computer!

INNOVATION

Making miracles, little by little

Progress in the tiny world of nanotechnology could launch quantum advances in computing.

By Karen O'Leary



ANNE KNUDSEN

Standing by the vacuum system used to grow and image various types of nanoscale objects, HP Labs researchers Phil Kuekes (left) and Dr. Stan Williams examine the chamber in which the structures are grown. The smaller chamber to the right (which looks like an old-style diving helmet) contains the scanning tunneling microscope used to obtain atomic resolution pictures of the objects.

Scientists at Hewlett-Packard Labs have garnered worldwide attention for their expedition into the new frontier of molecular technology—likely the foundation for the computer industry of the next century.

Dr. Stan Williams, director of the Quantum Structures Research Initiative (QSRI), and Phil Kuekes, a physicist and computer architect at HP Labs, along with colleagues from UCLA, are developing atom-sized wires and switches—the essential building blocks of computers—that could lead to machines that are a billion times more efficient than they are now.

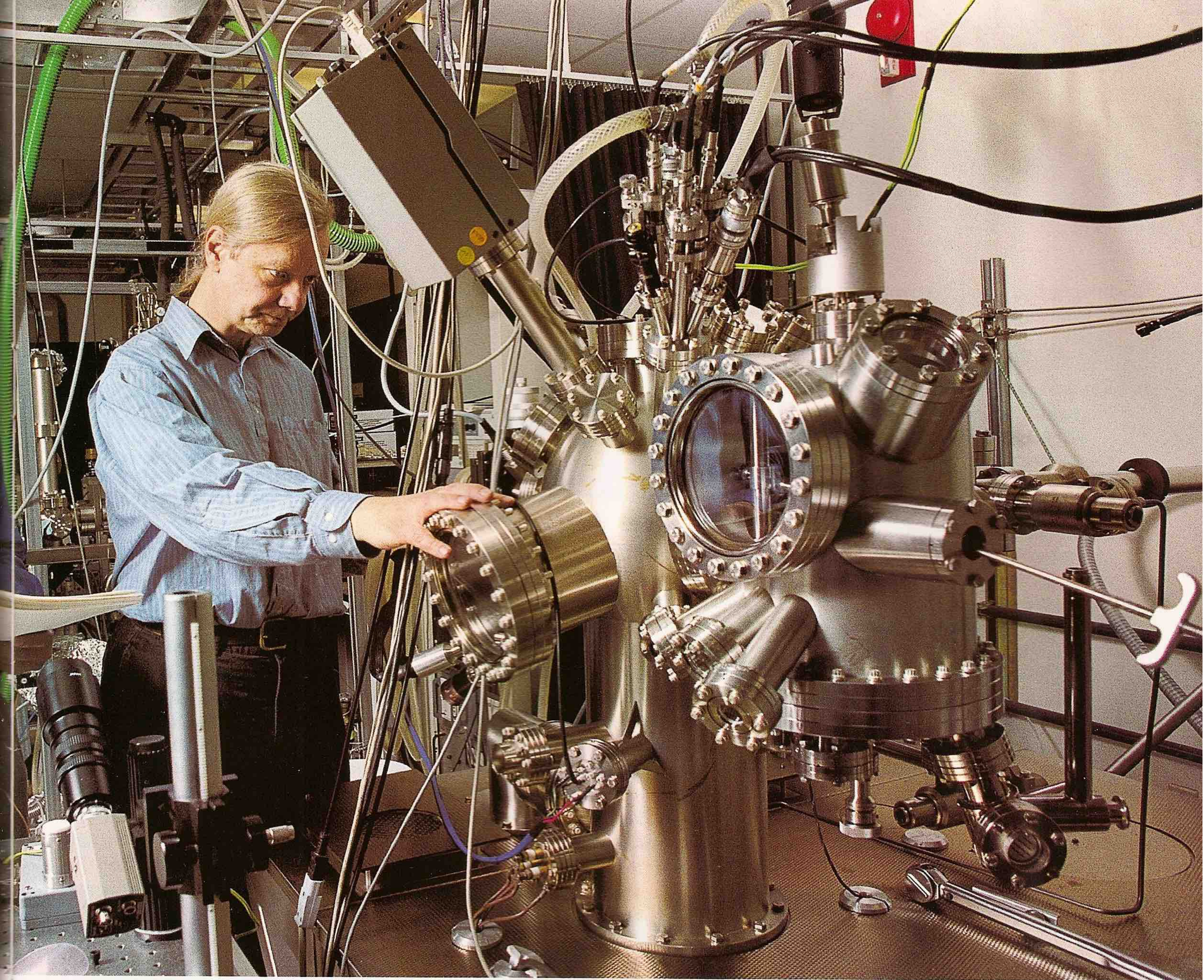
The HP-UCLA team essentially is attempting to "grow" computers chemically, creating wires and switches that assemble themselves molecule by molecule. The chemically based components are mere billionths of a meter or "nanometers" wide in size. If the team's efforts are successful, the scientists believe the computational power of 100 workstations will be able to fit on a platform the size of a grain of sand.

At the threshold of nanotechnology—the process of manipulating matter at the scale of atoms or molecules to create new things—the HP-UCLA team believes it is working with a technology that could develop vastly more powerful computers at a fraction of the cost of silicon-based machines. The key is to create huge numbers of wires and switches together that will assemble themselves in a useful electronic circuit, rather than try to place each component in a precise location.

Nanocomputers could become so easy and cheap to make that they will be embedded in every man-made object.

The movie *Fantastic Voyage* conjures images of orange juice that contains cell-repairing nanorobots as the remedy for cancer; a "gnat" that lands on a person's lapel serving as surveillance equipment; and automobiles built from precisely arranged carbon atoms that will have the strength and lightness of a diamond at a fraction of the cost of metal and plastics.

Still in embryonic stages, nanotechnology was conceived in 1959 by Nobel laureate Richard Feynman, a physicist from CalTech, who posed the question, "What would happen if



we could arrange atoms, one by one, the way we needed?"

"When I came to HP to start a group in nanoscale science, the first thing I tried to do was climb a tall tree and scout out the landscape," Stan says. "HP and Agilent are companies that are about information—gathering it, storing it, processing it and displaying it in a way that makes it useful.

"What would happen if we could arrange atoms, one by one, the way we needed?"

"I wanted to understand the physical laws of information better," he adds. "Richard Feynman said that it's physically possible, according to the laws of relativity and thermodynamics, to compute a billion times more efficiently than the most advanced technology can now. That's a powerful thing to think about."

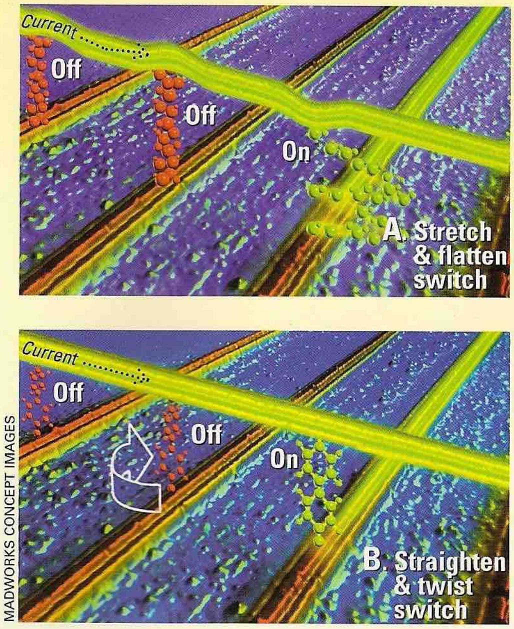
Though Stan recognized that it was physically possible to create vastly higher-performing computers, it was clear that the technology based on silicon was beginning to hit its limitations.

"There's been a lot of discussion in the newspapers lately that we're coming close to the end of silicon technology," he says. "We're almost to the point where silicon will not be able to improve exponentially as time goes on. I put the year at 2010."

There are a lot of reasons for that, Stan adds. Things are getting so small that everything is more difficult. You have to exclude smaller and smaller dust particles, for example. And it's getting incredibly expensive.

But the computer revolution is based on the fact that computers have been getting exponentially more powerful on a regular, predictable basis.

"I started designing computers in the 1970s that did millions of operations per second," says Phil Kuekes. "In the '80s, I built machines that did



MADWORKS CONCEPT IMAGES

Little by little

There are several different mechanisms by which molecules can act as electronic switches for use in nanocircuits:

Figure A illustrates how an interconnected molecule can switch on and allow current to flow from an overhead wire to lower wires. The molecule folds to pull the wires closer together and then switches off by stretching to push the wires apart.

Figure B illustrates how an interconnected molecule can switch on and switch off by rotating one of its components to be perpendicular to the other.

Scientists activate a switch by applying a voltage across the two wires holding the molecules. Smaller voltages are used for reading the state of the switch (low current is off, high current is on).

GILBERTO MEDEIROS-RIBEIRO, YONG CHEN & DOUGLAS

billions of operations per second; and in the '90s, I was involved with the Teramac machine, which did a trillion. Mega ops, giga ops and tera ops. But how do you keep up that kind of growth?"

Early in the 1960s, Gordon Moore, the co-founder of Intel, predicted that the number of transistors that could be incorporated onto a single integrated circuit chip would increase exponentially over time. His prediction held and came to be known as "Moore's Law."

Challenged by the limitations of silicon, Stan and his team set out to build systems with the size and density that could lead to an era of quantum mechanical computation that is a billion times what we have now.

"It would take us far beyond what silicon can do," Stan says. "It would allow us to continue the Moore's Law of continual improvement in computing technology for at least another 50 years. Our best Pentiums (chips) are no more than an abacus compared to what people will have in a few decades' time," Stan adds.

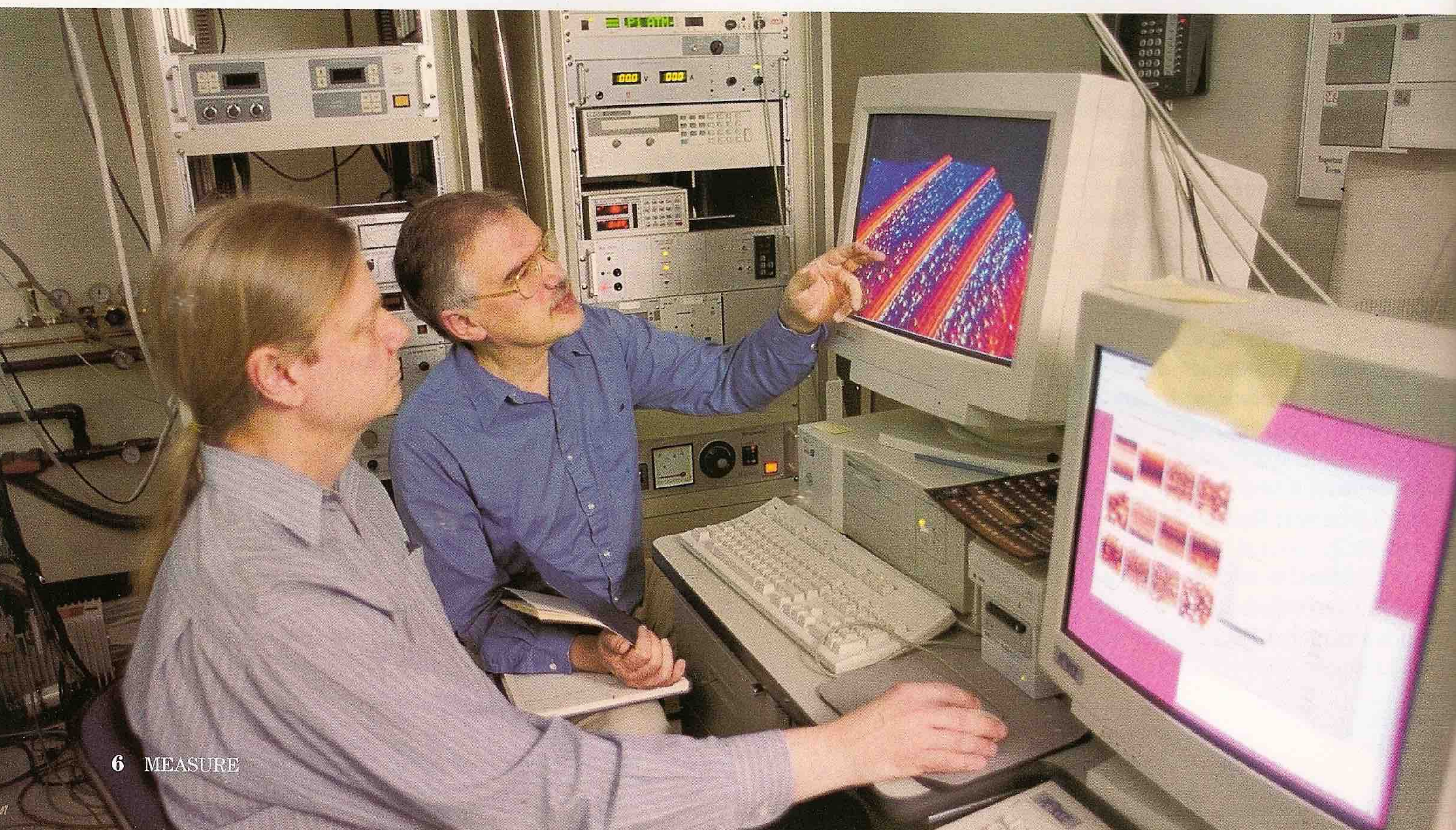
The now-world-famous collaboration began in a casual, inauspicious way.

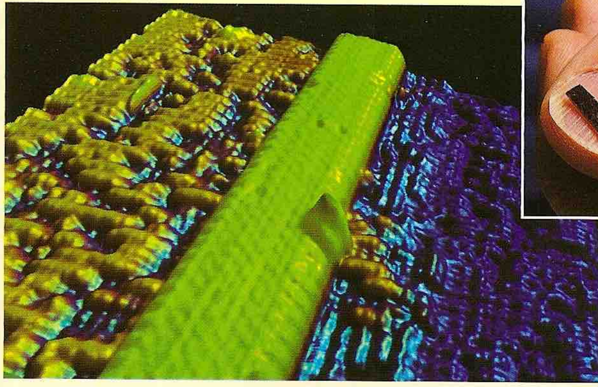
"I wandered down to see Stan about three years ago, knocked on the walls of his cubicle and introduced myself," Phil says. "I had been thinking about the limitations of computing and I knew Stan was working on the scale of things. We had some of the same concerns."

At the same time, Jim Heath, a chemistry professor from UCLA, was working with Stan in the lab.

With a common desire to perpetuate the exponential growth of computing power, the three-person team began to put in time after hours to discuss the issues from each of their areas of expertise—physics, chemistry and computer architecture.

"After Jim was finished in the lab, Phil would come up from the 1501 Page Mill Road site (in Palo Alto) and we would either sit in one of the





On Phil Kuekes' thumb sits an unassumingly small chip of silicon that has more than 1 mile (2 kilometers) of wire. Since the 8- to 10-atoms-wide wire is too small to photograph—the wires are smaller than 1/1000 the wavelength of light—a special scanning tunneling microscope senses the presence of atoms that a computer ultimately makes into a color-enhanced image.

The ratio of the size of one atom to Phil's thumbnail is about the same as comparing his thumbnail to the island of Hawaii.

This image is of such a small area on a silicon substrate that actual atoms are visible as fuzzy bumps. The wire is made by chemicals that assemble themselves in a straight line, 8 to 10 atoms wide, across the silicon.

The small spike sticking up from the wire is an imperfection that could make the equivalent of a diode in the wire. In other words, controlling the formation of the wire can result in the creation of circuit components at the atomic level.

SCANNING TUNNELING MICROSCOPE IMAGE

coffee rooms here or we would go out for pizza and beer and we would just talk. This went on periodically for almost 18 months."

An "ah-hah" moment occurred for the team when Phil told them he had a computer design that could be imperfect and still work.

"What interested Stan the most was the Teramac's defect tolerance," says Phil, who had been the project manager of the 400-pound, multi-architecture computer that contained 220,000 defects yet still operated perfectly.

The Teramac, it turned out, provided the HP-UCLA team with the groundbreaking insight that there existed a computer architecture that was both high-performing and defect tolerant—just what they needed to work in the realm of chemically based components.

"In a standard computer, any one of the Teramac's 220,000 defects would have killed it," Stan says.

ANNE KNUDSEN PHOTOS

Phil Kuekes (right) indicates the remarkable, colored topographic detail revealed in the image of the three rows of wires—8 to 10 atoms wide—grown in HP Labs' vacuum chamber. The image reveals order and imperfection at the atomic level. Stan Williams displays the labs' custom-software image derived from the raw-data images seen on the right monitor.

But its defect-tolerant architecture outperformed today's best high-end workstations by 100 to 1 in some applications, proving that defect tolerance—rather than the absence of defects—can provide the architecture for a powerful and reliable machine.

"Jim and I understood very well that it was impossible using chemical means to make something perfect," Stan says. "It can't be done. That was the thing that was holding people back from all this."

Computers made of silicon are complicated and must be perfect, while anything made chemically is simple and inevitably has defects.

"At that point, Jim Heath came to me and said, 'This is the most valuable course I've ever taken,' " Stan says. "It was the idea that these discussions were a class and that Phil was somehow the professor of the class. We decided we had to write a term paper just to make sure we really understood it."

Once the paper was written, Jim mentioned it casually to an editor at the journal *Science.*

"To our absolute horror, the editor sent it out for review to three computer scientists," Stan reports. "Then to our shock, we got back three critical but encouraging reviews. We were still in the exploring and playing mode and these three people took it all very, very seriously.

"After rewriting it for publication," Stan adds, "we sent it back, the three reviewers took another look, they loved it and—boom—it got published."

One of the results that the published paper generated was interest at the Pentagon.

"The people at DARPA (the Defense Advanced Research Projects Agency) essentially threw the gauntlet at our feet and challenged us to build a 16-bit memory that would fit inside a square that's 100 nanometers on a side," Stan says. "And they wanted us to do that in two years." That's currently one of their endeavors. In the process of writing the DARPA proposal, they developed six other technologies for which they have submitted patent applications.

"We're looking at possible creative collaborations with people who can do things with molecular electronics that we haven't even imagined."

Asked if the constant demands of the press have inhibited their ability to make progress, Phil says, "On the contrary. We potentially have a very interesting new technology and we alone are not remotely going to think of all the applications.

"When combined with other people's creativity, it's a technology that will become much more powerful. We're looking at possible creative collaborations with people who can do things with molecular electronics that we haven't even imagined. There's a lot of creativity out there, so it's important to get the word out."

"Are we at a pinnacle in computing or are we still at the beginning, at the bottom of the mountain?" Stan asks. "My own view is that we're at the beginning. As cool as we think everything has been in the 20th century, we haven't seen anything yet." **M**

(Karen O'Leary is a freelance writer based in Palo Alto, California.—Editor)