nanometers, or about 15 body-lengths, each second—and it's reversible, too. "It's a triumph of engineering," gushes Blair. To tease out the motor's "parts list," Blair has been altering genes coding for proteins in the motor and studying the effect of each change. So far, the only part he's clearly identified is the "fuel injector"—a proton channel that provides the motor's energy source—but he expects to be able to nail down parts corresponding to a rotor, stator, motor mount, and transmission.

Blair notes that transferring the motor intact to a different structure would be difficult, but he doesn't rule it out. He also points out that the motor seems to be constructed of molecular rings that might be useful by themselves as tinker-toy-style connectors or as "junction boxes" in other structures. "Or maybe we can use the motor to make really tiny CD players," he says. "Just kidding."

To install the motor in a larger structure, or to assemble any combination of switches, reaction chambers, and other biomolecular widgets, the well-equipped bionanoengineer will need a scaffolding. And for that purpose, New York University biochemist Nadrian Seeman thinks DNA may be just the thing. Seeman credits his original idea that DNA could be coaxed into a lattice structure to an M.C. Escher print that suggested a scheme for interweaving the DNA strands. Last year, by altering key sequences in the molecule, he got an assembly of DNA branches to fold itself into a cube, and he's confident more complex structures will soon follow. "The next step is to have other molecules associate with the DNA," he says. "Then you could have molecules with electronic properties riding the DNA into place, forming circuits."

The idea of trying to subvert DNA's function, transforming it from genetic material into molecular assembler, may strike some biologists as audacious, even irreverent. But bionanotechnologists are getting used to their colleagues' raised eyebrows. Even one Japanese funding group's stated goal of assembling biomolecular circuits into a working replica of what may be nature's most exquisite mechanism—the human brain—fails to affront as it would have just a few years ago. "When I first heard about that, I thought they were crazy," says Stanford's Boxer. "Now I look at it like people once thought about going to the moon, or building the SSC. It's, well, interesting."

■ DAVID H. FREEDMAN

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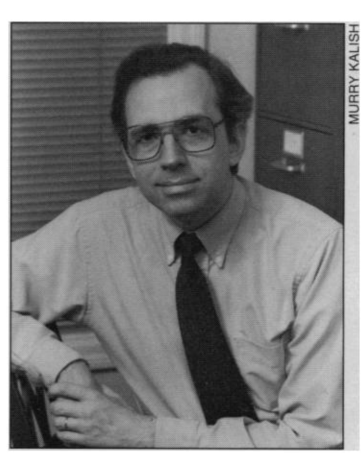
The Apostle of Nanotechnology

K. Eric Drexler has made it his mission to tell the world how far molecular-scale technologies could be taken

K. ERIC DREXLER LIKES TO THINK OF HIMSELF as a technology visionary with a message the world can't afford to ignore. In a matter of decades, he says, the fabric of human culture will be in for a drastic reweaving by protein-sized machines capable of manufacturing, molecule by molecule, anything an engineer might design within the constraints of nature. Over the past 10 years, Drexler's tireless promotion of that vision has turned him into "Mr. Nanotechnology," at least in the public eye.


MURRAY KALISH

To some researchers working in the field, however, he is anathema. "The man is a flake," says Phillip Barth, a microdevice developer at the Hewlett-Packard Company in Palo Alto. Others, such as electrical and microengineer Richard S. Muller of the University of California, Berkeley, fear that Drexler's fantastic descriptions of future technologies will plant unrealistic expectations in the minds of the public, policy makers, and grant committees. And some bench scientists simply think Drexler, who does his "exploratory engineering" research by pushing ideas to their theoretical extremes and running molecular modeling programs through powerful computers, rather than by building working devices, is just plain wrong in his visions of what might be.

Nanotechnology "will bring changes as profound as the industrial revolution, antibiotics, and nuclear weapons all in one." —Eric Drexler

But whatever they might think of him, many scientists agree that the bookish, soft-spoken, 36-year-old Drexler has had an impact on their field. An independent theoretician and occasional lecturer at Stanford University, Drexler wields formidable organizational skills and an ability to communicate ideas to nontechnical audiences. By writing an endless stream of books, encyclopedia articles, and technical papers, spawning nanotechnology study groups at universities, giving dozens of lectures around the world, and even speaking to Congress, Drexler has probably done more to raise public consciousness about nanotechnological possibilities than any other scientist. Along the way, he has attracted a nationwide stable of devotees who see the future exactly as he does.

His promotional zeal isn't confined to the popular realm, however. When a dozen or so established researchers who are pushing the envelope in building molecular-scale structures and devices shared their work with another 100 or so scientists, onlookers, and journalists in Palo Alto earlier this month, for example, they did so at Drexler's invitation. And some mainstream researchers give him credit for that kind of effort. Robert Birge, a respected player in molecular electronics at Syracuse University, says Drexler "has gotten a lot of people to think about what might be possible." Birge also praises Drexler for getting people in different areas of molecular science to talk to one another. "If there has been a flaw, it is that he hasn't submitted his ideas to refereed journals where he would get feedback to tone down his ideas."

Toning down is just what Drexler's popular writings seem to invite. Take his first book, *Engines of Creation: The Coming Era of Nanotechnology*, published in 1986, in which hypothetical protein- and organelle-sized machines "bring changes as profound as the industrial revolution, antibiotics, and nuclear weapons all rolled up into one massive breakthrough." Among Drexler's minute epoch-makers are life-prolonging molecular machines that tour the cells of the human body and repair proteins gone bad, and solar-powered nanofactories that yank greenhouse gases like carbon dioxide out of the air, spit out oxygen, and put the carbon atoms back into the coal and oil reservoirs whence they came.

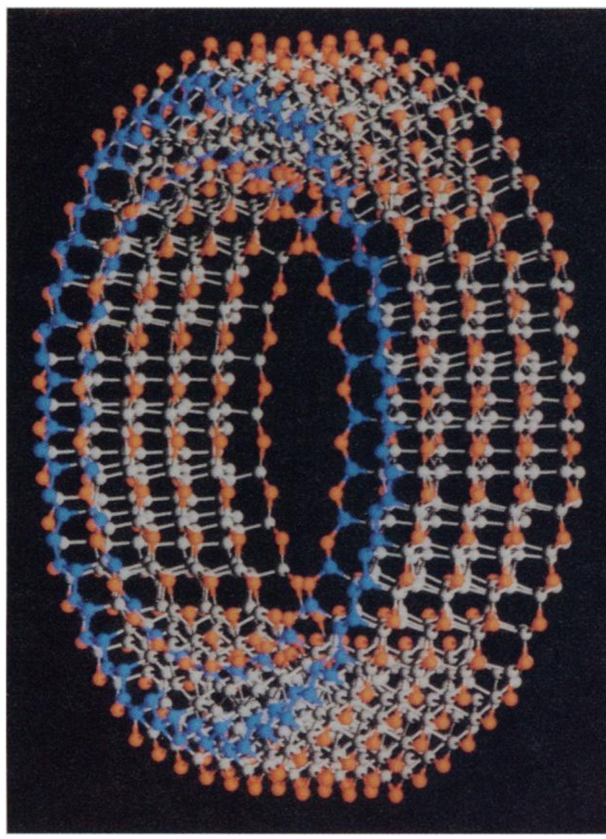
No surprise that such ideas didn't exactly get rave reviews from other researchers, but Drexler, undaunted, is still painting the same scenarios 5 years later. The just-published *Unbounding the Future: the Nanotechnology Revolution* (which Drexler coauthored with Chris Peterson, his wife and fellow nanotechnology aficionado, and Gayle Pergamit, a story teller friend) spins a tale of molecular "assemblers," capable of starting with atomic and molecular ingredients and turning them into such things as super-strong tents complete with cooking facilities and air conditioning, which future Red Cross workers might deliver to disaster areas. And why not? ask Drexler and his devotees. To them, summary rejection of such scenarios just shows that the nay-sayers haven't considered their philosophical and scientific grounding.

Like other futurists, Drexler stresses the value of trying to come up with plausible pictures of the near future to give context to today's decisions and head off problems before they arise. That's a habit of mind, he says, that comes in part from his college and graduate years at the Massachusetts Institute of Technology, where he earned a master's degree in 1979 for work on "space industrialization engineering." "People in that field plan concretely 10 years out, and think seriously 20 and 30 years out," he remarks.

Drexler's graduate years planted the seeds of his current obsession by giving him a chance to "filter feed" on books, articles, and courses all across the technical landscape. "I ended up learning a lot about chemistry, materials science, and manufacturing, and thinking a lot about chemical transformations," he says. One set of transformations that seemed to open realms of engineering possibilities were those of molecular biology, in which nanometer-scale biomolecular machinery under the guidance of data stored and read out by DNA and RNA crank out all the materials and structures of living things.

"The notion of molecular nanotechnology gelled in my mind in the spring of 1977," Drexler remembers. To him, the way seemed open for what he calls molecular nanotechnology: constructing analogous, nonbiological molecular machines for large-scale manufacturing on Earth and in space.

"It [this conviction] was exciting at first, but then increasingly disturbing," Drexler said. The cold war was still roaring and "I started seeing potential down sides"—governments developing nanotechnological warfare, for example. "I decided not to say much about it." But he changed his mind, he says, when he began to see hints of his vision appearing in published research. Open, cooperative development, he decided, would be the best hope for reaping nanotechnology's benefits and managing its risks and social consequences. He outlined his vision in his first paper, "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation," published in September 1981 in the *Proceedings of the National Academy of Science*.



DREXLER AND MERKLE

Gear in tomorrow's nanomachinery? *A hypothetical wheel of carbon atoms, designed by Drexler and Ralph Merkle.*

Reaction from the scientific community was sparse, he remembers, but the nonscience sector saw something in it. *Smithsonian* magazine, for example, asked him to write a simpler version for a 1982 issue. As his stock began rising among nonscientist technophiles, scientists began sitting up and taking notice—sometimes bemused, sometimes enraged.

Since then, as Drexler has pursued his mission to prepare the world for molecular nanotechnology, he's built bridges to mainstream research. From their spartanly furnished house in Los Altos, for example, he and Peterson—an MIT-trained engineer—direct the 1000-member Foresight Institute, which they founded in 1986. Besides keeping its members informed about scientific, political, and other developments related to Drexler's predictions and spreading the word to the public and to policy makers, the institute also holds technical conferences like the one early this month. Drexler has even set up a nanotechnology funding source: the Institute for Molecular Manufacturing (IMM), founded this year with $175,000 in seed money from an unnamed donor. The IMM is meant to serve as a vehicle for raising grant money and sponsoring research "to speed the development of molecular manufacturing or molecular nanotechnology."

Drexler is also making an effort to appear more credible in the eyes of his critics. He finally earned a Ph.D.—in molecular nanotechnology—from MIT 2 months ago, and he has written a technical tome called *Nanosystems: Molecular Machinery, Manufacturing, and Computations*, to be published next year by Wiley & Sons, says Drexler. He contends that the book, which is self-consciously fat with equations and theory, will provide a firm theoretical grounding for the futurist tales he has been spinning. "This book will get people to say molecular nanotechnology is real," predicts Ralph Merkle, a fierce Drexler champion and a full-time molecular nanotechnology researcher at Xerox's Palo Alto Research Center.

But will all these efforts win Drexler ungrudging acceptance in the mainstream? Probably not. Barth of Hewlett-Packard speaks for hardliners when he dismisses Drexler's vision of nanotechnology: "You might as well call it nanoreligion." But the same messianic energy that feeds Barth's suspicions also means that, like him or not, researchers in the field may have to reckon with Drexler for a good long while. By then, the future will have arrived and Eric Drexler's foresight or folly will be on full display.

■ IVAN AMATO