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The Incredible Shrinking Man

K. Eric Drexler was the godfather of nanotechnology. But the MIT prodigy who dreamed up molecular machines was shoved aside by big science – and now he's an industry outcast.
By Ed Regis

It was a clear sign that the world's smallest technology had hit the big time. At the Department of Energy's NanoSummit, held in June in Washington, DC, energy secretary Spencer Abraham gave the opening speech before an array of scientists from universities, industry, and national labs. Former chief arms control negotiator Paul Robinson spoke at a luncheon. The closing address was delivered by Richard Smalley, the Rice University chemist who shared the 1996 Nobel Prize for discovering Buckminsterfullerene, a soccer ball-shaped carbon molecule, and its permutations, known as fullerenes. In between, luminaries from the increasingly glamorous world of nanotechnology outlined the fledgling discipline's future.

There was only one person missing: Eric Drexler, the undisputed godfather of nanotechnology, the man who coined the term. Back in 1977, while an undergrad at MIT, Drexler came up with a mind-boggling idea. He imagined a sea of minuscule robots that could move molecules so quickly and position them so precisely that they could produce almost any substance out of ordinary ingredients in a matter of hours. Start with a black box of so-called molecular assemblers, pour in a supply of cheap chemicals, and out would flow a profusion of gasoline, diamonds, rocket ships, whatever, all built without significant expenditure of capital or labor. In the bloodstream, tiny machines could cure diseases. In the air, they could remove pollutants. Drexler's vision inspired a generation of chemists, computer scientists, and engineers to focus on science at the nanoscale.

"Drexler captured the imagination, especially of younger people," says William Goddard, a Caltech professor who specializes in molecular simulations. "He got people to buy into the idea that there are really neat things you can do by thinking small. And he's still way out there in front. He's a hero."

Yet there have always been scientists who considered Drexler part of the lunatic fringe. Six months before the NanoSummit, his critics landed what may be a decisive one-two punch. On December 1, the technical journal Chemical and Engineering News published a series of letters between Drexler and Smalley in which the Nobelist made his position clear: Molecular assembly is impossible. "Chemistry of the complexity, richness, and precision needed to come anywhere close to making a molecular assembler - let alone a self-replicating assembler - cannot be done simply by mushing two molecular objects together," Smalley wrote.

It was a public takedown from the man fast replacing Drexler as nano's leading light. But Smalley wasn't done. In remarks so overheated that they bordered on bizarre, he accused Drexler of terrorizing the world with the prospect that self-reproducing assemblers might escape the lab and devour everything in their path, turning the Earth into an inert, undifferentiated blob of gray goo.

"You and people around you have scared our children," Smalley fairly shouted in print. "I don't expect you to stop, but I hope others in the chemical community will join with me in turning on the light and showing our children that, while our future in the real world will be challenging and there are real risks, there will be no such monster as the self-replicating mechanical nanobot of your dreams."

The second blow to Drexler came only two days later, when President Bush signed the 21st Century Nanotechnology Research and Development Act, allocating $3.7 billion for molecular-scale R&D. In the months leading up to the signing, the bill had promised to catapult Drexler's agenda to the forefront of the nation's scientific priorities. But in the end, no money was earmarked for molecular manufacturing. Instead, the funds were largely allocated to projects using variations on conventional chemistry to develop novel materials "with new combinations of characteristics, such as, but not limited to, strength, toughness, density, conductivity, flame resistance, and membrane separation characteristics."

With these two events, Drexler suddenly found himself marginalized in the very field he had inspired. He had been pursuing the dream of molecular manufacturing all his adult life, with a single-mindedness that left him with little attention for anything else. Now his shining dreams of unprecedented material abundance, miracle medicine, and environmental revitalization lay in shambles.

Sitting on the corner of a bed in a Palo Alto hotel room, Drexler is bloodied but combative. His salt-and-pepper beard and hunched posture make him look older than his 49 years. He speaks in apocalyptic terms. "In a competitive world," Drexler says, conjuring the frightening prospect of hostile forces wielding gray goo nanoweapons, "suppression of research in molecular nanotechnology is the equivalent of unilateral disarmament." The outcome, he claims, could be nothing less than "the destruction of the United States as a world power."

Drexler's rejection by the scientific and political establishments comes at a particularly bad moment. Last year, he divorced Christine Peterson, his wife of 21 years and president of his nonprofit think tank, the Foresight Institute; now she's resigning her post to write a book on nanotechnology. Never a rich man, Drexler is barely solvent. He recently moved from his three-bedroom ranch house in Silicon Valley into a modest apartment.

Feeding his anger is a fear that years of effort have come to naught. What especially galls him is that the very name he coined for his ideas has been appropriated by forces pursuing something altogether different. "I never expected that a bunch of researchers would pick up the label nanotechnology, apply it to themselves, and then try to redefine it. That's a shock, and it has led to a tremendous mess for everybody."

For everybody, yes. Especially for Drexler.

Kim Eric Drexler was born on April 25, 1955, in Oakland, California, to a mother who was a mathematician and a father who was a speech pathologist. A bookish boy, he was lost in the company of his peers. "Eric was always something of a social outcast," says his childhood friend Dave Anderson. "He was your classic nerd taken to the extreme."

As a freshman at MIT in 1974, he presented a paper about mining asteroids to the First Princeton Conference on Space Colonization. At the time, he envisioned a career as a space scientist, taking humanity to the outer planets on craft propelled by solar sails.

But these were also the formative years of genetic engineering. Drexler, who spent several nights a week poring over the latest research, began to wonder whether it was possible to reproduce mechanically what cells manage biologically. Mimic the functions of DNA, ribosomes, and enzymes with tiny machines, he reasoned, and you ought to be able to do anything that biology does – and lots more. It would be not genetic but molecular engineering, the technology to end all technologies. "That rapidly began to look like something very big and important," he says. "Because if you have this general ability to manipulate atoms in complex patterns, you can make essentially anything that's physically possible."

Though Drexler arrived at this insight independently, he soon learned that he wasn't the first. Reading in the library one night in November 1979, he came across a similar proposal by Richard Feynman, the physicist widely regarded as one of the greatest scientific minds since Albert Einstein. In a 1959 lecture, "There's Plenty of Room at the Bottom," Feynman asserted that "we can arrange atoms the way we want: the very atoms, all the way down!"

Giving humankind that ability became Drexler's crusade. It would not be easy. For one thing, the MIT prodigy was short on the schmoozing skills necessary for success in big science. For another, many of his interests were outrageously eccentric. At MIT during the 1980s, he and his wife organized weekend retreats in the backwoods of New Hampshire, where students discussed such topics as the prospect of immortality through cryonics. Nonetheless, Drexler's ideas were respectable enough that in 1981, the prestigious Proceedings of the National Academy of Sciences published his first major paper, "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation."

His first book, Engines of Creation, published in 1986, introduced the term nanotechnology to the world at large. In addition to describing the technology's potential benefits, it sketched out the gray goo scenario and suggested ways to avoid it. The foreword was written by Marvin Minsky, the MIT mathematician and patron saint of artificial intelligence. Minsky proclaimed that "nanotechnology could have more effect on our material existence than those last two great inventions in that domain - the replacement of sticks and stones by metals and cements, and the harnessing of electricity."

Drexler finally earned his PhD in 1991. MIT awarded him the first-ever degree in molecular nanotechnology.

Despite his distaste for politics, Drexler presented his theories to Congress in 1992. He testified before the Senate Subcommittee on Science, Technology, and Space during a hearing about "new technologies for a sustainable world." Subcommittee chair Al Gore declared his enthusiasm and vowed to fund exploratory research.

The same year, Drexler published a 550-page blueprint for a molecular manufacturing system titled Nanosystems: Molecular Machinery, Manufacturing, and Computation. Packed with equations, charts, and illustrations, the tome showed how a stream of feedstock molecules could be sorted and purified, oriented in space, and transported to manipulator arms that could deposit them, thereby building an object from the molecules up.

Nanosystems was a solitary masterpiece, a work that had no predecessors and, as yet, no successors. But for all its rigor, the volume was hardly noticed by the scientific press, perhaps because it fell between the cracks of so many disciplines. The only major review, in Nature, noted that the feasibility of Drexler's scheme "has not even begun to be demonstrated."

This tentative assessment hinted, if only faintly, at the questions that have dogged Drexler from the start. Are his ideas feasible or fantastical? Dangerous or ridiculous? Products of a transcendent insight into the nature of physical reality or a fundamental misunderstanding of chemistry? Even at MIT, his work divided the faculty.

"It's very impressive, there is no question," said MIT chemist Rick Danheiser, who served as Drexler's thesis adviser, in 1992. "I couldn't have done a better job."

"It showed utter contempt for chemistry," countered Danheiser's colleague Julius Rebek. "And the mechanosynthesis stuff I saw in that thesis might as well have been written by somebody on controlled substances."

Even people who believe in Drexler's vision share his fear that molecular assembly could have unimaginably dire consequences. In the April 2000 issue of Wired, Sun Microsystems cofounder and chief scientist Bill Joy speculated that although Drexler's assemblers could be invented within 20 years, it would be a great mistake to do so. "Nanotechnology has clear military and terrorist uses," Joy wrote, "and you need not be suicidal to release a massively destructive nanotechnological device." Then there was gray goo, a nemesis "that could stem from a simple laboratory accident. Oops."

Not long afterward, Michael Crichton depicted just such a mishap in his best-selling novel Prey. A cloud of "nanoparticles" is released from a lab. The particles reproduce, evolve a distributed intelligence, and swarm across the Nevada desert devouring jackrabbits, foxes, and people. Crichton prefaced his narrative with an introduction that quoted Drexler at length. Although the events portrayed in the book were fictional, the technology behind it, Crichton warned, was all too real.

It's one thing to be reminded that your ideas are dangerous, quite another to be told they're pure fantasy. In the September 2001 issue of Scientific American, Richard Smalley first presented his view that molecular assembly couldn't possibly work. A nanoassembler, he argued, would need a multitude of fingers to control all the atoms involved in a reaction - too many to fit in the minute space available. "There's not that much room" at the bottom, Smalley quipped, taking a potshot at the heretofore inviolable Feynman.

Under attack from all sides, Drexler was nonetheless poised for victory in Washington. After years of lobbying by the Foresight Institute, in May 2003 the House passed the Nanotechnology Research and Development Act by a lopsided vote of 405 to 19. The bill contained a provision - written by California representative Brad Sherman, a Drexler supporter who had spoken at Foresight's annual conference the previous year - calling for a study to "develop, insofar as possible, a consensus on whether molecular manufacturing is technically feasible." If the technology was deemed feasible, the study would find "the estimated time frame in which molecular manufacturing may be possible on a commercial scale; and recommendations for a research agenda necessary to achieve this result."

With this language, Congress was on the verge of making Drexler's dream a reality. But by November - five months later - the provision had vanished from the legislation.

What turned the tide on Capitol Hill? Drexler's ideas had always been outlandish and his political skills underdeveloped. That combination became an Achilles' heel as opposition emerged from two quarters. First, a group called the NanoBusiness Alliance entered the fray. Formed in October 2001, the alliance wasn't interested in anything as starry-eyed or scary as self-replicating molecular assemblers; it wanted to sell newfangled products like "nanotech" suntan lotion, ski wax, and paint. One of the founders, venture capitalist F. Mark Modzelewski, was a notorious opponent of Drexlerian notions; in a later email exchange with blogger and nanotech booster Glenn Reynolds, he likened Drexler's theories to "a wino's claims on skid row that bugs are crawling under his skin."

Meanwhile, support for Drexler's ideas softened elsewhere in Washington. The White House's Office of Science and Technology Policy worried that fears whipped up by the likes of Crichton and Joy would turn the public against nanotech, just as similar scares had fueled opposition to GM foods and nuclear power. As New Hampshire's John Sununu remarked on the Senate floor, "some people have expressed concern that nanotechnology will lead to a superrace of humans or a situation where nanomachines attack or even dominate human beings."

Molecular manufacturing is a "loaded term," a Senate staffer says. "It upsets a lot of people."

The sponsors of the House bill were more interested in making sure it got through the Senate than they were in preserving funding for Drexler's ideas. Thus, when House and Senate staff members met to discuss their respective bills, they scuttled the molecular manufacturing study. In the Senate version, Arizona's John McCain introduced an "amendment in the nature of a substitute" in which the provision no longer appeared.

The watered-down bill was passed by the unanimous consent of the Senate on November 18 and signed into law by Bush on December 3. During the ceremony, Richard Smalley stood at the president's side.

Congress' December surprise laid bare a schism in the nanotechnology community. On one side stands Drexler and his radical vision of molecular assembly. On the other stands Smalley, and with him a majority of scientists. In their view, nanotechnology means any work at the nanoscale. It's essentially small-molecule chemistry, or materials science at the atomic level.

Sitting in his hotel room at June's NanoSummit, Smalley explains that he was once captivated by Drexler's notions. "I was enchanted by Engines of Creation," he says. "I read it in a single sitting, and then I reread it." As late as 1999, he testified to Congress about "what will be possible when we learn to build things at the ultimate level of control, one atom at a time."

But doubts crept in as Smalley pondered the theory. "For months I said to myself, How could we have missed this? Is it really possible to do chemistry in this way? After a while I thought I saw what might be some problems. The more I thought about it, the more troublesome they appeared. Finally I ended up thinking, it's just hopeless."

Smalley recalls a meeting he arranged with Drexler at Stanford about a decade ago. "I wanted to talk about the tip," he says, referring to the business end of Drexler's machines. "I love the idea of the assembler. So I tried to drag him into a conversation about the tip, and he stonewalled. It was as if the tip was a job for later."

Drexler remembers the same meeting with no less frustration. "I found it very hard to explain things to him," he says. "He was asking for an irrelevant and impossible control of the motion of every atom. The question isn't, Are there some things that won't work? The question is, Are there enough things that will?"

The fact is, Smalley lost interest in Drexler's ideas. Instead, he began looking for ways to create chemical structures with extraordinary properties. The results were twofold. First, the chemist discovered the class of molecules called fullerenes. Second, he formed a company to exploit his discovery. Carbon Nanotechnologies, of which Smalley is chair of the board, bills itself as "the preeminent world producer of Buckytubes," better known as nanotubes.

Nanotubes are 100 times stronger than steel and more electrically conductive than any other substance known - a superior material for things like long-haul power cables. Nanotube wires will be so efficient, Smalley predicts, that they might "easily replace every high-voltage cable in the world."

It was practical applications like this - developments with a far quicker payoff than nanoassembly - that Congress embraced when it abandoned molecular manufacturing. Companies led by Smalley and others stand to profit from that decision. Drexler, meanwhile, has only lofty visions of a land of plenty.

Between sessions at the annual Foresight Institute conference, held in May in Palo Alto, Drexler's acolytes heap scorn on Smalley. His "scaring the children" comment in Chemical and Engineering News comes under attack as speaker after speaker asks something like, "This is scientific criticism?"

On a screen, Drexler projects an illustration of a molecular mill, a wheel that transfers one atom at a time to a succession of molecules as they move past on a conveyor belt. The image, the latest expression of Drexler's vision, is absurdly oversimplified. The machinery is rendered with solid surfaces rather than the atoms they must actually comprise - a choice that plays into the hands of his critics.

Yet there are indications that Drexler wants to remain a player – even if that means backpedaling and retrenching. First, he has abandoned his staple rhetoric. "Self-replicating nanomachines are not necessary for molecular manufacturing and should be de-emphasized as a goal," he wrote in the January 2004 issue of Foresight's newsletter. Instead, they would be replaced by "desktop nanofactories," conceived as "general purpose manufacturing systems." Second, he now regularly invokes Richard Feynman's name, calling his claim that molecules can be positioned mechanically "the Feynman thesis." Finally, he has proposed renaming his vision of molecular manipulation zettatechnology, a tacit acknowledgment that he has lost the tug-of-war over the term he coined.

No matter what critics say, the principal question concerning Drexlerian nanotech – whether molecular manufacturing is possible - can't be settled by theories, simulations, conferences, debates, or feasibility studies. As a scientific question, it can be resolved only by experiment. It might be several years before sponsors emerge who are willing to fund the necessary tests. Until then, Drexler's machines will remain a tantalizing possibility, nothing more and nothing less.

Meanwhile, for Drexler there's nowhere to go but back to square one, trying once more to convince the skeptics. Doggedly chasing his dream, he writes technical papers, creates pictures of molecular machines, and, to let off steam, takes long, lonely walks in the hills.

The Theory.
In Drexler's conception, the goal of nanotechnology is to build molecular assemblers – nanoscale factories capable of constructing objects at any scale, atom by atom. Unlike conventional chemistry, in which innumerable molecules react en masse, Drexler's proposed method of "mechanosynthesis" involves positioning individual molecules close together so stronger chemical attractions can overcome weaker ones in a controlled way, depositing or removing atoms as desired.

The Technology.
In this image of a hypothetical molecular mill, a conveyor belt carries the production line beneath an assembly wheel outfitted with tool tips of reactive germanium - exchangeable with alternative tips to deposit or remove different types of atoms. The mechanism places a single hydrogen atom on each molecule as it passes. As Drexler sees it, a system of such machines would be able to build just about anything, quickly and inexpensively.

The Problem.
In practice, Drexler's critics charge, chemistry is more complicated. Each atom in a molecule interacts with every other atom nearby, including those in the proposed tool tips, conveyor belt, mill wheel, and so on. Thus, to deposit a single atom, a nanoassembler would need to restrain every atom in the vicinity. The sheer number of atoms that would need to be controlled, and the machinery it would take to control them, make mechanosynthesis a practical impossibility.

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