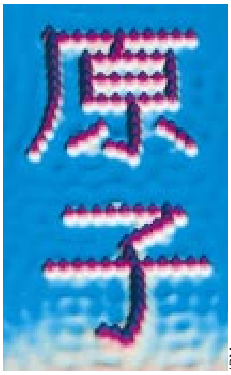
Waiting for Breakthroughs

by Gary Stix, *staff writer*



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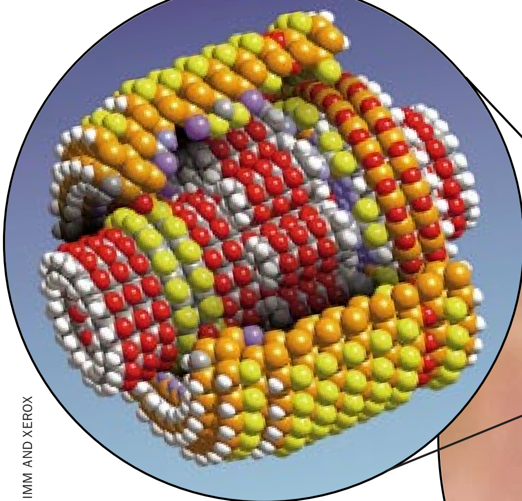
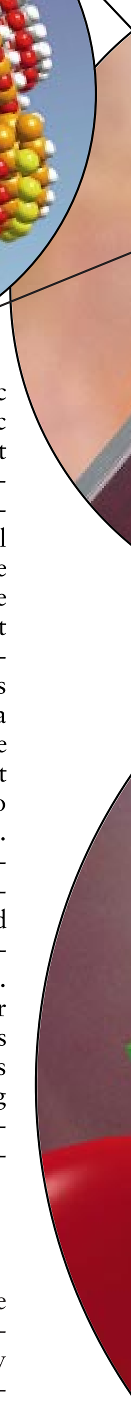


IMM AND XEROX



"That's the messiah," confides Edward M. Reifman, D.D.S. The Encino, Calif., dentist has paid hundreds of dollars to attend a conference to hear about robotic machines with working parts as small as protein molecules. Reifman nods toward K. Eric Drexler, the avatar of nanotechnology. Drexler has just finished explaining to a strange mix of scientists, entrepreneurs and his own acolytes that nanotech may arrive in one to three decades. The world, in his view, has not fully grasped the implications of molecular machines that will radically transform the way material goods are produced.

Nanotechnology is the manufacture of materials and structures with dimensions that measure up to 100 nanometers (billionths of a meter). Its definition applies to a range of disciplines, from conventional synthetic chemistry to techniques that manipulate individual atoms with tiny probe elements. In the vision promulgated by Drexler, current nanoscale fabrication methods could eventually evolve into techniques for making molecular robots or shrunken versions of 19th-century mills. In the course of a few hours, manufacturing systems based on Drexler's nanotechnology could produce anything from a rocket ship to minute disease-fighting submarines that roam the bloodstream. And, like biological cells, the robots that populate a nanofactory could even make copies of themselves. Finished goods in this new era could be had for little more than the cost of their design and of a raw material—such as air, beet sugar or an inexpensive hydrocarbon feedstock. The Drexlerian future posits fundamental social changes: nanotechnology could alleviate world hunger, clean the environment, cure cancer, guarantee biblical life spans or concoct superweapons of untold horror.

Scientific visionaries have shifted their attention from outer to inner space, as the allure has faded from dreams of colonizing another planet and traveling to other galaxies. Computer mavens and molecular biologists have replaced rocket scientists as the heroes that will help transcend the limits imposed by economics and mortality. "Whether or not Drexler's utopian ideas are correct, they come at a time when a variety of fields have reached stasis," says Seth Lloyd, a professor and specialist in quantum computation at the Massachusetts Institute of Technology. "You don't come across many fields that have as bold a project as the space program was."

Submicroscopic machines that can save or destroy the world appeal to anyone from a retired navy admiral to a technophile dentist to eager students—all of whom attended the nanotechnology conference. Reifman, the dentist, is a disciple who carries the message of nanotech to patients waiting nervously in his dental chair. He tells them of robots as small as a microbe that will painlessly refurbish a tooth or build a new one from scratch. "You'll be able to be a chocoholic without guilt," he predicts.

Drexler has purveyed his nanovisions for almost two decades. In recent years, however, his intricately constructed pictures of the next century and beyond have begun to be overtaken by real investigations into nanotechnology. What inspires actual researchers at the nanoscale is infinitely more mundane than molecular robots—but also more pragmatic. Nanotechnology, in this guise, may not contain the ready promise of virtually limitless global abundance and human mastery of the material world. But it may move beyond mere speculation to produce more powerful computers, to design new drugs or simply to take more precise measurements.

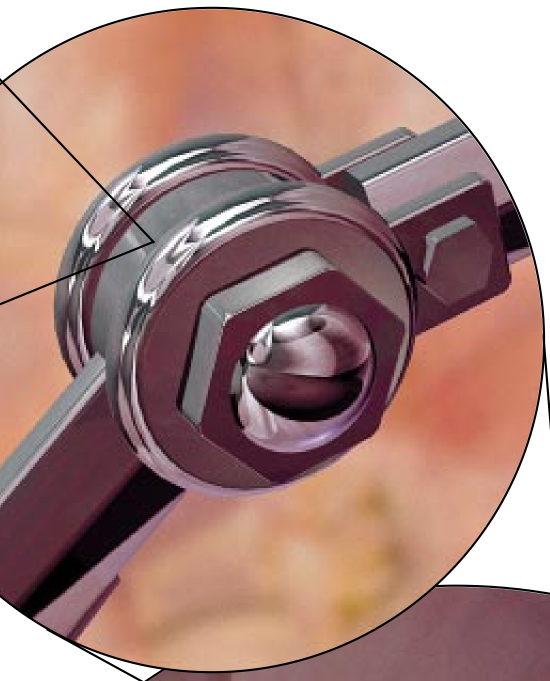
Researchers can now manipulate atoms or molecules with microscopic probe elements, marshal the 20 basic amino acids to form new proteins not found in nature, or help organic molecules spontaneously assemble themselves into ordered patterns on a metal surface. This work certainly presents the prospect of providing new tools for the engineering community. Ironically, it also demonstrates the difficulties of using individual atoms or molecules as building blocks, given the presence of a host of physical forces that may displace them. In fact, some of Drexler's sharpest critics are engineers and scientists who spend their time toiling in the nanorealm.

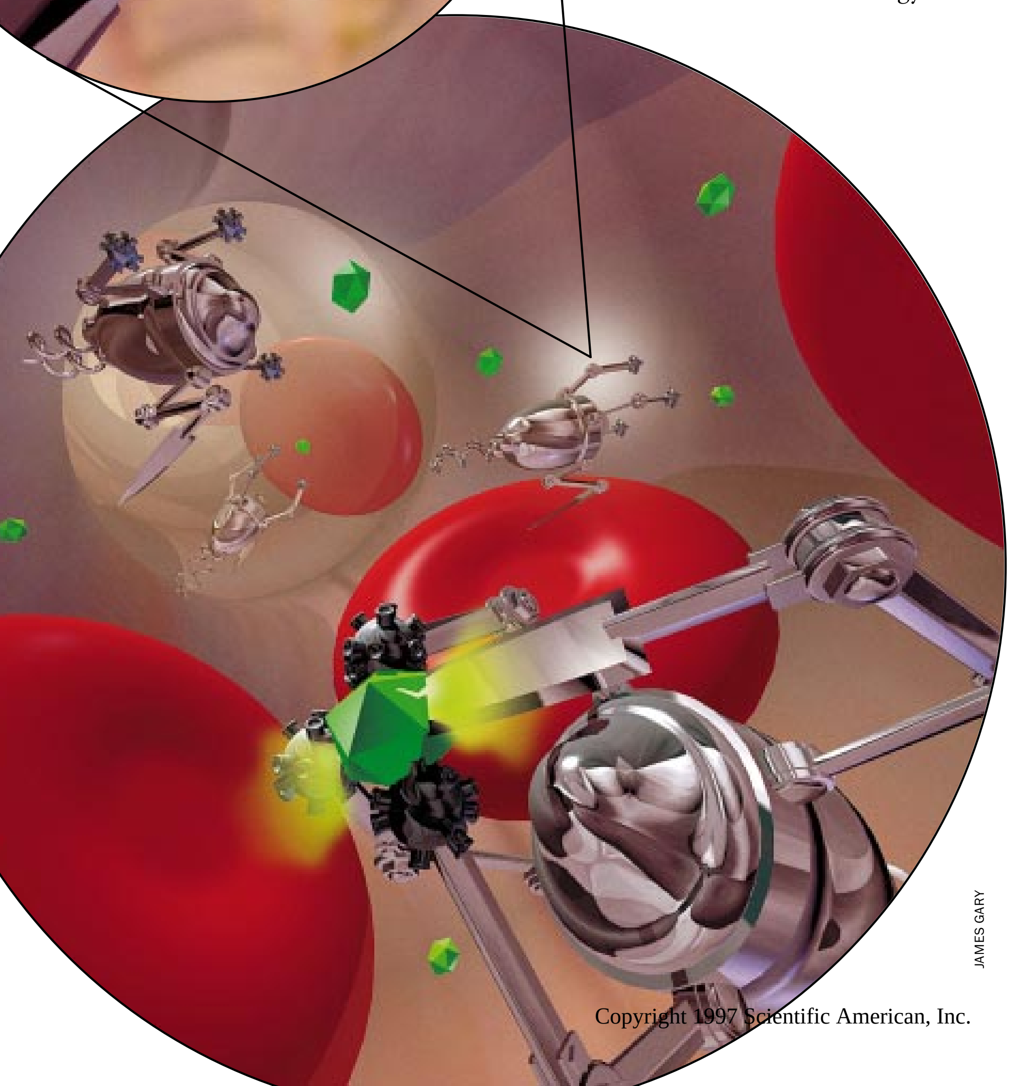
Drexler's fanciful scenarios, nonetheless, have come to represent nanotechnology for many aesthetes of science and technology. The phenomenon is not uncommon in the sociology of science. The public image of a certain field or concept, shaped by futurists, journalists and science-fiction scribes, contrasts with the reality of the often plodding and erratic path that investigators follow in the trenches of day-to-day laboratory research and experimentation.

Nanoism

Drexler, the 40-year-old guru of the nanoists, speaks with an exaggerated professorial tone that is faintly reminiscent of the pedantic 1960s cartoon character Mr. Peabody. Over a buffet lunch in early November at the biennial conference sponsored by his Fore-

"Nanoists" envision global abundance emerging from the manipulation of single atoms and molecules. But this prophecy has been challenged by researchers who work at a scale of billionths of a meter





JAMES GARY

sight Institute—an organization he set up in Palo Alto, Calif., to help pave the way for nanotechnology—Drexler pours milk into his ice tea. He explains that the milk binds the tannins that may lead to throat cancer.

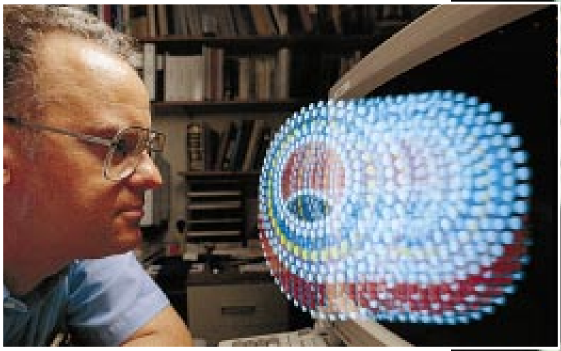
During the meal, he complains about the shortsightedness of the scientific and technological research establishment in the U.S., which has largely ignored his brand of nanotechnology. Drexler is familiar with dreams that don't come true. In the 1970s he volunteered to work with space colonization advocate Gerard K. O'Neill to plan various scenarios for extraterrestrial living; he even wrote a paper on mining asteroids in his freshman year at M.I.T. Drexler and other nanoists view their technology as a means to rejuvenate a moribund space program that has no immediate plans to create retirement communities on Mars. Nanotechnology would allow the manufacture of strong, light materials that would go into space transport vehicles.

The basic ideas behind small, self-replicating machines did not originate with Drexler. The renowned mathematician John Von Neumann, a father of the field of artificial life, ruminated about a machine that could make copies of itself. And in a much cited 1959 speech, Nobelist Richard P. Feynman talked about the ability to build things by placing each atom in a desired place. The self-assured Feynman used to toy playfully with the notion of making things small, musing on the theme with the humor of a Brooklyn-accented, Borscht Belt comic. Feynman even proposed a competition between high schools: "The Los Angeles high school could send a pin to the Venice high school on which it says [on the pinhead], 'How's this?' They get the pin back, and in the dot of the 'i' it says, 'Not so hot.' " Drexler, unlike the puckish Feynman, approaches his passion with a dour earnestness. The message: Nanotechnology is coming; we must prepare now.

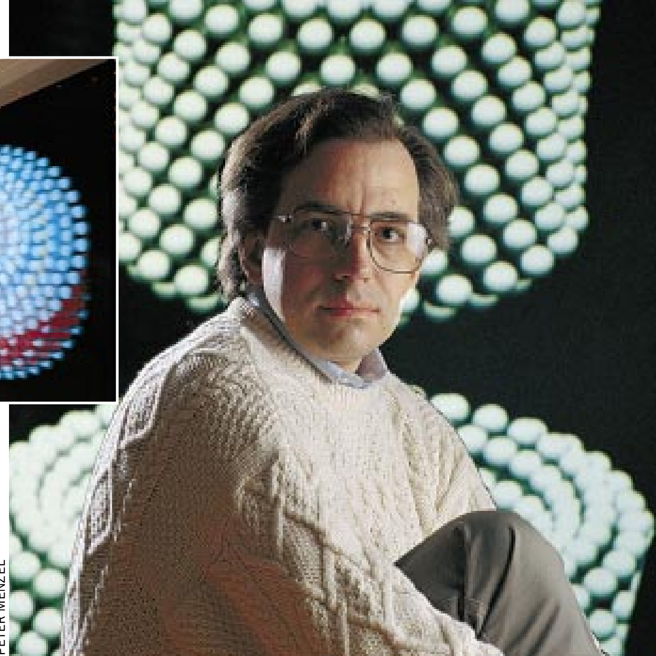
Drexler, though, can rightly claim credit for bringing wide exposure to an enticing idea. In his 1986 work *Engines of Creation,* Drexler, like Jules Verne and H. G. Wells, succeeded in depicting a world altered forever by the advent of a new technology. In *Engines,* Drexler introduced the concept of an "assembler," a robotic device with dimensions of a tenth of a micron (a millionth of a

IMMUNE MACHINES could destroy viruses roaming the bloodstream in the futuristic visions of nanotechnologists (*left*). Inside these robots would reside tiny gears no bigger than a protein molecule. (The atoms in the gear can be seen as colored balls in the top illustration.) In the laboratory, meanwhile, researchers have actually used atoms to spell the word "atom" in Japanese (*far left*).

meter) or less, that can pick up and position a reactive molecule so that it interacts with another molecule, as though it were a Lego block snapping into place. He has also described mills equipped with belts and rollers to process molecules. A battery of nanocomputers—perhaps collections of molecular rods that change position to represent distinct logic states—could broadcast instructions to trillions of assemblers at once. The computers could also instruct assemblers to self-replicate. In his book, Drexler set down a detailed description of how society would be transformed by nanotechnology. *Engines* presents a picture of a Manichaean balance of utopian/dystopian scenarios.



PETER MENZEL



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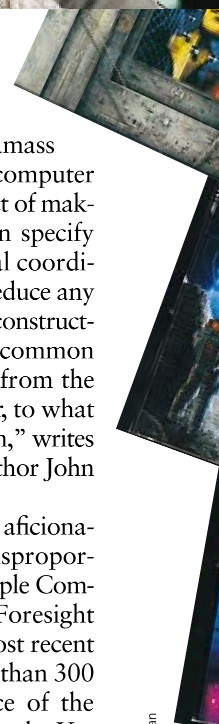


K. ERIC DREXLER (*right*) and his colleague Ralph C. Merkle (*above*) have articulated a vision of a society transformed by machines that can construct objects large and small by moving single atoms and molecules. This dream has attracted science-fiction writers (*book covers*) and an Encino, Calif., dentist, Edward M. Reifman (*bottom*).

BOOKS (*top to bottom*): Courtesy of Bantam Spectra, illustration by Bruce Jensen; Courtesy of Bantam Books, art by Pamela Lee; Courtesy of Baen Books, art by Stephen Hickman

The Good and the Goo

Combining nanocomputers with molecular machines would allow almost anything that can be designed to be made from a variety of inexpensive raw materials, perhaps even dirt, sunlight and air. Assemblers could string together atoms and molecules so that most goods could be made from diamond or another hard material, giving the most ordinary objects a remarkable combination of strength and lightness.

The cost per kilogram of goods produced by nanomanufacturing would equal the price of potatoes. The resulting nanoworld, in which everyone is wealthy because of the drastic reduction in the cost of goods, would flummox economists, those scientists of scarcity. A jumbo airliner could be purchased for the current price of an automobile. A homeowner would pour acetone into a household manufacturing system, similar in appearance to a microwave oven. An hour later, out would come a computer, a television set or a compact-disc player. A home food-growing machine could rapidly culture cells from a cow to create a steak, a godsend to the animal-rights movement.

Minuscule submarinelike robots made by assemblers would extend life or reverse aging by killing microbes, by undoing tissue damage from heart disease or by reversing DNA mutations that cause cancer; the nanomachines would help revive bodies preserved in cryogenic storage by repairing frostbite damage to the brain and other organs. (Drexler, in fact, plans to sign up to have his body frozen after death.) *Engines of Creation* even speculates about nanotechnology providing the basis for telepathy or for radically changing one's body.

On the dark side, assemblers would streamline the production of superweapons, allowing rapid fabrication of a tank or a surface-to-air missile. And then there is the "gray goo" problem—the possibility that nanodevices might be designed to replicate uncontrollably, like malignant tumor cells, and reduce everything to dust within days.

Ruminations in *Engines of Creation* about gray goo and extended life spans provoked guffaws from many scientists. In 1992 Drexler responded to the criticism with *Nanosystems,* which attempts to give his tiny machines a grounding in the underlying essentials of physics, chemistry and biology. *Nanosystems*'s heavy technical emphasis was a plea from Drexler for respectability. The subtext: I am not a flake. But the book remains largely an object of curiosity to the scientific community. It has been hard for many scientists, engineers and technicians to take seriously a section at the end that shows components of assemblers similar to large-scale mechanical devices. For example, a six-legged platform imitates the ones used to tilt flight simulators into different attitudes of yaw, pitch and roll. Its size: only 100 nanometers across, no bigger than a virus. "This is not science—it's show business," says Julius Rebek, a leading researcher in the chemistry of self-assembly at M.I.T.

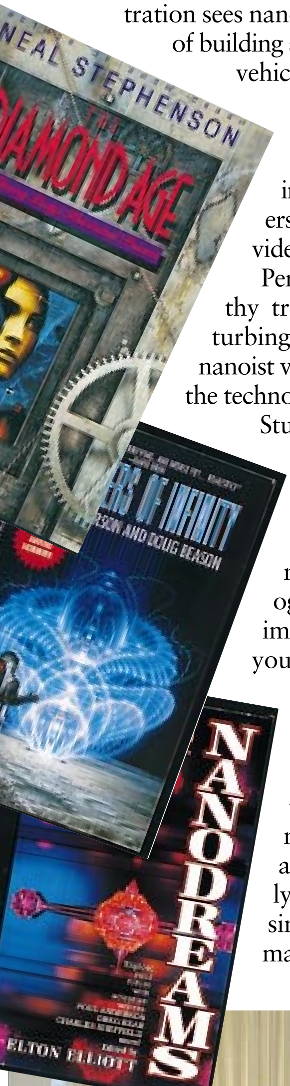
Despite his alienation from mainstream science and engineering, Drexler continues to amass devotees, particularly among computer scientists enticed by the prospect of making tangible anything they can specify with a set of three-dimensional coordinates. "Nanotechnology will reduce any manufacturing problem, from constructing a vaccine that cures the common cold to fabricating a starship from the elements contained in seawater, to what is essentially a software problem," writes physicist and science-fiction author John G. Cramer.

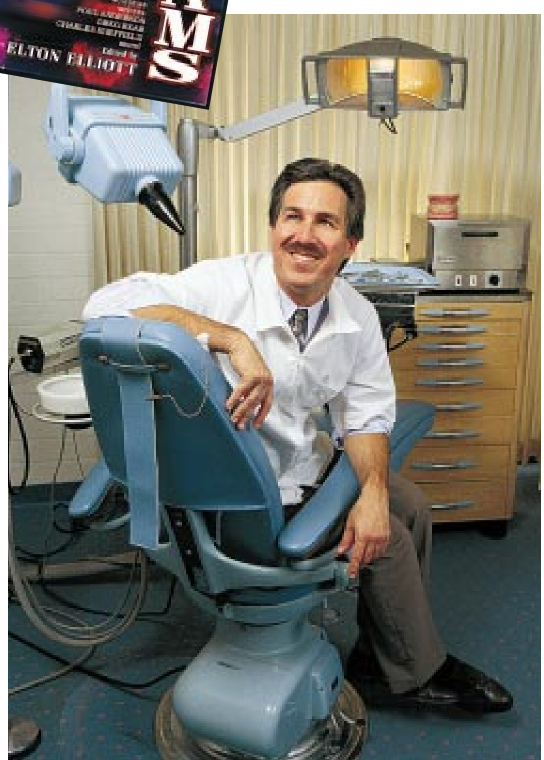
Silicon Valley, that mecca for aficionados of things small, hosts a disproportionate number of nanoists. Apple Computer has helped sponsor the Foresight Institute's conferences—the most recent one last November drew more than 300 people, double the attendance of the 1993 gathering. A researcher at the Xerox Palo Alto Research Center, Ralph C. Merkle, who made a name for himself in computer cryptography, spends his time creating models of molecular machine components. (Merkle has already signed up to have his head frozen.)

In 1991 John Walker, the reclusive founder of Autodesk, a California software company, donated $175,000 to help start the Institute for Molecular Manufacturing, a research organization. Most of the institute's grant money has gone to pay Drexler to work on projects such as computer simulations of molecular gears, bearings and other parts.

The Drexler following includes speculative thinkers such as artificial-intelligence pioneer Marvin L. Minsky. Nanotechnology also seems to inspire government laboratories seeking to remake their image. Oak Ridge National Laboratory has let one of its modeling groups devote extensive effort to simulations of molecular bearings and shafts. Administrator Daniel S. Goldin of the National Aeronautics and Space Administration sees nanotechnology as a means of building smaller and lighter space vehicles. And the NASA Ames Research Center has scheduled a workshop for this spring to examine how its supercomputers might be used to provide models of nanodevices.

Perhaps the most noteworthy trend—or the most disturbing one, to critics of the nanoist vision—is the appeal that the technology holds for students. Study groups in nanotechnology have established themselves at universities such as M.I.T. and the California Institute of Technology. "It's captured the imagination of bright, young scientists and engineers," says William A. Goddard III, a professor of chemistry and applied physics at Caltech. Goddard, an admirer of both Drexler and Merkle, occasionally works with them on simulations of molecular machine parts.





JAMES ARONOVSKY *Zuma*

Drexler and his nanoist disciples view molecular nanotechnology as a grand challenge of science and technology. And they comb the pages of journals such as *Science* and *Nature* for evidence of research advances that might lay the groundwork toward the ultimate self-replicating assembler. At the Foresight conference last fall, Merkle showed a schematic chart illustrating how the current work being done at a scale below 100 nanometers by chemists and materials scientists might one day lead to nanomachines. Lines on the left of the chart represented experimental approaches, such as probes that can manipulate atoms, tubes of graphite about a nanometer in diameter, and novel types of proteins. On the right side resided lines that corresponded to computer simulations of molecular machine parts for assemblers. In the center appeared a noticeable gap.

Real Nanotechnology

Most researchers whose work moves beyond computer simulations and into the laboratory do not view the challenges of nanotechnology as leading toward the goal of nanoists such as Merkle. A number of them, some of whom even capitalize on the "nano" label in promoting their work, pursue a series of more modest objectives. Differences of opinion about Drexlerian nanoism do not prevent the two camps from occasionally rubbing elbows.

Harvard University chemistry professor George M. Whitesides presented a review of his work at the Foresight conference. Whitesides investigates how simple natural objects self-assemble by minimizing thermodynamic instabilities at a surface, such as those between air and water [see "Self-Assembling Materials," by George M. Whitesides; SCIENTIFIC AMERICAN, September 1995]. At the meeting, Whitesides described how he and his colleagues have used self-assembling hydrocarbon molecules, called alkanethiols, to form ordered rows on a gold surface. They have demonstrated how this fabrication method might be used in a process to pattern far thinner circuit lines on a computer chip than can be achieved through conventional lithographic methods. Eventually, self-assembly of small silicon cubes that contain devices that alter information might lead to new methods for manufacturing computer processors.

Whitesides does not see the goal of his work as edging toward the assembler. He distinguishes between his investigations into self-assembling monolayers and the still distant goal of achieving self-assembly by following a coded set of instructions. Biological cells use this latter approach to make copies of themselves, and so would nanoassemblers. "What makes [Drexler's vision] exciting is self-replication, and at the moment, it is pretty much science fiction," Whitesides says. "Even after a fair amount of thought, there's no way that one could see of connecting this idea to what we know how to do now or can even project in the foreseeable future."

The complexity of making objects with individual molecular building blocks may eliminate any of the dramatic cost savings envisioned by the nanoists, except in a few clearly delineated technological areas. Fabricating computer chips has already become a form of engineering the small, with the tiniest circuit elements measuring less than a micron. The cost of a new semiconductor plant now reaches into the billions of dollars, in part because of the technical challenges posed by the need to craft ever smaller features onto the surface of a chip. Chipmakers can still justify the added expense because packing circuits more densely leads to higher computational performance and ultimately lower costs. For most other goods, nanotechnologies may receive tough competition from Mother Nature. "Drexler's grand vision is a nice one, but sometimes some of the specifics are not entirely correct," comments Jane A. Alexander, who established the nanoelectronics program at the Advanced Research Projects Agency. "I once heard him say we'd make tables out of nanotechnology. Wood is awfully cheap, and trees do it very nicely."

Keeping every atom in its place may also prove exceedingly onerous at the atomic level. David E. H. Jones, a researcher in the department of chemistry at the University of Newcastle upon Tyne, who may be best known as the author of the irreverent "Daedalus" column in *Nature,* has provided a pointed critique of the idea that individual atoms and molecules could serve as construction elements in the ultimate erector set. Jones made his case a year ago in a review of a popular book about Drexler by science writer Ed Regis, called *Nano*. Regis's account generally treats the chief nanoist's ideas favorably.

Jones describes the contortions often

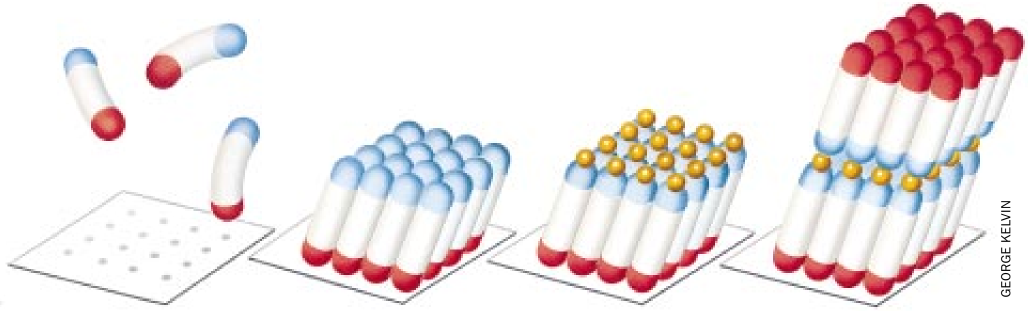
Nanometer Manufacturing

Although K. Eric Drexler's molecular machines may forever remain computer-based apparitions, laboratory research on materials science below the scale of 100 nanometers continues. A few nanotechnological fields described include:

DAVID SCHARF

Scanning probe microscopy. A tiny sharpened tip, such as that on a scanning tunneling microscope, can move atoms and create atomic-scale images. If many developmental hurdles can be overcome, the technology holds the promise of being suitable for storing bits of information by moving atoms on or off a surface.

Self-assembling monolayers. A layer of organic molecules, evenly spaced, adsorbs to a substrate, creating a two-dimensional crystal structure. Different chemical groups can be attached to the exposed tips of molecules, allowing them to build additional layers. They might be used for making optical diffraction gratings or in lithography for making computer chips.



GEORGE KELVIN

required to achieve atomic control of matter. In 1989 two IBM researchers penned their employer's acronym by manipulating 35 xenon atoms with a scanning tunneling microscope—a device that dragged the atoms across a nickel surface. The atoms moved because of chemical bonding interactions that occurred when the microscope's tungsten tip came to within a tenth of a nanometer or so of each atom. Jones notes the difficulties involved: The IBM logo was created in an extremely high vacuum at the supercooled temperature of liquid helium using inert xenon atoms. Outside this rarefied environment, the world becomes much less stable. "Single atoms of more structurally useful elements at or near room temperature are amazingly mobile and reactive," Jones writes. "They will combine instantly with ambient air, water, each other, the fluid supporting the assemblers, or the assemblers themselves."

Jones believes that the nanoists fail to take into account critical questions about the thermodynamics and information flow in a system of assemblers. "How do the assemblers get their information about which atom is where, in order to recognize and seize it? How do they know where they themselves are, so as to navigate from the supply dump [where raw atomic material is stored] to the correct position in which to place it? How will they get their power for comminution [breaking up material] into single atoms, navigation and, above all, for massive internal computing?" The list continues before Jones concludes: "Until these questions are properly formulated and answered, nanotechnology need not be taken seriously. It will remain just another exhibit in the freak show that is the boundless-optimism school of technical forecasting."

The nanoists' response to this fusillade is simple: read Drexler's technical tome *Nanosystems,* which contains a response to virtually any general point raised by detractors. Acoustic waves, for example, can be used to supply power to assemblers, an answer to one of Jones's objections.

Drexler contends that his critics, with their need to focus on new products or the next grant-funding cycle, have trouble thinking far enough into the future. "To people outside who don't understand that you're talking about the year 2020 or whatever, these ideas raise confused, unrealistic expectations about the short term," Drexler maintains. "That makes researchers uncomfortable because it's not a yardstick they want to be measured by. It also brings in ethics and the future of the human race, which are not the usual cool, scientific, analytical concerns."

For engineers who build things, finding the relevant page in *Nanosystems* is not enough. Drexler touts his work as "theoretical applied science": research constrained only by physical law, not by the limits of present-day laboratory or factory manufacturing capabilities. To hard-nosed engineers, though, the juxtaposition of "theoretical" and "applied" quickly becomes an oxymoron. Their response to the author of *Nanosystems*? Come back when you can tell me how to make those things.

The accumulation of small details may doom the best theories for small machines. Phillip W. Barth, an engineer at Hewlett-Packard, characterizes simulations of molecular bearings as "computer-aided speculation." "The holes are bigger than the substance," he says of *Nanosystems.* "There's a plausible argument for everything, but there are no detailed answers to anything." Barth is a leading engineer in micromechanics, a field that builds microscopic sensors and machines from silicon [see "Silicon Micromechanical Devices," by James B. Angell, Stephen C. Terry and Phillip W. Barth; Scientific American, April 1983]. Barth observes a lack of discussion of a number of basic engineering considerations that could make many of Drexler's nanodevices impossible to build. Drexler's nanobearings may be molecularly stable. But *Nanosystems,* he notes, does not address the stability of structures synthesized during intermediate steps in building the bearings. Unresolved details, moreover, may not be so trifling. "Energy is a fundamental concern," Whitesides declares. "It is no good to say it comes from somewhere—acoustic waves or whatever. If we can forget the details of energy supply, we have a perpetual motion machine."

The present inability to build an assembler—coupled with elaborate speculation about what the future may hold—gives nanotechnology a decidedly ideological or even religious slant, in Barth's view. In early January he posted a mes-

ANDREAS THESS AND PAVEL NIKOLAEV *Rice University*

Nanotubes. Cylindrical tubes of graphite, as small as one nanometer in diameter, can be fabricated up to a tenth of a millimeter in length, creating nanoscopic wires. This material has extraordinarily high tensile strength, conducts electricity well and might one day be used to build cathodes to illuminate picture elements on a computer display.

D. EISENBERG AND W. DEGRADO

Artificial proteins. During the past decade, several research and development teams have made new types of proteins by starting with groups of amino acids and getting them to fold into novel shapes. De novo protein design, as it is called, lends a deeper understanding of how a linear chain of amino acids forms into three-dimensional molecules. It might also allow the design of proteins specifically tailored for pharmaceutical or industrial needs.

sage to an Internet bulletin board (sci.nanotech) suggesting that subscribers comment on whether molecular nanotechnology has the makings of a mass social/political movement or a religious faith in the traditions of Marxism or Christianity. Barth bolsters the case for nanoism as a form of salvation by citing a passage from a new magazine called *NanoTechnology:* "Imagine having your body and bones woven with invisible diamond fabric. You could fall out of a building and walk away."

On the Border of Science and Fiction

The nanoists' legacy may be to stoke science-fiction writers with ideas for stories. The latest genre in science fiction employs nanotechnology as its centerpiece. A follow-on to the cybernetic fantasies of authors such as William Gibson, it is sometimes even called "nanopunk." The world depicted by nanowriters goes beyond cybernetic mind control and downloading one's brain into a computer. It postulates ultimate control over matter. "It seems like nanotech has become the magic potion, the magic dust that allows anything to happen with a pseudoscientific explanation," says Istvan Csicsery-Ronay, Jr., an editor of the journal *Science-Fiction Studies,* published by DePauw University.

A collection of "nano" stories that appeared last year features the imaginings of noted science-fiction writers, such as Poul Anderson. The volume, *Nanodreams,* even contains an introductory essay by Drexler on the merits of science fiction as a means of exploring the societal implications of a nanotechnological future. "Saying something sounds like science fiction should not be regarded as a form of dismissal," Drexler said in a recent interview. "Much of what science-fiction writers described in the 1950s happened, and you need to distinguish between antigravity and flying to the moon, between time travel and making a robot that works in the factory."

Nanodreams includes a story in which the pain experienced by a fetus during an abortion is telecommunicated to nanomachines that reproduce the sensation within the father of the child—and then, finally, kill him. Another nanotale describes a company that has just achieved a breakthrough by making nanomachines that can repair tissue damaged by a bullet wound. In one scene a poster on a laboratory wall depicts Albert Einstein handing a candle to Drexler.

The fantasies of nanoists posted on Internet bulletin boards and World Wide Web sites often outstrip the imaginings of the best science-fiction writers. Take the often discussed idea of a utility fog: nanobots that link together to create materials and objects in a desired form and shape, from paint to furniture. "When you got tired of that avant-garde coffee table, the robots could simply shift around a little, and you'd have an elegant Queen Anne piece instead," reads one description on the Web.

Chemistry has distant roots in alchemy, the belief that transmutation of materials will bring health and wealth (though perhaps not ultimate mastery of interior decoration). Nanoism resembles a form of postmodern alchemy—and one that awards cash for molecular machine parts. Toward the end of November's Foresight conference, an announcement was made about a new prize, named for Feynman.

The prize of $250,000 comes courtesy of Jim Von Ehr, an executive at Macromedia, a software company in San Francisco, and Marc Arnold, a St. Louis venture capitalist. It is to be awarded for the fundamental breakthroughs that will usher in the era of molecular nanotechnology: a robot arm and a computing component for an assembler.

For the time being, the nanoists can only wait for these breakthroughs to arrive, while continuing to formulate their computerized models of molecular machine parts. It may be a long time coming. In fact, Drexler himself has said that his fortitude has been weakened by jibes from critics and that he might consider a calling other than nanotechnology. "I'm tired of it," he says.

Nanoists' convictions about the inevitability of a breakthrough evoke memories of another idea once posed by Feynman, their adoptive mentor. In a commencement speech given to the 1974 graduating class at Caltech, Feynman noted that some Pacific Islanders religiously awaited the return of the U.S. troops who had landed in World War II. He described the elaborate preparations the islanders made for the return of the planes that would bring them advanced technological accoutrements and limitless wealth. Fires mark the sides of runways. A man plays air-traffic controller by sitting in a hut with carved wooden headphones from which pieces of bamboo stick out, like antennas. The believers wait patiently in this preindustrial imitation of an airfield.

"They're doing everything right," Feynman said. "The form is perfect. It looks exactly the way it looked before. But it doesn't work. No airplanes land." Similarly, some scientific endeavors rely on wish fulfillment—and an inability to consider why something may not work, Feynman noted. "So I call these things cargo cult science," he concluded, "because they follow all the apparent precepts and forms of scientific investigations, but they're missing something essential, because the planes don't land." Until the nanoists can make an assembler and find something useful to do with it, molecular nanotechnology will remain just a latter-day cargo cult. SA