“Machines of Inner Space”

K. Eric Drexler

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MACHINES OF INNER SPACE
by K. Eric Drexler

Taking cues from chemistry and biology, scientists and engineers are boldly sketching futuristic machines smaller than living cells—some no larger than proteins—that could literally build matter atom by atom.
Human beings live in bodies made of atoms in a world made of atoms, and the way those atoms are arranged makes all the difference. To be healthy is to have tissues and cells composed of correctly patterned sets of atoms. To have wealth is, in large measure, to control collections of atoms organized in the form of useful objects, whether foodstuffs, housing, or spacecraft. If people could arrange atoms as they pleased, they would gain effectively complete control of the structure of matter. Nanotechnology offers to provide this control, bringing with it possibilities for health, wealth, and capabilities beyond most past imaginings. This sort of dominion over matter will not arrive overnight but will come only after years of hard work in various enabling technologies. Nonetheless, examples from chemistry and biology already demonstrate many of the basic possibilities.

Chemists have long known that atoms bond together to form molecules. Every diamond, for example, is a single, huge molecule made of carbon atoms. Every breath of air contains pairs of nitrogen and oxygen atoms, each pair a small molecule. Whether large or small, molecules are objects. Each has such properties as size, shape, mass, strength, and stiffness. Nanotechnology envisions using molecular-scale objects as components of molecular machines.

Nature shows that molecules can serve as machines because living things work by means of such machinery. Enzymes are molecular machines that make, break, and rearrange the bonds holding other molecules together. Muscles are driven by molecular machines that haul fibers past one another. DNA serves as a data-storage system, transmitting digital instructions to molecular machines, the ribosomes, that manufacture protein molecules. And these protein molecules, in turn, make up most of the molecular machinery just described. Nanotechnology aims to exploit a similar strategy, using programmable molecular machines termed assemblers to build things, including more molecular machines. Assemblers will work like tiny industrial robots, directing chemical reactions by positioning molecular tools to build complex structures atom by atom.

Microtechnology enables construction on a scale of micrometers, or millionths of a meter. Nanotechnology will enable construction on a scale of nanometers, or billionths of a meter. The term nanotechnology is sometimes used (especially in the U.K.) to refer to any technology giving some control of matter on a nanometer scale. This definition would seem to include glass polishing, the manufacture of thin films, and ordinary chemistry. As used in this article, however, the term describes a technology giving nearly complete control of the structure of matter on a nanometer scale. Since atoms are themselves about a third of a nanometer in diameter, this sort of nanotechnology will require a general ability to control the arrangement of atoms.

Even this control will not allow what the alchemists sought—a way to turn lead into gold. In essence, nanotechnology will be a vast elaboration of ordinary chemistry and biology. It will move atoms around as in chemical reactions, not fuse them or split them as in nuclear reactions. To transform one element into another will be beyond its ability.
How might one bridge the gap between present abilities and nanotechnology? Two very different paths are being pursued today; one is a top-down strategy of miniaturizing current technologies, while the other is a bottom-up strategy of building ever more complex molecular devices, atom by atom.

The top-down approach
The top-down strategy sees the problem as one of scale, of pushing back the frontier of miniaturization. Such is the tradition of the watchmaker and the manufacturer of integrated circuits. The 20th century has seen great progress in miniaturization—from the shrinking of clockwork into fingernail-sized boxes to the shrinking of computers onto fingernail-sized chips—and this progress continues.
The same deposition and etching techniques used for fabricating thousands of semiconductor components on a single chip recently have allowed researchers to build simple mechanical micromachines.

A pair of microtongs (this page, top) converts linear motion to rotary motion; length of the white reference dashes near the top is 100 micrometers (100,000 nanometers). A gearbox (center) comprises three interlocking gears having diameters of 180, 125, and 125 micrometers, left to right; individual teeth are about 20 micrometers wide, roughly the diameter of a living cell. A turbine 125 micrometers in diameter (bottom) can be rotated at high speed with jets of air sent through one of the connecting channels. On the opposite page, an electric micromotor (top) has a rotor 60 micrometers in diameter that can be driven by electrostatic forces. A four-joint crank (center) has a total length of 150 micrometers; the two inner joints are free from the substrate, while the two outer ones are pinned. Spiral springs (bottom) are each 100 micrometers in diameter.
One of the great visionaries of the top-down strategy was physicist Richard Feynman. In 1959 he gave a talk in which he proposed that large machines could be used to make smaller machines, and those to make machines still smaller, working step-by-step toward molecular dimensions. He envisioned microscopic lathes and described problems with building microscopic automobiles for mites. At the end of his talk, however, he turned to the molecular-size scale and hinted at the need for a bottom-up approach. “The principles of physics, as far as I can see,” he said, “do not speak against the possibility of maneuvering things atom by atom.” He went on to remark, “But it is interesting that it would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the orders, and the physicist synthesizes it. How? Put the atoms down where the chemist says, and so you make the substance.” Nevertheless, Feynman suggested that these substance-synthesizing machines “will be really useless” because chemists will be able to make whatever they want without them.

Modern microtechnology has followed a different path, also discussed by Feynman in his talk. Microtechnologists use beams of light or electrons to make patterns on surfaces and then apply such techniques as selective chemical etching or the deposition of thin films of metals, oxides, and semiconductors to develop those patterns into structures. The patterns can be micrometers or fractions of a micrometer across, and the structures can be wires and transistors or even mechanical devices.

Microtechnology as applied to electronics is an old yet fast-developing story; it has provided modern computer technology. Microtechnology for machines is more recent and is still in the research phase. Investigators have deposited patterned films of silicon over films of oxide and then dissolved the oxide to release silicon parts. Using clever patterns of deposition, Kaigham Gabriel and William Trimmer of AT&T Bell Laboratories, Holmdel, New Jersey, have shaped interlocking silicon gears, trapped against the surface by silicon flanges but left free to rotate. Streams of air can spin these gears like turbines at over 15,000 revolutions per minute. Richard Muller of the University of California at Berkeley has made the first electrostatic micromotors using a similar technology.

Silicon micromachining is pushing back the frontier of miniaturization, but how close has the top-down approach come to nanotechnology? In scale, it remains vastly different. Microgears and micromotors are now tens of micrometers in diameter, but nanogears and nanomotors will often be tens of nanometers in diameter or less—a thousandth the linear dimension and a billionth the volume of current micromachines. This is analogous to the difference between a truck and an integrated circuit.

More fundamental, however, is the difference in quality of construction. Micromachining, whether with microlathes or with etched patterns, can only shape materials from the outside. It cannot build them from the inside, from the bottom up, and so it cannot give complete control of the structure of matter. These top-down technologies have many uses (consider microcomputers) and may even yield nanoscale devices, but they cannot evolve into true molecular nanotechnology.
The bottom-up approach

In contrast with the top-down strategy, the bottom-up strategy sees no problem with making things small; chemists and biochemists already make small molecules with ease and in abundance. From this perspective the problem is to make things large while keeping detailed, molecular control of structure.

The bottom-up strategy was originally inspired by chemistry and molecular biology. For more than a century, chemists have understood molecules as small three-dimensional objects to be broken down and built up. In 1926 physicist Erwin Schrödinger supplied the foundations for a quantum mechanical theory of molecules and chemical bonding. In 1944 he wrote a book, *What Is Life?*, that correctly viewed life as based on molecular objects and machines. In 1953 James Watson and Francis Crick determined the three-dimensional structure of DNA, and four years later J. C. Kendrew and his colleagues in England were the first to describe the three-dimensional structure of a protein. Since then, molecular biologists have detailed the structures and functions of molecular devices at an ever increasing rate.

It was the existence of a wide range of natural molecular machines (see Table) that led me to propose artificial molecular machines, ultimately including such things as molecular assemblers, assembler-based replicators, mechanical nanocomputers, and cell-repair machines. Molecular machines in nature showed that a bottom-up approach to nanotechnology would work. Indeed, the most clearly workable bottom-up approach begins by mimicking nature, by designing new protein-based devices.

Proteins are polymers made by joining many smaller molecules—amino acid monomers—to form linear chains. The amino acids of protein chains form specific sequences, like the letters in a specific sentence. The sequence of amino acids in a protein likewise has a special significance: it determines how the chain will fold, or coil back on itself, to form a compact three-dimensional object. A folded protein can be as stiff as a piece of wood or engineering plastic. Furthermore, depending on its shape, surface properties, and so on, a folded protein can do things; for example, it can serve as an enzyme, as a structural element, or even

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Adapted from K. E. Drexler, *Proceedings of the National Academy of Sciences*, vol. 78, pp. 5275–78, 1981
as part of a molecular motor. Just as a protein chain can fold up to form an object, so can a collection of proteins stick together to form a larger, more complex object, thus enabling construction of complex molecular machines.

Nonmolecular machines may also be of use in nanotechnology. In 1982 Gerd Binnig and Heinrich Rohrer at IBM’s research laboratory in Zürich, Switzerland, announced their development of a device called the scanning tunneling microscope (STM). Like its younger relative, the atomic force microscope (AFM), the scanning tunneling microscope can move a sharp tip over a surface with atomic precision. This capability immediately suggested a modified bottom-up strategy for developing nanotechnology, using the STM tip to position molecular tools for precise molecular construction.

In the long term, the approach used to reach nanotechnology will make no difference because the early, clumsy technologies will swiftly be left behind. In the short term, however, the rates of progress in different approaches will be decisive, determining not only which approach pays off but how fast nanotechnology itself arrives.

Building with molecules
Various bottom-up approaches have produced experimental results. Bare STM tips, those without molecular tools, have made molecular-scale modifications on surfaces. At AT&T Bell Laboratories, Murray Hill, New

Small enough to be held in the hand, the scanning tunneling microscope, or STM (above left), can image surface detail down to the level of individual atoms. In its operation (above) a sharp metal tip is scanned within a few nanometers of the sample surface with piezoelectric positioners, while a voltage is applied between the tip and the sample. By means of a quantum mechanical process called tunneling, electrons flow across the gap between the tip and the sample. The positioners, which are materials that expand or contract with changes in electric voltage, respond to this flow by continually readjusting the tip height to maintain a constant gap distance as the tip scans the surface. A computer translates the movement of the positioners into a topographic map of the surface. The ability of the STM to scan a surface with atomic precision suggests an approach to nanotechnology—using the STM to position molecular tools for precise molecular construction.
A bottom-up strategy for developing nanotechnology with the STM has been encouraged by recent experiments in which bare STM tips were used to make molecular-scale modifications on surfaces. In the STM image above, the mountainous peaks rising above a flat plain represent an organic molecule pinned to a clean graphite surface by an electrical pulse from the STM tip. Other images revealed that application of a second pulse caused such peaks to disappear completely or partially, as if the molecule had been either removed or cut into two pieces. Thus far, however, such manipulation has not produced the consistent, controllable results needed for building nanomachines.

J. S. Foster, J. E. Frommer, and P. C. Arnett, IBM Almaden Research Center, San Jose, Calif.

Jersey, R. S. Becker, J. A. Golovchenko, and B. S. Swartzentruber have produced what appear in STM images as atom-sized bumps on germanium crystal surfaces, apparently accomplished by evaporating single atoms of germanium from the tip of the STM. At IBM's Almaden Research Center, San Jose, California, J. S. Foster, J. E. Frommer, and P. C. Arnett produced bumps on graphite crystals, chemically pinning fragments of single molecules to the crystals' surfaces using current from an STM tip. The presence and absence of such bumps might be used one day to store the ones and zeros of binary-coded computer data, crowding many trillions of bits into a square millimeter.

Thus far, however, such experiments have failed to produce specific, controllable molecular changes; the detailed nature of the bumps has been unpredictable. It seems unlikely that bare STM tips, even those ending in a single atom, can provide the precise, molecular control needed for building nanomachines. Whether or not nanotechnologists use STM or AFM devices for positioning, they will likely need molecular tools to construct the first generation of nanomachines.

In the long run, nanotechnology probably will use robotlike molecule-sized assemblers to position molecular tools, but assemblers are not necessary to begin building with molecules. Instead, one can use self-assembly to form larger structures from molecular components suspended in solution, using principles familiar to chemists and molecular biologists. Even assembler-style positioning using STM or AFM tips, if the technique becomes useful, will probably begin by the use of a self-assembly process to cap those tips with molecular tools.
Self-assembly differs radically from ordinary manufacturing techniques. It involves small pieces joining together automatically to form larger objects. Making a molecular device this way will be much like growing a crystal, whereby a solid, three-dimensional object is built up by adding layer after layer of molecules to its surface. Whereas crystals have simple, regular structures made of only a few kinds of molecules, molecular machines will be complex, irregular structures made of many different kinds. The component molecules themselves could be made by chemical synthesis, by mixing reactive compounds together in the right order under the right conditions.

Chemical synthesis and self-assembly have real advantages over atom-by-atom positioning. Using these methods to synthesize even a thousandth of a gram of a typical protein (a modest amount, by current standards) results in more than a million billion \( (10^{15}) \) molecular components, without the need for performing some billion billion \( (10^{18}) \) molecular assembly operations. In making a gram of devices, each self-assembled from a thousand molecular components, one would again make \( 10^{15} \) molecular objects and save another \( 10^{18} \) individual assembly operations. To pull cost numbers out of the air, at a millilenth of a cent per assembly operation, this would mean a savings of $10 billion. Also, unlike alternatives, this kind of synthesis and assembly is already known to work in the laboratory and in nature.

How, though, can self-assembly work for molecules when it does not for cars or computers? The key principles are selective stickiness and thermal motion. Proteins and other large molecules can have complex shapes and surface properties. Two such molecules can fit like pieces in a jigsaw puzzle, having not only complementary shapes but complementary patterns of attractive forces; for example, electrical charge. They will stick to each other but not to molecules that lack this complementarity—this is selective stickiness. Warm molecules bounce about (which is the reason the molecules in air do not fall to the floor and stay there). In a liquid these thermal motions affect everything, including large molecules.
and molecular devices suspended in solution. Thermal motions have little effect on large objects like automotive and computer components, but they can bring molecular components together in all possible positions and orientations. Selective stickiness can then cause self-assembly.

Self-assembly can be swift and effective. In a solution thermal motions shift a typical protein by its own diameter every millionth of a second and twist it to a substantially different angle in a ten-millionth of a second; fine motions (of an atomic diameter or so in size) happen many billions of times per second. These constant motions allow molecules to "explore" their environments quickly, finding any complementary molecules and sticking to them.

Nevertheless, to make self-assembling machines, one must first make their parts. Nature often uses proteins as parts, each containing hundreds or thousands of atoms. Modern advances in chemistry and genetic engineering make new proteins reasonably straightforward to produce. The challenge, however, has been to design protein chains that fold up correctly to form solid molecular objects with the desired properties.

In recent years this challenge has been taken up by many groups, including those led by David and Jane Richardson of Duke University, Durham, North Carolina, Bruce Erickson of the University of North Carolina, and David Eisenberg of the University of California at Los Angeles (UCLA). William DeGrado of the Du Pont Co., Wilmington, Delaware, and Robert Hodges of the University of Alberta have shown some of the first successes. Indeed, it has proved possible to design proteins more stable than those found in nature—proteins that can better serve as building blocks for engineering design. The design techniques needed to make a single protein fold correctly are much like those needed to make separate proteins self-assemble to form a larger structure. Thus, these successes in protein design mark a major milestone on the self-assembly path to nanotechnology.

Proteins show promise enough, but there are alternatives. In 1987 Donald J. Cram of UCLA and Jean-Marie Lehn of Louis Pasteur University, Strasbourg, France, and the Collège de France, Paris, received the Nobel Prize for Chemistry (shared with U.S. researcher Charles J. Pedersen) for synthesizing relatively simple molecules that perform functions like those of natural proteins, selectively binding other molecules. Such molecules could be designed to self-assemble, providing an alternative to proteins for building molecular machines. Myron L. Bender of Northwestern University, Evanston, Illinois, and Ronald Breslow of Columbia University, New York City, have made nonprotein molecules that function as enzymes. These general structures are easier to design than proteins because their three-dimensional shapes do not depend on a complex folding process. The catch is that they are often hard to synthesize and hard to scale up.

An alternative strategy, not yet explored, would be to use folding polymers much like proteins but to build them from a set of molecular subunits chosen to simplify synthesis and folding. This would sacrifice a key advantage of proteins, the convenience of biologic production, but
would combine some of the ease of design offered by general structures with some of the ease of synthesis offered by polymers.

Any of several bottom-up strategies using self-assembly seem feasible. The question is not which can be made to work but which can be made to work first, with the lowest costs or the highest payoff. Today's technology is already working with molecular devices; the challenge is to make them larger, more complex, and more capable.

Goals along the way
With or without the long-term goal of assemblers and nanotechnology, researchers are already following bottom-up strategies motivated by short-term payoffs. Scientists have designed folding proteins to answer scientific questions. Protein engineers have built enzymes more stable than their natural counterparts so they will last for months in detergent bottles on store shelves. They aim to build new enzymes to help make industrial chemicals and pharmaceuticals. Other molecules will be engineered to serve as chemical sensors or as detectors for medical diagnostics. Each step will hone skills in the design and fabrication of molecular objects.

Electronics has inspired yet more ambitious goals. Microelectronics has followed a top-down strategy of miniaturization, but bottom-up researchers are mounting a challenge under the rubric of molecular electronics. From early work by Ari Aviram of IBM's Thomas J. Watson Research Center, Yorktown Heights, New York, and Forrest Carter of the U.S. Naval Research Laboratory, Washington, D.C., to current work by such researchers as Richard Potember of Johns Hopkins University, Baltimore, Maryland, Robert Birge of Carnegie-Mellon University, Pittsburgh, Pennsylvania, Kevin Ulmer of seQ, Ltd., Cohasset, Massachusetts, and Mark Wrighton of the Massachusetts Institute of Technology, interest has grown. The first applications will likely involve piling up large numbers of molecules having special electronic properties to make quantities of new electronic materials. Over the longer term, many researchers hope for nothing less than molecular electronic circuitry in which individual molecular parts can serve the roles of wires and transistors.

A molecular electronic circuit or perhaps an entire computer would be made by self-assembly, possibly using proteins as scaffolding. Picture a snap-together puzzle, with each piece having a transistor or a piece of wire glued to it. The puzzle pieces link to form a circuit board, and their interlocking shapes determine just how the electronic components join up to form circuits. Self-assembly of molecular electronics could work this way, with large molecules as the puzzle pieces and attached electroactive molecules as the components. Unlike the essentially two-dimensional integrated circuitry of today, however, these puzzle pieces would go together to form a three-dimensional block of circuitry.

Interest in molecular electronics has been strong in Japan, where it is a focus of the international Frontier Research Program of RIKEN (the Institute of Physical and Chemical Research). Interest has also been high in the Soviet Union and Eastern Europe, where it is seen as a possible way of leapfrogging Western semiconductor technology.
Before entire computers can be made by self-assembly, similar techniques probably will enable the construction of moderately complex molecular machines. A machine only a few times more complex than a typical enzyme (and far simpler than a ribosome) could help synthesize special folding polymers, perhaps including copies of itself. Using tools to help build better tools is an ancient story in engineering; it is at the heart of most progress.

It will eventually make sense to construct assembler-like devices in order to help build molecular structures that are impossible to make through self-assembly. These protoassemblers (whether purely molecular or a self-assembled hybrid of molecular tools and an AFM- or STM-style positioning mechanism) would have only a limited ability to position a limited range of tools, but they could be used to build better tools. The process will culminate in general assemblers—molecular machines that can serve as powerful engines of creation, opening the era of true nanotechnology.

**Assemblers and nanotechnology**

Assembler-based nanotechnology will give nearly complete control of the structure of matter, enabling the construction of the smallest, strongest, fastest devices possible under natural law as it is understood today. The road to nanotechnology may pass through protein technology, using parts as stiff as wood, but nanotechnology itself will use materials like diamond, 4 times as stiff as steel and 50 times stronger. Parts comprising such materials cannot be made by mixing ordinary chemicals or by coaxing large molecules to self-assemble; they will be made through direct control of chemical reactions, using robotlike assemblers wielding reactive molecules as tools.

Crude, early assemblers will be made by protoassemblers. Later assemblers, however, will be made using advanced assemblers, which means that they themselves can be made of strong, rigid materials like diamond. To picture such a device, one should imagine not a protein molecule or a biological cell but a jointed, computer-directed industrial robot arm, full of gears, bearings, and drive shafts, yet only a ten-millionth of a meter long.
Assemblers can do their jobs using reactions like those familiar to chemists. What they will add is control; whereas a chemist mixes molecules in solution, letting thermal motions bring them together haphazardly (and often with unwanted side effects), an assembler arm will bring molecules together with precision, making a single reaction occur in a specified location. Enzymes show this sort of control, but they are specialized for particular jobs; assemblers will tackle general construction tasks.

The uncertainty principle of quantum mechanics places some limits on how accurately a molecular tool can be positioned, but at ordinary temperatures thermal motions pose a greater problem. The solution is to make the arm stiff enough to hold its position with sufficient accuracy. This will require careful design, but calculations show that it can work.

Today what humans can do is strongly limited by what they can build. It would be straightforward to design a billion-bit computer memory chip, but no one bothers because no one can build such a thing. By contrast, assemblers will enable construction of almost anything having a chemically reasonable arrangement of atoms. Then what mankind can do will be limited not so much by fabrication abilities as by cleverness and by the limits inherent in natural law.

Small products

In nanomachines a single atom can serve as a gear tooth, and a single bond between two atoms can serve as a bearing. Whole arrays of atoms sliding over one another can serve as stronger bearings in larger devices. Drive shafts, cams, roller bearings, levers—a full range of familiar mechanical devices—can be built on a nanometer scale. Standard electromechanical devices, such as electromagnetic motors, will not work on this scale, but while electromagnetic motors lose power in small sizes, other motors gain power. Calculations indicate that direct-current electrostatic motors just 50 nanometers in diameter can provide mechanical power at a rate of hundreds of trillions of watts per cubic meter; that is, many nanowatts per motor. With motors and mechanical parts, complex systems will become possible, including assemblers and computers to control them.
At this stage the study of nanotechnology rests on what may be termed exploratory engineering, involving studies of what can be built with tools that do not yet exist. Exploratory engineering differs from science in that it aims merely to apply existing scientific knowledge, not to uncover new facts about nature. It differs from standard engineering in that it attempts only to make the case that certain future systems are, or are not, physically possible, not to actually design and build those systems today. The discipline of exploratory engineering uses both analogy and calculation. The above case for assemblers uses analogies from biology and chemistry; the case for molecular computers, however, must rely more on calculations.

From the perspective of standard engineering, molecular electronic computers will likely prove best, but from the perspective of exploratory
engineering, they pose problems. Their operation involves the complexities of molecular quantum mechanics, raising difficulties of design, modeling, and calculation. This gives reason to consider what can be done with molecular mechanical computers. Although likely to be far slower than molecular electronic computers, mechanical nanocomputers have the virtue of being easy to analyze with classical physics. Their projected performance can set lower bounds on what future computers can do.

Whereas today's electronic computers move signals by putting a voltage on a conductor, a mechanical nanocomputer would do so by displacing a molecular rod. In an electronic computer, signals on one conductor can control signals on another by means of transistors. In a mechanical nanocomputer, signals would control one another through mechanical locks. Thermal motions will tend to disrupt these operations, but again the problem can be solved by building parts with adequate stiffness.

Mechanical systems are intrinsically slower than electronic systems of comparable size, but smaller systems operate proportionally faster. Cutting size in half doubles speed (the moving parts have less far to travel), and a mechanical nanocomputer with a central processing unit a fraction of a micrometer across would be moderately faster than current electronic computers. Moreover, a half trillion of them (with space for cooling channels and interconnections) could fit in a cubic centimeter, putting more computing power in a desktop machine than exists in the entire world today.

Raw computer power does not translate directly into intelligence, for without suitable software the most powerful computer could not even add a column of figures. But raw power must be some help. It is worth noting that current artificial intelligence research has been trying to coax humanlike behavior out of computers with roughly a "microbrain" of computing power; i.e., a millionth that of the human brain. With nanocomputers a desktop machine could have a raw computational power level in the "megabrain" range. This capability might make a difference.

Single nanocomputers running conventional software (like that used in automated factories) can be used to operate assemblers. Given fuel, raw materials, and the right instructions, assemblers will be able to make virtually anything, including more of themselves. This will make possible replicators, nanomachines able to copy themselves in vats of suitable chemicals. Calculations suggest replication times of about a thousand seconds, letting a single, microscopic replicator give rise to many tons of product replicators in a day or so. After reprogramming, the product replicators would team up to build other things, again by the ton.

**Big consequences**

It should come as no surprise that self-replicating molecular machines can build big and at low cost. After all, this is the way redwood trees come into existence. And like plants, nanomechanisms will be able to use solar power, but at least an order of magnitude more efficiently. With efficient solar-electric energy converters as inexpensive as grass and with strong, tough diamond-fiber composite hardware as inexpensive as wood, much

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*Illustration by Leon Bishop*

An early protein-based nanomachine constructs another from partly self-assembled natural and artificial proteins floating in a "broth" of components. While nanotechnology may pass through protein technology, in its mature form it will use superstrong materials like diamond assembled by robotlike devices exerting direct control of reactions on the level of individual atoms. Given raw material, energy, and instructions, nanomachine assemblers will be able to build an enormous range of desired products, including more of themselves, by the ton.

A design for a mechanical nanocomputer (opposite page) makes use of rods of linear carbyne molecules equipped with particular molecular configurations serving as blocking and probe knobs and all sliding within channels of a three-dimensional matrix. Signals would move through the computer by displacement of the rods and would control one another by interaction of the probes and blocks. While mechanical computers are slower than electronic computers of the same size, smaller systems are proportionally faster.
In this fanciful conception of an approach for counteracting environmental degradation, nanomachines suspended in the air like volcanic dust work to break down atmospheric pollutants into harmless compounds. Nanomachines may prove to be inexpensive, efficient alternatives to more conventional solutions for many problems in industry, medicine, and the environment.

Illustration by Leon Bishop

will become possible. Inexpensive fuel and efficient spacecraft made by nanomachines, for example, should eventually make spaceflight less expensive than air travel is today.

Parallels with other products of natural molecular machinery suggest further applications. For example, plants gave Earth its oxygen atmosphere and accumulated the carbon found in coal and oil. Today people fear that rising atmospheric carbon dioxide levels from the burning of fossil fuels may overheat the Earth through the greenhouse effect. If the solution does not come first in some other way (perhaps by the planting of more trees), solar-powered nanomechanisms could reverse the carbon dioxide buildup, taking a few years of operation to turn all the excess carbon dioxide back into carbon and oxygen.

Nanomachines, with their broad ability to rearrange atoms, will be able to recycle almost anything. Using nothing but sunlight and common ma-
terials, and with no by-products other than waste heat, they will produce a wide range of products. With production costs similar to those of plants, they will enable the clean, rapid production of an abundance of material goods. The benefits could be especially dramatic for the third world.

Potential medical applications also show that small systems can have big effects. Cells and tissues in the human body are built and maintained by molecular machinery, but sometimes that machinery proves inadequate: viruses multiply, cancer cells spread, or systems age and deteriorate. As one might expect, new molecular machines and computers of subcellular size could support the body’s own mechanisms. Devices containing nanocomputers interfaced to molecular sensors and effectors could serve as an augmented immune system, searching out and destroying viruses and cancer cells. Similar devices programmed as repair machines could enter living cells to edit out viral DNA sequences and repair molecular damage. Such machines would bring surgical control to the molecular level, opening broad new horizons in medicine.

While contemplating the potential benefits of nanotechnology, though, one would be well advised to spend time contemplating its potential harm. The chief danger is not likely to be that of runaway accidents; replicators, for example, need no more have the ability to function in a natural environment than an automobile has the ability to refuel from tree sap. Deliberate abuse is another matter. One need only consider the prospect of programmable “germs” for biological warfare to see the seriousness of the problem.

Nanotechnology will let humankind control the structure of matter, but who will control nanotechnology? The chief danger is not a great accident but a great abuse of power. In a competitive world, nanotechnology will surely be developed. If democratic institutions are to guide its use, it must be developed by groups within the political reach of those institutions. To keep nanotechnology from being wrapped in military secrecy, it seems wise to emphasize its value in medicine, in the economy, and in restoring the environment. Nanotechnology must be developed openly to serve the general welfare. Society will have years to shape policies for its beneficial use, but it is not too soon to begin the effort.

FOR ADDITIONAL READING
Foresight Update (Foresight Institute, Box 61058, Palo Alto, CA, 94306).