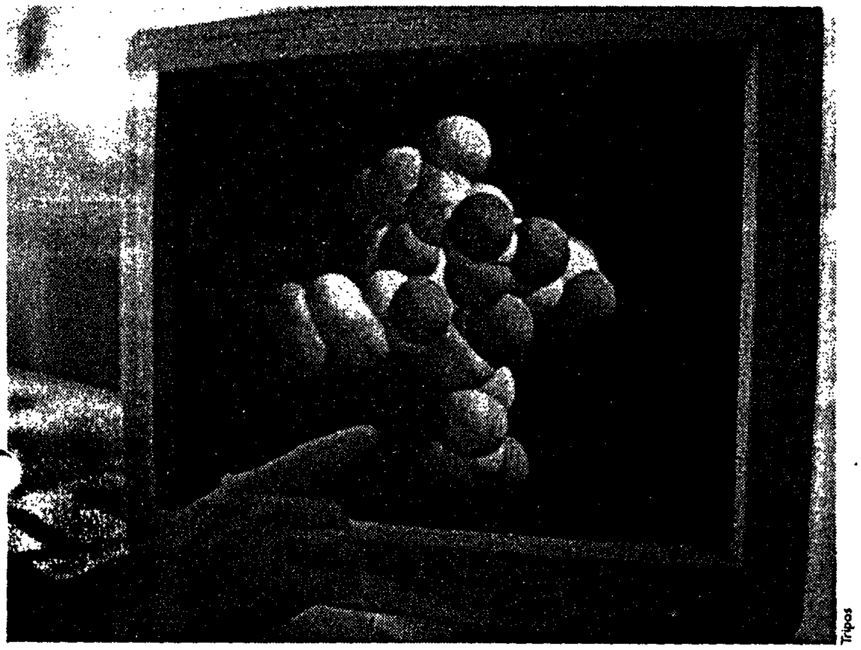
CRITIQUE OF NANOTECHNOLOGY: A DEBATE IN FOUR PARTS

1. Chemistry says it can't happen.

BY SIMSON GARFINKEL



Tripos

One nanotechnology tool is molecular modeling software, such as SYBYL, shown here. The program represents not only the 3D image of atoms but also their surrounding force fields. Images of atoms brought together will behave like real atoms, binding or repelling in a correspondingly "atomic" way. Simulated chemistry such as this is now being used to design pharmaceuticals, in order to build drugs "rationally," atom by atom, much as nanotechnology forecasts.

Nanotechnology is a new engineering skill which promises great power by manipulating matter at the atom level (see WER #54, p. 8). To date, the debate over its consequences (solution or problem?) have assumed its inevitability. Critiques of the proposed science — can it actually be done? — have been nonexistent in the public discourse. The following critique of nanotechnology doesn't address all the questions this technology brings up, but what a relief to have any technical challenge. Simson Garfinkel, a reporter for the Christian Science Monitor, *has a master's degree in science journalism from Columbia and graduated with a triple major in chemistry, political science, and history of technology at MIT. He starts off this four-part debate by challenging the underlying technical details this new power is based on. Eric Drexler, Visiting Scholar at Stanford University and a key visionary of nanotechnology, offers his rebuttal. Garfinkel responds, and Drexler counters. Lastly, Steven Levy, author of* Hackers, *reports on the first conference dedicated to the issues raised here.*

—Kevin Kelly

THE WORD "nanotechnology" means very different things to different people. While most would agree that Nanotechnology is technology performed on the scale of nanometers — one nanometer being about the size of four zinc atoms laid side-by-side — that is where the agreement often ends.

To Howard Craighead, director of the National Nanofabrication Facility at Cornell University, Nanotechnology is a science that uses the chip-making techniques of the microelectronics revolution to produce devices of increasingly smaller dimensions.

To Rick L. Danheiser, a professor of chemistry at the Massachusetts Institute of Technology, Nanotechnology is a word that describes synthetic organic chemistry — a science which seeks to place atoms in precise and complex arrangements in order to accomplish exacting goals.

To K. Eric Drexler, an author and visiting scholar in the Computer Science department at Stanford University, Nanotechnology describes a technology of the future — a technology based upon self-replicating microscopic robots controlled by tiny mechanical computers, capable of manipulating matter atom by atom.

Who is right? Everybody and nobody, really, because "nanotechnology" isn't a scientific term. Nanotechnology is a mind set, an ideology, a way of solving big problems by thinking small — thinking very small.

My first exposure to Nanotechnology was several years ago when I was a student at MIT. A new student activity was forming called the Nanotechnology Study Group, a band of individuals committed to exploring the technology and implications of "Nanotechnology."

The Study Group's handouts were drawings of atoms arranged into nanometer-sized gears and bearings, as well as arrangements of atoms that were supposed to be memory circuits and logic building blocks for nanometer-scale computers. But the people in the Study Group weren't chemists and physicists: they were computer scientists. The questions that the Study Group was interested in exploring were not "will these particular drawings of nanodevices work?" — it was taken for granted that if these didn't, others would — but rather, what would be the uses and implications of such robots to medicine, science, industry and warfare; what would happen if an army of nanorobots got out of control; and what would be their long-term impact on society. The people of the Nanotechnology Study Group were the forerunners to today's cult of Nanotechnology.

The basic tool of the Nanotechnologist is the "assembler," according to *Engines of Creation*, the book by K. Eric Drexler that reads like the Nanotechnologist Manifesto. No larger than a few hundred atoms across, assemblers would be constructed from gears that use single atoms for teeth and turn on frictionless pivots made from single chemical bonds. These nanomachines would come equipped with a computer and a robotic arm, and have the remarkable ability to construct ("assemble") materials or molecule-sized devices a single atom at a time. Assemblers would reproduce by building exact copies of themselves — thus it would only be necessary to build a single assembler, and this first assembler would build the rest.

Although it would be slow for a single assembler to construct anything larger than a fly speck, billions of assemblers working together could do almost anything. You could set a fleet of them about the task of covering your car's paint job with a micron-thin coating of diamond, constructed an atom at a time by assemblers using carbon from carbon dioxide plucked from the surrounding air: forget about rust and car washes. Assemblers could restore the ecological balance of the planet by making more ozone in the upper atmosphere. They could clean up oil spills by eating up the oil, or alternatively they could make oil from air and seawater. In wartime, assemblers would be the ultimate weapon, programmed to be '"omnivores" and rip apart attacking armies atom by atom.

There is certainly evidence that such manipulations at the atomic level are possible. Every cell of every living thing is constantly manufacturing, using and destroying tremendous numbers of relatively simple nanomachines called proteins. Some of them are structural, some of them perform chemical reactions, and some of them transmit messages. But proteins are almost always single-purpose devices which require nearly all of the machinery of the cell to produce and regulate them. No protein does all of the things that an assembler would supposedly be able to do.

One of the most intriguing of the proposed nanomachines is the nanosub, a device a little smaller than a red blood cell which could swim through a person's circulatory system in search of plaque or fatty deposits. Whenever the sub bumped into something that doesn't belong, it would switch on a powerful set of drills and shred the offending blockage. With a few robot arms, the sub could even repair damage. Sort of a nano-Fantastic Voyage, the concept of this sub has appeared in prestigious newspapers like *The New York Times* and *The Wall Street Journal*, as well as magazines such as *Scientific American*. The sub represents the best of what Nanotechnology has to offer: the ability to make our lives better.

The Cult of Nanotechnology paints a future in which technology has grown unimaginably more powerful than it is today. As a much bigger lever than any technology before it, they argue, it would do us well to think about the potential of the technology before the revolution happens: this is what they are doing. The problem with these people's ideas is that they envision working with atoms the same way a model-

Scientific American

A visualization of a nanomachine swimming through a capillary blood vessel, chewing away a fat deposit, lower left. Glucose and oxygen in the blood power two tiny screw propellers. The nanobot randomly wanders through the capillaries, programmed to eat only fat. One can easily imagine both the advantages and problems of such a device.

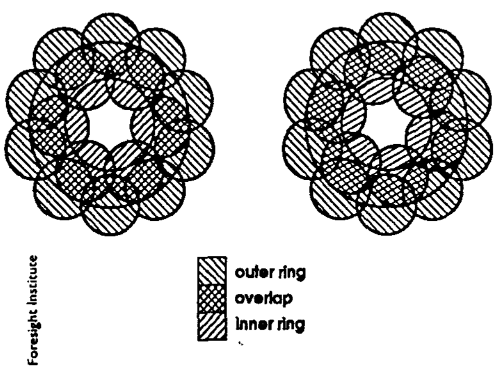
maker might work with wooden sticks and styrofoam balls — breaking a bond here, moving an atom to the other side, and forming a new bond. It is that conceptual model which is at the heart of all the Nanotechnologists' drawings of gears, motors and nanocomputer parts, as well as the very idea of the assembler's robot arm and the nanosub's drill. But atoms don't work that way.

"[Drexler] discusses these molecular systems as mechanical systems," says Robert J. Silby, a professor of chemistry at MIT. "He bangs them and they go." The problem is, Dr. Silby explains, "molecules are not rigid — they vibrate, they have bending motions."

Even cross-linked or interlocked networks of carbon atoms exhibit these characteristics, Silby explains. "Therefore these will not act, mechanically, in the way he has written down. There is more to it than he has said."

Take the example of the assembler's '"robot arm." Such an arm could probably pick up a single atom, since lone atoms are very reactive and likely to stick to anything that they come into contact with. Getting the atom off the arm, on the other hand, would require a lot of energy — quite possibly more energy than the nanomachine would have available.

The robot arm might have a little more luck working with groups of atoms, called molecular fragments. The energy required to work with molecular fragments is much lower than the energy needed to work with single atoms — this is the reason that proteins almost always work with molecular fragments. The only ways that a robot arm could hold a molecular fragment in place would be by making a chemical bond to it or by clamping the fragment in place with some sort of molecular cage.



An idealized van der Waals bearing, a key component in nanomachines. The molecular structure is similar to the "bearing" in certain bacteria, allowing its flagellum to spin (see illustration, p. 111). Artificial nanobearings have not been built yet, although organic ones are built by the most primitive life forms.

There are plenty of proteins that move molecular fragments around by using chemical bonds. But it is always the case that the proteins can form these bonds only with one or two specific fragments. It is doubtful that an arm could be designed to bond with any arbitrary piece of an arbitrary molecule.

Molecular cages do occur in nature, but they tend to be bulky and unwieldy. While there are some proteins which hold molecules in their active sites with flaps constructed from chains of amino acids, such active sites are always at the heart of the protein — not on flexible arms which can easily be maneuvered around. And, as with molecular bonds, the cages and the molecular fragments they hold always come in matched sets.

Presuming an "arm" could be constructed, it would need some sort of "eye" to locate molecular fragments that it would reach out and grab. What sort of sensors would the nanocomputer at the heart of the assembler use to locate the fragments in the first place? What would such a sensor be based on? Visible light has a wavelength fifty to a hundred times the size of a molecule. Light does not "bounce off" a molecule but more often goes straight through, only causing slight disturbances in the very outermost electrons of the molecule's atoms.

Light that has atomic-sized wavelengths is known as X-rays. However, even if the nanomachines could not generate enough energy to emit an X-ray without breaking apart, there is no way that they could detect the reflected rays or collimate them into recognizable images. Perhaps the nanomachine will use electrons or some other sub-atomic particle as a kind of atomic "radar," but there seems no way that a nanomachine could generate a predictable stream of such particles or interpret their reflections.

Nature gets around the imaging problem by relying on molecular diffusion and randomness to bring molecules to the places where chemical reactions can take place. As a protein comes into contact with a target molecule, thermal noise and motion cause molecules to explore trillions of positions and orientations every second. But Drexler and other Nanotechnologists maintain that nanomachines will not rely on diffusion because it is not precise enough for their purposes. Unfortunately, it is all that you have at the atomic level: even the biological process of active transport which moves molecules across membranes relies upon diffusion and random motion to get the molecules into the molecular pumps.

The idea of a universal assembler is somehow a very comforting one: a programmable machine, capable of manipulating atoms and carrying out reactions the way that a blacksmith might repair a horseshoe with anvil and fire, is an easier image than proteins or inorganic catalysts carrying out complicated chemical reactions by transferring electrons from atom to atom. And indeed, in the beginning of his book, Drexler describes an assembler grasping "a large molecule (the work piece) while bringing a small molecule up against it in just the right place. Like an enzyme, it will then bond the molecules together."

The idea of using a few well-crafted machines to make billions, and then using a billion machines to solve the world's problems is really an appealing one. It is especially appealing to a generation of computer scientists that has been raised on ideas such as recursion (a way of solving a problem with a function that refers to itself) and massive parallelism (an approach that uses thousands or millions of simple computers, all working together in unison to solve different chunks of complicated problems in seconds, instead of the days that a conventional computer might take.) Nanotechnology is the physical embodiment of these mathematical ideas. It is no accident that Nanotechnology's loudest spokesmen have been computer scientists, rather than chemists and biologists and materials scientists — people who have experience at moving atoms around on the nanoscale.

An assembler would necessarily be far more complicated than anything that has been built by nature on the atomic scale. This isn't an argument that such constructions aren't possible: a lap-top computer is another good example of something more complicated than nature can build. But natural or not, assemblers would have to exist in the same environment as the biological molecules that they would be designed to operate on.

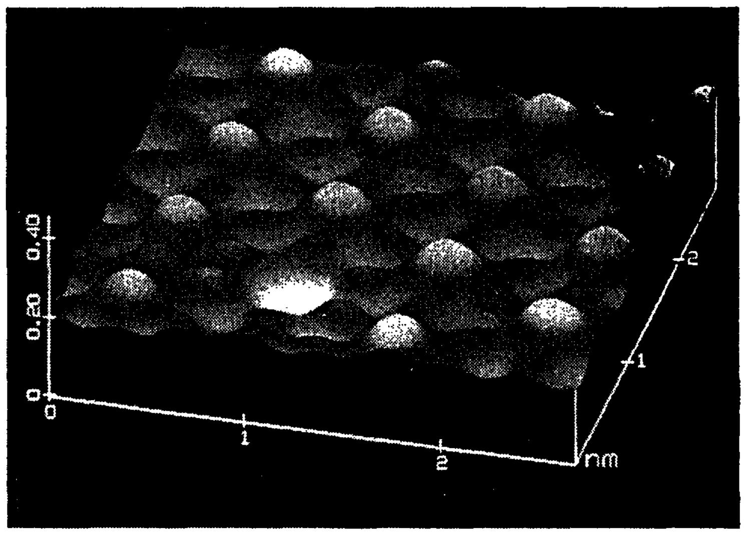
At MIT, professor of chemistry Rick L. Danheiser says that just because some advocates of Nanotechnology haven't had a training in chemistry doesn't mean that their ideas shouldn't be taken seriously.

"I see some anti-aromatic structures that can't possibly exist," Danheiser says, referring to the designs that Drexler has proposed for the "rod-based logic" of a nanocomputer. "It's unfortunate that he draws something that doesn't look so good, because a lot of people see it and discredit the whole thing."

Nevertheless, Danheiser says, "I think that they are doing a great service. Students in high school are reading *Omni*, thinking 'that's really neat.' "

Indeed, what the advocates of Nanotechnology are doing, Danheiser says, is "putting a lot of glamor into chemistry. Chemistry suffers compared to physics and biology. . . . That's why I hesitate to do anything to puncture their balloon."

What upsets Danheiser is some of the descriptions of chemistry that are used by advocates of Nanotechnology — a description, he says, that seems based on a freshman chemistry course's understanding of the field. One common analogy used by Drexler, for example, is that chemists throw bolts and nuts into a bag, shake it, and hope for a machine to come together.



Digital Instruments

A scanning tunneling microscope no bigger than a high-school microscope produces portraits of atoms. This image made by the Nanoscope II shows iodine atoms absorbed on the surface of a platinum crystal (notice the missing atom). Being able to detect matter at the atom level is one step in learning to control the location of atoms.

"That's not an accurate picture of what one does in organic synthesis," says Danheiser. "We take nuts and bolts that are cleverly machined so that they self-assemble in a specific manner."

James S. Nowick, who is completing a doctorate in organic chemistry at MIT and plans to work in the field of molecular devices, puts it this way: "My main criticism of Nanotechnology, or more in particular, of Drexler, is that he's coming forth as being sort of a visionary without actually doing anything. . . . Whatever he is putting forth as science has to be tempered by the fact that we are dealing with somebody who is basically making predictions. . . . In my field, for instance, if you have a prediction of how something will work you can't just go publish that. You really have to have scientific results.

"I think that there are some problems and unreasonable aspects of some of the structures that Drexler has drawn. However," Nowick says, "I see them essentially as a sketch that one might give an architect."

The most important developments in modern chemistry, Danheiser says, is by "very, very serious chemists who are actually involved in molecules that have complex function. This is rudimentary nanotechnology, although I don't think that they would call it that."

For example, the 1987 Nobel Prize in chemistry was awarded to three scientists who had done pioneering work in the field of molecular recognition — which in a way can be thought of as "robot arms" that are pre-programmed to "pick up" specific molecules.

Danheiser is also enchanted by the idea of a nanosubmarine that swims around a person's circulatory system, looking for cancerous cells to destroy. But Danheiser describes the sub as a large molecule with an artificial antibody on the front, grafted to a molecule of snake venom — a molecule which nature has given the capacity to cut up and destroy cells.

Such a machine, Danheiser stresses, wouldn't have to self-reproduce or even self-repair to be a medical success. The machine could be made synthetically, in a laboratory, and it could be "reprogrammed" by chemically removing one antibody and replacing it with another one.

"Chemists are getting the short end of the stick," says Nowick. "The best thing that chemists can do is get one or more spokespeople who are willing to beat the drum for the public, saying that 'this is chemistry, this is exciting technology, you should be interested in it, young people should pursue careers in it, and congressmen should provide more funding.' " □►

2.
Under special conditions, chemistry *can* build stable nanostructures.

BY K. ERIC DREXLER

Berger, McMullen, Macaulay

The world's smallest Christmas card — only five square micrometers, about a billion times smaller than usual — produced by drilling holes four nanometers across in a layer of aluminum fluoride crystal. If it were possible to write all the books in the Library of Congress at this nano-scale, you could fit them onto the head of a pin, and still have room for all the volumes in the rest of the major libraries of the world. The holes (below) are "drilled" by dislocating atoms using a beam of electrons. Storing information by nanotechnology may be its most probable first use.

I HAVE BEEN ASKED to reply to the preceding critique and have done so in a hypertext style [to refer to Simson Garfinkel's comments]; *Whole Earth Review* plans to give Mr. Garfinkel another ability that hypertext will provide more widely — the ability to respond to a response.

1. What is nanotechnology?
Simson Garfinkel says that Howard Craighead defines nanotechnology as advanced microtechnology, while Rick L. Danheiser defines it as synthetic organic chemistry. As this shows, these fields already have names. So far as I can tell, it was I who introduced the term "nanotechnology" into general use, and as Mr. Garfinkel's paragraph on my usage suggests, there is no commonly accepted alternative name for the capabilities that "nanotechnology" is generally taken to describe. If this technology is important, then it needs to be discussed and it needs a brief, unambiguous name. Sticking with the original meaning of "nanotechnology" would be useful for this reason. (There is no perfectly clear line between synthetic organic chemistry and nanotechnology, but neither is there a perfectly clear line between night and day; they are distinct, though one leads to the next.)

2. Why are computer scientists prevalent among those interested in nanotechnology?
Chemists and physicists are best placed to critique proposals in nanotechnology, but their orientation is that of scientists, not of engineers. The tend to focus on what can be studied today, not on what can be built tomorrow. Computer scientists (despite their name) are, in this sense, engineers. Further, they recognize the value of tiny, fast, controllable things, and they are habituated to technological revolution.

3. What are we to make of the excitement caused by the concept of nanotechnology?
I believe Marx once said, "I am not a Marxist." I may be forced to echo this remark. The basic concepts of nanotechnology are technical and open to technical criticism. If they are true, then they have enormous consequences, and it is natural for people to become excited and for some to become starry-eyed. It would be an *ad hominem* fallacy, however, to judge the validity of technical concepts by emotional characteristics of the response they raise. Still, it is a good rule of thumb to be especially skeptical of ideas that people seem to want to believe; accordingly, in my technical talks I urge my audiences "to be harshly critical of any ideas they hear labeled 'nanotechnology', starting with my own."

4. Can gears turn on frictionless pivots made from single chemical bonds?
All pivots (or bearings) have some sliding friction, or *drag*, though they can be made to have a negligible amount of static friction, or *stickiness.* Single chemical bonds are too weak and elastic to use as bearings for the gears mentioned here, but there are other, more adequate approaches based on sliding surfaces. Like many of the points that follow, this was discussed in my course at Stanford, "Nanotechnology and Exploratory Engineering."

5. Will assemblers build devices a single atom at a time?
In general, probably not, though I have sometimes used language that may suggest literal atom-by-atom construction. A more accurate statement would be something like "Assemblers will maneuver reactive chemical moeties to tenth-nanometer precision, effecting a series of elementary chemical reactions, each of which adds one or several atoms to a workpiece, giving precise control of the resulting molecular structure." And even this is a simplification, since a typical

operation will often do something a bit more complex, such as adding three atoms while removing one. The shorter description gives a clear picture of the net effect.

6. Will assemblers do all these things?
Not directly. Assemblers will be general-purpose manufacturing machines, able to make almost anything so long as they are given the right raw materials, fuels, operating conditions, and instructions. They will be used to make many special-purpose machines, and the latter will do most of the work. To make a particular product in quantity, it will make no sense to use general-purpose assemblers; these will instead be used to build a special-purpose production line, like an engine fabrication line in Detroit. These production lines will then be used to turn out devices like Simson Garfinkel's hypothetical diamond-coating-appliers (perhaps formulated into a rub-on paste?), or the more desperately needed devices able to clean up the mess made by 20th-century industrial technology.

Weapons are among the potential products we need to worry about, but ripping attacking armies apart atom by atom is rather too crude and too dramatic; one suspects that the military mind will find other applications for a manufacturing technology characterized by the construction of precise and sophisticated devices. In general, having an image of assemblers doing everything in the future would be a bit like having an image of lathes and milling machines doing everything today.

7. What does nanotechnology assume about how atoms and molecules work?
Gears, motors, mechanical nanocomputer parts, and Simson Garfinkel's proposed drill would work in an essentially mechanical fashion, as would the positioning operations of assembler arms (resembling those of industrial robot arms). The actual chemical transformations effected by assemblers, however, have little resemblance to familiar mechanical operations. Note that describing molecular motions in mechanical terms (e.g., in the field of molecular mechanics) is a standard part of chemistry.

8. What about elasticity and vibrations?
Every physical object is a collection of atoms; nanomachines will simply be very small physical objects. Everything vibrates, everything bends, and machines work regardless; the differences here are more quantitative than qualitative. On a very small scale, the vibrations associated with heat itself become of tremendous importance, and are a crucial issue in nanomachine design and operation. I mention this issue in *Engines of Creation*, and have done quantitative analyses of thermal vibrations in both logic systems for mechanical nanocomputers and in assembler arms. There is a lag in publication and distribution of information in new, interdisciplinary fields, though, so it would be surprising if these results were universally known in the MIT chemistry department.

9. What about problems with picking up and placing lone atoms?
See (5).

10. Need an arm bond with any arbitrary piece of an arbitrary molecule?
Assembler arms will wield a variety of tools, each with a standard "handle" fitting a standard "hand"; the tools themselves will be specialized. Further, only a limited range of tools would be needed to build a wide variety of products, since even a complex product can be built through a complex series of simple operations. All this is familiar from macroscopic manufacturing technology.

11. Will nanomachines use x-ray or electron-beam "radar" to spot molecules?
Surely not, for reasons well-stated here (I have not seen this proposed elsewhere). Further, freely moving molecules would elude grabbing even if they could be seen; assembler arms would simply be too slow. Industrial robots typically pick pre-positioned, pre-oriented parts off something like a conveyor belt, rather than rummaging around in a bin — and this despite the greater ease of vision on a macroscopic scale. I expect that assemblers will work in a similar fashion.

12. Will nanomachines rely on diffusion?
There is a distinction to be drawn between relying on diffusion *somewhere*, and relying on it *everywhere*. Assemblers will enable precise construction of large, complex molecular systems because they (i.e., their positioning arms) will be able to direct chemical reactions with a specificity and reliability that cannot be achieved when molecules are free to bump together in all possible positions and orientations. Thus, they avoid diffusion when moving molecules to the site of reaction. General-purpose assemblers are expected to pluck tools incorporating reactive molecules off conveyor belts which have been loaded with activated tools by special-purpose systems of somewhat enzyme-like machinery, which in turn have gotten their raw materials from the surrounding solution. This earliest step will involve the transfer of molecules — by diffusion — from that solution to selective binding sites like those familiar in proteins and supramolecular chemistry.

13. How complicated are assemblers?
Assemblers and nanocomputers will be roughly as complex as industrial robots and microcomputers, because they will contain similar numbers of parts performing similar functions. All these devices, however, will be far less complex (and adaptable) than living organisms; they will have broader capabilities in some respects, but not in all.

14. Can these anti-aromatic structures exist?
For quantum-mechanical reasons, some molecules that can be drawn as rings with alternating double and single bonds are especially stable (like the six-membered benzene ring) and others are especially unstable (like the four-membered cyclobutadiene

ring). One of my nanomechanical designs contains a ring resembling the latter; it has the advantage of having a useful shape for the purpose. Is its "instability" a problem?

Chemists regard chemicals as unstable when (for example) they spontaneously dissociate, or rearrange, or react with themselves at a high rate, or when they readily react with a variety of other molecules. This final process is not intrinsic to the molecule, but results from the presence of other reactive molecules. In a different environment, the molecule will be stable. Chemists ordinarily work with molecules in solution, and in vast numbers; these molecules are free to encounter others of the same kind, so any reactions that occur will be unavoidable. This is a stronger kind of instability, typically dealt with by studying molecules under low-density, near-vacuum conditions, or in solid matrices of noble gases at temperatures near absolute zero.

Under the latter conditions, cyclobutadiene exists, but it begins reacting with itself on even slight warming (to 25 degrees Kelvin). In a nanomachine, of course, molecules do not wander freely; they encounter only certain other structures in certain orientations. Under these conditions, the cyclobutadiene ring can indeed be stable (as it is at room temperature when surrounded by bulky, branched side-chains). A call to Rick L. Danheiser confirmed that he shares this view of stability and its application to the case at hand; I had run these structures by another organic chemist for criticism before publishing them. Only instability in the sense of a molecule falling apart or rearranging spontaneously can be used to criticize a structure out of context (and even then a suitable molecular environment can create exceptions, left as an exercise for the nanotechnologically inclined chemist).

15. What about these freshman-chemistry-course analogies?

They are intended to inform readers with diverse backgrounds, sometimes lacking even freshman chemistry itself. They are useful in the same way that Danheiser's reference to "machined" molecules is useful — as metaphors to convey a qualitative understanding of some aspect of the subject matter, such as the ability of synthetic organic chemists to make a wide range of moderately complex structures with precision. (For perspective: in chemical synthesis, a hundred-atom structure is considered large and complex but an assembler arm will likely have on the order of a *million*).

16. Should one talk about what has not been demonstrated?

James S. Nowick is correct that predictions are not publishable in many fields of science. However, nanotechnology is not a branch of science (as I have taken pains to point out in *Engines of Creation*); it is an engineering discipline based on established science. Engineering projects are often discussed and written about before they are undertaken. Indeed, in the 1930s members of the British Interplanetary Society performed feasibility studies which argued that one could fly to the Moon with rockets. With care, feasibility studies can be done today in the field of nanotechnology. The required intellectual discipline includes strict avoidance of areas of scientific uncertainty (or pursuit of designs which are robust despite a given range of uncertainty); it is thus closer to engineering than it is to science. To scientists, engaged in learning new facts about nature, talk of future knowledge is speculative and often pointless. To engineers, engaged in building new devices, talk of future possibilities *grounded in established science* need not be speculative and is often essential.

The above is a fragmentary sketch of some issues in the methodology of exploratory engineering. A chapter-length exposition is available (see the closing note for further information).

If one can indeed understand something about future technologies, should we ask that *everyone* refrain from doing so (or at least from publishing the results) before these technologies are demonstrated? To do so would be to request that society turn a blind eye to a significant scrap of knowledge regarding our future. I believe that exploratory engineering deserves a genuinely tiny fraction of society's technical effort, and that its products, when they seem interesting, deserve rigorous criticism — or partial, carefully hedged approval, when merited — from those with competence in a relevant field.

17. Are we doing nanotechnology today?

The developments and goals cited here are relevant, and show how short-term objectives are leading toward steadily more sophisticated molecular devices. In my work I have focused on long-term developments, and have described devices that no one would consider trying to build today (because we lack the tools) and that no one is likely to build tomorrow (because we will then have better designs). Still, even the crude nanotechnology I am able to describe and defend would have capabilities far beyond what has been achieved today. We are speaking of the difference between a mousetrap on the floor and a gripper on an industrial robot arm backed up by a computer.

In closing . . .

I thank Simson Garfinkel for a stimulating critique of my work; it has provided an occasion to explain several points previously made only in teaching or in conference proceedings. A general observation seems in order, however, given a natural and widespread misunderstanding of my view and the it-would-be-nice-if tone of his essay: I have not *advocated* nanotechnology, I have advocated *understanding* it. Reporters, hearing me describe a technology that can accomplish many long-sought goals, often assume I must think that it is an unalloyed blessing, or at least a good thing — even when I emphasize its great potential for abuse (*Engines of Creation* has a chapter titled "Engines of Destruction"). My position seems just a shade too subtle to fit a simple, stereotyped story: I believe that in our diverse, competitive world, basic human motivations make nanotechnology effectively inevitable, and that, in light of this, we need to understand its great potential for good and ill so that we can formulate and act in accord with effective policies.

Nanotechnoloy will, I believe, be the dominant manufacturing technology of the coming century, making possible a host of amazing products. What we build with it will make a vast difference to human life, the biosphere, and the future of the world. Ideas regarding nanotechnology need to be taken seriously, which means evaluating them with proper care and skepticism. □

3.
Molecules are too unstable to be controlled the way Nanotechnology needs.

by Garfinkel

A BIT OF BACKGROUND . . .

In January, I found myself in a lecture room in California, talking with Stewart Brand about the possibility of machines no larger than a wavelength of light. "I don't believe in Nanotechnology," I finally said, referring to the lectures and writings of K. Eric Drexler. It wasn't that I didn't believe that atoms couldn't be placed into precise arrangements, I explained. I simply didn't believe that the laws of physics and chemistry would ever allow the creation of machines as small, yet as complex, as Drexler's would necessarily have to be.

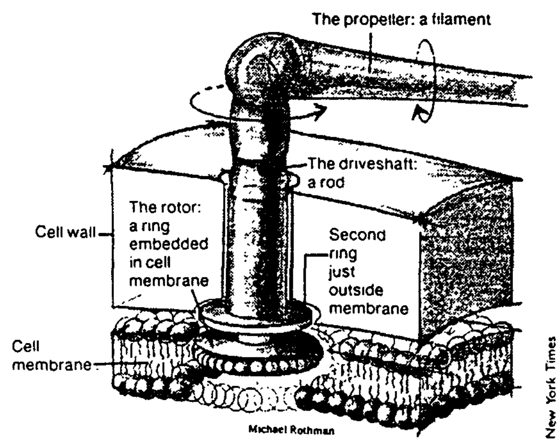
Brand invited me to write an article explaining my objections, so when I returned to Cambridge I started showing Drexler's papers to chemists and physicists whose opinions I respected. Many of them laughed, saying that Drexler's predictions were "'impossible." Others refused to comment, hoping to stay away from what they saw as science fiction masquerading as scientific controversy.

Making predictions is a tricky art, and Mr. Drexler, whose training is in computer science, not chemistry, is bound to misplace a bond here or there. But in formulating my disagreements with Drexler, I came to realize that many of his writings contain the seeds of possibility, if some of his words were translated and not taken at face value, and so my first article was born.

The heart of my continued disagreement with Mr. Drexler is summed up by the matter of capitalization: Drexler believes that the word "Nanotechnology" should not be capitalized, just as the words "biotechnology" and "'microtechnology" are not capitalized. But Nanotechnology is not like biotechnology or microtechnology: Both biotechnology and microtechnology exist: there are laboratories where work is done, journals where results are published, and physical devices which put these technologies to work.

Nanotechnology has none of these physical trappings; it is not yet an "engineering discipline," as Drexler maintains [16], because there is nothing that is being engineered in any conventional sense. This is why many scientists think Nanotechnology is science fiction. It isn't that "there is a lag in publication and distribution of information in new, interdisciplinary fields," as Drexler contends [8]. Indeed, an astounding number of people are familiar with his work.

Perhaps the word "nanotechnology" (the uncapitalized version) wasn't in wide use when Drexler started out, but it is now, and it is generally regarded by those in the microelectronic and microfabrication com-



Each propellor-like filament that propels a bacterium is driven by a motor under the bacterium's cell wall. The filament's drive (transferred through a 90-degree elbow "gear") is an electric motor turned by a chemically induced flow of protons. A similar design can be used to move nanomachines.

munities to mean lithography at the nanometer scale. "Nanotechnology" and "'nanotechnology" therefore mean different things to different people, and this is my reason for insisting on the capital-N. Names are important, because they are the place-markers that we use for ideas.

Science fiction — or, more appropriately, speculative fiction — serves many useful purposes. Drexler's predictions force one to think about the problems caused by chemistry, biotechnology and physics, and how to solve them. But to talk about Nanotechnology in such certain terms as Drexler does, always writing about what it "'will do," leaves a bad taste in the mouths of many scientists.

It isn't that chemists and physicists "tend to focus on what can be studied today, not on what can be built tomorrow," [2] as Drexler asserts. Scientists simply tend to focus on what they think is allowed under the laws of chemistry and physics. Whether Drexler's Nanomachines follows these laws remains to be seen.

In Drexler's world of Nanotechnology, atoms do exactly what he wants them to do. Drexler's atomic bonds, for example, are extremely rigid — they have to be, so that his atom-sized gears will turn instead of simply having their teeth bent. Likewise, physical effects like diffusion seem to turn on or off as needs are dictated by Drexler's designs. Small reactive molecules, for example, never, ever slip into the Nanomachines and gum up the works. "In a nanomachine, of course, molecules do not wander freely; they encounter only certain other structures in certain orientations," Drexler writes [14]. How does a Nanomachine protect itself? How does it repair itself when it breaks?

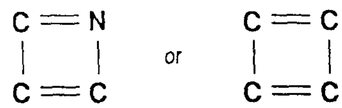
It all goes back to the very mechanistic view of atoms and bonds which most of Drexler's work is based on. While "describing molecular motions in mechanical terms is a standard part of chemistry," [7] chemists do not think about chemical reactions in such terms. The most important thing in chemistry is the movement of electronic charge, not the movement of atoms. Once electrons move, atoms rearrange themselves automatically, because at the atomic level electrostatic force is thousands of times stronger than mechanical force. Nevertheless, Drexler continues to write about atoms if they were so many wooden balls, pegs and springs.

To say, as Drexler does, that the arms of Assembler need not be able to bind to arbitrary molecules — instead, they wield tools that have this ability [10], is to restate the question, not answer it. How will a "limited range of tools" be used to "build a wide variety of products?"

"Macroscopic manufacturing technology," it turns out, is a very bad model for how to build things at the molecular level. I can lift a quarter from a table top with a tweezer, a pair of pliers, or even with two chopsticks. But biology teaches us that nearly every molecular fragment must be manipulated by a unique tool, a special-purpose protein designed specifically for the task. Other proteins simply don't work: they either can't pick up the particular molecular fragments (because the fragments don't fit properly and slip out due to vibrations), or they can't let go (because the fragments irreversibly bind to the tools.)

Likewise, if Assemblers do not need radar or vision because they pick "pre-positioned, pre-oriented parts off something like a conveyor belt," [11] the next logical questions to ask is "how do the parts get on the conveyor belt in the first place?" and "what pre-positioned and pre-oriented them?"

I was quite surprised that Drexler defended his published structures as stable. Although it is impossible to know with certainty whether or not a proposed molecule is stable without actually making it, there are many guidelines that chemists follow to assess stability. In general, four-member rings, such as:



are intrinsically unstable because they place carbon bonds at 90-degree angles, instead of the preferred tetrahedral angle of 109.5 degrees. Yet it is these instable structures that appear in Drexler's proposed "Probe knob structure" and "Gate knob structure," which are the basis of his mechanical Nanocomputer. If these structures begin to disintegrate at 25 degrees Kelvin [14], how will they last inside a Nanocomputer? Even if the computer were supercooled, the smallest amount of mechanical energy (perhaps a result of the computer's operation?) would be enough to set them off.

In my original article, I tried to stay clear from arguments about whether this or that arrangement of atoms would be stable or not, because such arguments cannot be productive. It is impossible to prove that something cannot exist. If by some chance I should convince Drexler that he made a mistake, all he would have to do is come up with some alternative arrangement of atoms and say, "Well, how about this one?"

I agree with Drexler that he has "described devices that no one would consider trying to build today (because we lack the tools) and that no one is likely to build tomorrow (because we will then have better designs)." [17] I think that he should include this statement as a footnote to every molecular structure he publishes.

Certainly we should talk and think about things that have not been demonstrated; such discourse is at the heart of all future discoveries. But if we claim that such discussions are scientific, then it is important to stay within the laws of established science. I have read philosophy and scholarly discussion about the possibility and implications of time travel, but I do not consider it a serious possibility, nor would I write an article on all the things that we could do "when time travel is a reality."

I wouldn't say that "since time travel is an interdisciplinary study, it is understandable that many people are not familiar with the means by which it will be achieved." Drexler has made many such statements about Nanotechnology, angering and alienating many scientists.

In closing, as a science writer whose first scientific training was in chemistry, I can only hope that Drexler's graphic descriptions of his world of Nanotechnology stimulate more popular interest in the chemical and biological sciences. I simply fear that he has been too cavalier in many of his descriptions, and that scientific possibility has often been pushed aside for sensationalism.

To say flat out that "I don't believe in Nanotechnology" is probably a misnomer. I certainly believe that our ability to control the placement and arrangement of atoms will only get better as time goes on. A century from now, a student of history may discover Drexler's articles and, with some amusement, note the similarities between what Drexler predicted and what came to pass, just as I might read Charles Babbage's plans for a computer based upon a steam engine. But I think that the technology that future manufacturers use to arrange the placement of atoms will look a lot more like conventional chemistry and biology. And while this might be a "Nanotechnology" of a sort, it is a far cry from self-reproducing, self-repairing Nanomachines driven by tiny mechanical computers. □

4.
Natural materials prove that nanostructures can be built.

by Drexler

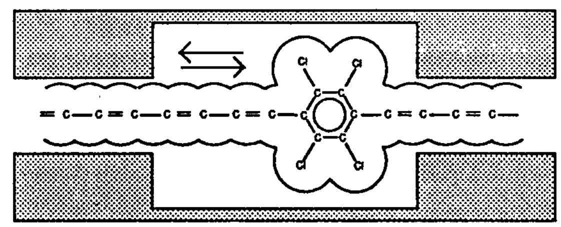
I AM SOMEWHAT disappointed by the tone of Mr. Garfinkel's response to my response; much of it shifts away from his original, valuable focus on technical criticism to a focus on style, words, and feelings. These are important in their place, but are scarcely scientific or professional in the context of a technical debate. Some of his criticisms amount to a request that I repeat certain elementary points throughout my writings. This might inhibit misunderstandings, but it would also inhibit communication of anything new. If the term "nanotechnology" were widely used in the U.S. in the manner that Mr. Garfinkel suggests, I would expect a reasonable fraction of technical papers and news articles to use it that way; they don't.

His strongest criticism, if true, would be my proposing unstable four-membered rings and thus revealing a dramatic ignorance of chemistry. But these rings do not "disintegrate" at 25 degrees Kelvin, they *dimerize*, and this requires that two molecules encounter one another in an orientation which would be prevented by mechanical constraints in the nanocomputer. Again, and more clearly: I have discussed this matter with Prof. Danheiser, whom Mr. Garfinkel quotes against me, and he agrees with my view of the matter. Indeed, he stated that he had never heard me say anything that was inconsistent with today's chemical knowledge, though he noted that he had heard some serious distortions at second hand.

Mr. Garfinkel speaks of "many scientists," "an astounding number of people," (etc.) as being critical of my work, but who are they, and what are their *substantive* criticisms? In the case of Prof. Danheiser we were given a name and a direct, substantive quote; after a few minutes of discussion with him, the difficulty evaporated. I have yet to encounter a major technical criticism of the core concepts of nanotechnology that does not evaporate once it is examined. There seems to be a lot of smoke in the air, but no fire — perhaps the haze is fog?

A few notes: My training is not in computer science, as Mr. Garfinkel states, but in interdisciplinary science and engineering. Molecular diffusion is indeed controllable, being rapid in gases and liquids and effectively blocked by suitable solid walls. I trust this explains why I assume that it occurs in some places and not in others. Molecular mechanics is indeed not the whole story of chemistry — it gives a decent description of molecular vibrations and rotations, but not of chemical reactions. Single-atom gear teeth will indeed bend under load (why would anyone assume that I think otherwise?), but they will also turn the gear, given any sort of reasonable bearing. How will a limited range of tools build a wide variety of products? In much the same way that they do in synthetic organic chemistry, in living organisms, in home workshops, and in flexible manufacturing plants; ask J. Baldwin. Time travel is a straw man, and no friend of mine.

Regarding Mr. Garfinkel's last two sentences, amen! But I have been at some pains to distinguish my designs from "predictions"; they are intended only to show that devices having certain capabilities are physically possible, so that we can try to prepare for their emergence in the real world. I am glad that this intertwined collection of arguments and design concepts has persuaded Mr. Garfinkel that these prospects are real. ■



One part of a nanotechnology computing machine is suggested by this structure devised by Eric Drexler. It is an "alignment knob" which slides back and forth in a slot and aligns the arrays of mechanical components (all small atomic assemblages) so that they can "calculate" in the manner of mechanical adding machines.

Readers in the U.S. can obtain copies of the essay "Exploratory Engineering," together with a *Britannica* reprint on nanotechnology, by sending a stamped, self-addressed large envelope with $1.25 postage to the Foresight Institute, P. O. Box 61058, Palo Alto, CA 94306. Outside the U.S., send $4 for airmail delivery.