



“TINYTECH”

Fred Hapgood

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Cover headline:

“Nanotechnology: Molecular Machines that Mimic Life”

First broad public exposure to the term “nanotechnology”

The primary origin of the classic “gray goo” mythos

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NANOTECHNOLOGY **MOLECULAR MACHINES THAT MIMIC LIFE**

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**NEURAL NETS:
COMPUTERS
THAT BEGIN
TO THINK**

**THE FIGHT TO FREE
LAB ANIMALS**

**SOVIET
CHILDREN'S
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EDITOR IN CHIEF & DESIGN DIRECTOR: BOB GUCCIONE

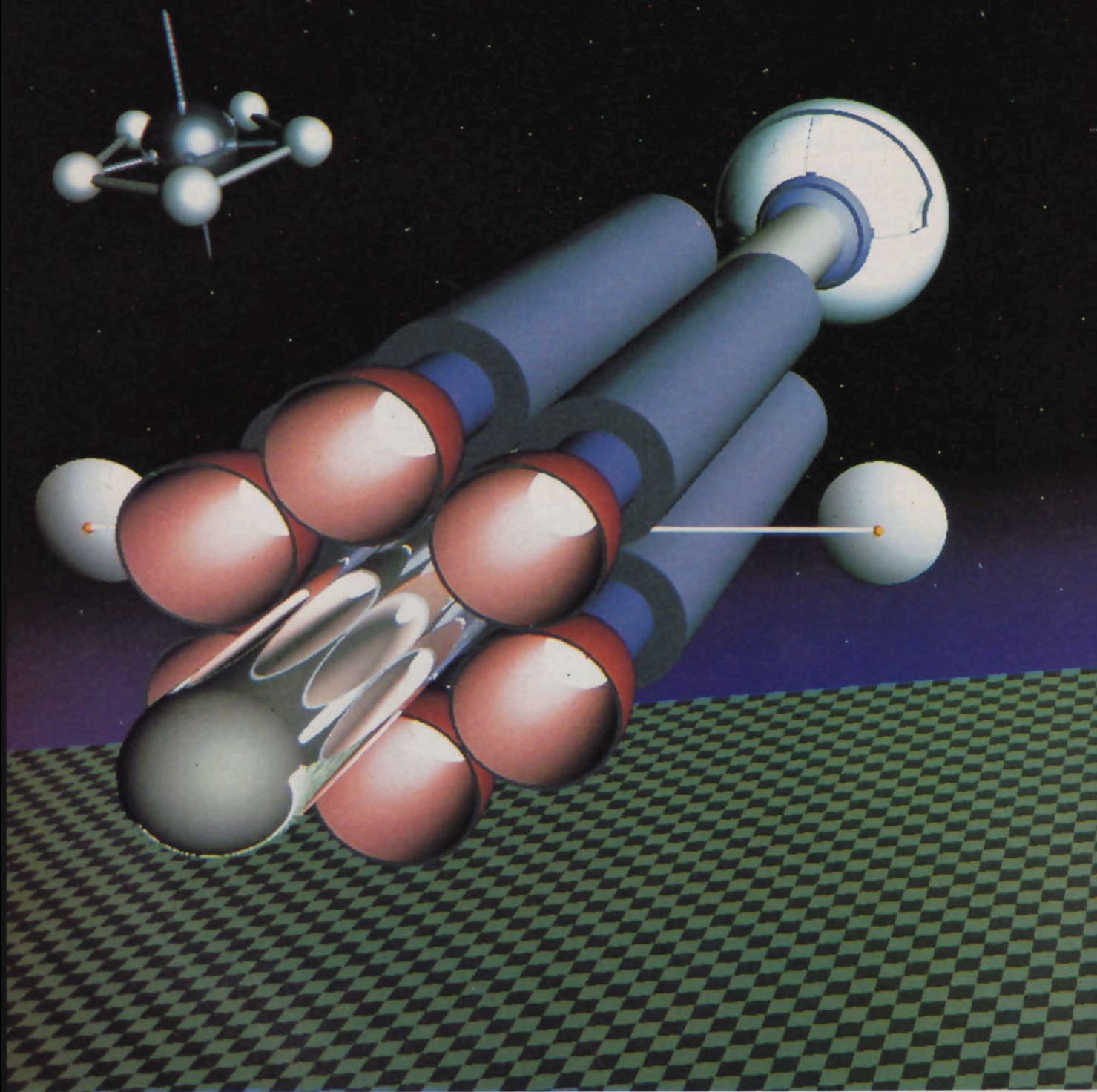
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The force of technology—its power, beauty, and ability to duplicate, or even improve upon, nature's own miraculous processes—is shown in this month's cover. The work was created by Dale O'Dell, a Houston-based photographer.

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TINYTECH

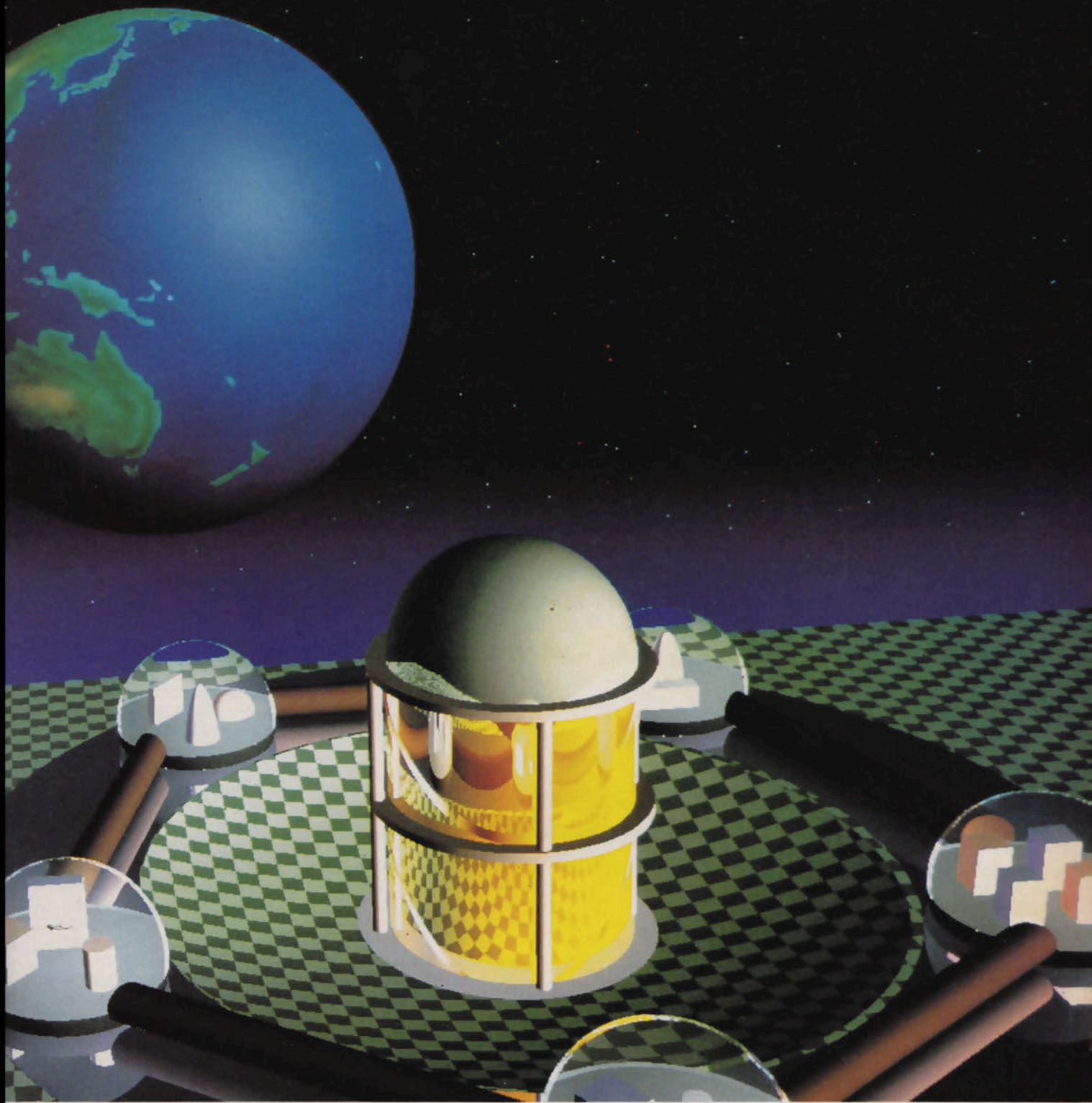
BY FRED HAPGOOD

*Meet the ultimate machine:
It's one cell large*

God, it was depressing. He'd driven hundreds of miles—from the bookstores and coffee shops of Cambridge, Massachusetts, to a cabin retreat in the wilderness of New Hampshire's great north woods. The reason for this pilgrimage: three days of brainstorming and the hope that he and his colleagues could explore man's final technological frontier. Fry had barely gotten out of

his car, though, when the conversation turned not to the nuts and bolts of this scientific revolution but to its effects: the importance of accidents when life span exceeds 500 years; the ability to monitor thoughts—*everyone's* thoughts—with molecular brain probes; flesh-eating robot hordes; the collapse of the economy we know today.

By the end of that workshop, Fry now



says, a few things were clear. "There were a lot of problems coming up fast over the horizon, and nobody was paying attention to them. We decided it was up to us to save the world."

Fry—not Dr. Fry, Albert Fry, George Fry, or even Aloysius Fry, just Fry—is a computer programmer at one of the several software houses around MIT's Tech Square, where the intense, highly

intellectual atmosphere is virtually indistinguishable from that of the university itself. When Fry speaks or listens a patina of sly humor glimmers over his face, giving him the air of a goblin. But behind his expression lies a fierce, eclectic curiosity. It was this that drew him, in the winter of 1985, to a series of MIT lectures on nanotechnology—designing and building incredibly

precise, infinitely varied machines one atom or molecule at a time.

The talks were given by K. Eric Drexler, then a research affiliate at MIT's Space Systems Lab. Drexler has a nervous affect, a shock of auburn hair, and conspicuously expressive eyebrows he has been told to keep under tighter control. His revolutionary ideas have caused some critics to say his bent for

science fiction is extreme. But when Fry heard him speak in the somber MIT auditorium that frigid January evening, he glimpsed a visionary whose ideas would catapult us, remarkably changed, into the twenty-first century.

Speaking before dozens of MIT students and professors, Drexler explained that the term *nanotechnology* is derived from the word *nanometer*—a billionth of a meter, or about ten times the diameter of a hydrogen atom. Nanotechnology is simply technology built on the atomic scale.

These days, Drexler said, machines and products are constructed with quadrillions of atoms at a whack. The clothing we wear, the jet planes we fly, even the minuscule integrated circuits that drive our computers are all thrown together in crude approximations of the absolute perfection achieved in the molecular realm. Indeed, at first glance the notion of building machines as fine-tuned as, say, a water molecule or a strip of DNA seems implausible. But this, Drexler declared, is exactly how most things on Earth are made. Almost every ounce of the huge weight of biomass that covers our planet is made of cells, and cells work by building structures one atom or molecule at a time. We fight off disease, for instance, when our immune system generates hundreds of different and wondrously complex molecules known as antibodies. If nature can do it, why can't we? "The first assumption of nanotechnology," Drexler insisted, "is that we can. Humans will soon be able to manipulate molecules as deftly as the living cell does."

Indeed, according to Drexler, an obvious application of nanotechnology is "the cell-repair machine," which would drastically extend our life spans and improve our general health. The remarkable devices "would enter tissues, identifying and destroying bacteria, viruses, cancer cells, parasites, blood clots, and deposits on bacterial walls." Once injected into the cells, the devices would subject DNA to error-checking tests far more exhaustive than those now imposed by the body itself. They could then repair whatever errors or anomalies they might find. If we wanted to replace a scar (laid down before cell-repair machines had been invented) with fresh tissue, Drexler added, it might be possible to do that, too. "Cell-repair machines," Drexler told his audience, "can be viewed as an upgrade of the biological processes already at work today."

But nanotechnology would not only improve upon the immune chemicals and DNA-repair enzymes laid down by nature. It would go *beyond* biology.

Consider, Drexler said, what a tiny fraction of the range of engineering ideas natural selection has chosen to adopt. The wheel, to pick a really basic example, hardly appears anywhere; neither do toothed gears, the block and tackle, or the screw and cam. Natural selection based the structure of life on just four elements—hydrogen, oxygen, nitrogen, and carbon—

instead of the 100-plus elements known to man. And living creatures make little use of the direct current associated with wires and electronics. Whatever electrical systems they *do* use seem easy to improve on. (Copper wire, for example, is *40 million times* more conductive than neural tissue.)

In light of all this, Drexler said, combining engineering concepts with the precision, durability, and blinding speed of molecules would revolutionize civilization. Suppose, for instance, that nanoengineers built rotary hammers just a few molecules long. We might use them to hit carbon atoms at just the right angle with just the right force—like a pool player putting a ball in the pocket—so that they formed diamond rods. Both man and nature now make diamonds in the imperfect form of lumps and grains. But perfectly regular, tight-knit diamond fibers would be ten times stronger than steel for each unit of weight, and their importance for the construction and aerospace industries would be incalculable. "To

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mention just one application," Drexler said, "space shuttles woven from these fibers would be so lightweight that the price of space travel would sink to that of air travel in general."

A whole *range* of molecularly perfect materials from plastics to metals would render structures lighter, stronger, and more durable than ever thought possible. But nanotechnology wouldn't just lead to *better* structures; it would also change our notion of just what a structure is.

"The members of many species of social insects—the army ants, for instance—sometimes group by the thousands to form artifacts like bridges and chambers and insulating blankets," Drexler explained. "These artifacts then serve the purposes of the colony as a whole. It is possible to imagine, given this model, a material composed of very large numbers of mobile units that could form any shape with any given color or texture: a raincoat, a bookcase, a bathtub, a bicycle. These mobile units would hold a particular shape until you told them what to turn into next."

Drexler even came up with the mechanism through which such chameleon

structures would work. "One would begin by designing the desired object on a computer," he said. The computer terminal would be connected to one of several trillion nanomachines, each perhaps as large as a bacterium. That first tiny machine would take on the shape dictated by the computer and then communicate the design to the machines surrounding it. "Each nanomachine might be connected to adjacent units through twitch cables just an atom thick," Drexler proposed. "These cables could twitch a billion times a second, propagating the design through millions of nanounits in no time at all."

Finally, Drexler proposed the controlling force behind all of nanotechnology: the nanocomputer itself. The nanocomputer, Drexler said, would work by clamping and unclamping one-atom-wide rods. Memory would be stored in long molecules. The presence or absence of certain chemical "side groups" along these atoms would represent the elements of a binary code. Such a machine, he thought, would have the power of the largest contemporary mainframe but would run about 100 times faster and occupy a thousandth the volume of a body cell. It would provide the intelligence for the nanomachines.

Sitting in the audience, Fry was drawn to Drexler's sweeping vision. He was captivated less by the *Twilight Zone* aspects of the talk than by the engineering challenge itself. "The point," he now says, "was to see just how large a fraction of contemporary engineering techniques might work in the molecular domain. All I had been thinking about was computers, and this seemed like an excuse to go beyond. So when I heard about Drexler's workshop in the north woods, I decided to go."

But despite Fry's desire to immerse himself in the nitty-gritty of the technology, Drexler had an agenda of his own. The difference was, Drexler had been thinking about nanotechnology for *years*.

Drexler dates his interest in molecular engineering back to 1976, when, as a graduate student in engineering (What sort of engineering? "Oh, generic engineering," he says), he decided to see what might be involved in building a biochemical computer. A biochemical computer would have to be built molecule by molecule, so Drexler took a few textbooks on molecular biology out of the MIT library.

Such texts are written by research scientists—organic chemists, molecular biologists, geneticists—whose goal is to understand how the cell works. Drexler, as an engineer, and a generic engineer at that, was impressed instead by the engineering versatility of the molecular realm. Atoms always perform to specifications. One atom can rotate around another for the lifetime of the universe without showing wear. They don't rust, rot, get dirty or wet, or indeed ever require any sort of maintenance. You can use them over a very wide range of combinations, circumstances, and time spans without altering their properties in

the least. The atomic constituents of a molecule will clasp each other with the exact same degree of force forever, assuming they are not blasted apart by a cosmic ray.

Further, atoms seem to *want* to make things; they snap together like Tinkertoys in highly defined, very stable structures. For a lot of molecular structures, once tab A and slot B get anywhere in each other's neighborhood, they will pounce and couple automatically. And the smaller things get, the faster they move, both because the accelerating impulse takes less time to travel from one edge to the other and because as parts shrink, they're better at resisting stress. A lever a few thousand atoms long, for instance, should be able to wave back and forth 50 million times a second without snapping. And the energy required would be minute.

Finally, when you build something atom by atom, you can build it right. Practically everything in our world, the macroworld, is shot through with impurities, dislocations, gaps, and cracks. When you get to specify the location of every atom, everything you build is just as good—just as strong, just as flexible—as theory allows. And the potential applications are limitless. If you work on that level you can build anything, because all anything is, ultimately, is just a particular arrangement of atoms.

"Atoms and molecules are the ultimate building components," Drexler now says.

"In 1976 this struck me as an awesome revelation. I'd found engineer's heaven."

Drexler's visionary gift, his ability to fathom the unimaginable in a leap of psyche and faith, blew him right out of his doctoral program and into his current career. Today, while supporting himself as a communications consultant in Palo Alto, California, he spends his free time publicizing nanotechnology's benefits and warning of its risks. He is essentially a combination Johnny Appleseed and Paul Revere. The MIT lecture that had intrigued Fry was delivered by the Appleseed side of Drexler—the fervent optimist spreading news of technical fruits to come. The recent New Hampshire retreat, convened to warn of nanotechnology's dangers, was led by a Cassandra, by Drexler/Revere.

"He took a large sheet of paper," Dave Forrest, an MIT graduate student in materials science, remembers, "and asked us to list fields of endeavor. Which we did: fashion, food, sculpture, architecture, war, communications, transportation, mining, religion, music, art, poetry, friendship, education, property rights, and on and on. Then he asked us which of the things on this list would *not* be affected by nanotechnology. Virtually everything we had named was going to get changed, usually a lot."

For instance, what are the likely social and economic consequences of construction material that can take on any shape or

form? In theory a consumer could buy a few hundred pounds of the stuff, and that would be it; all he'd need to buy thereafter would be designs (probably encoded in nanocomputer software) for his material to make. How would our economy deal with that? Our status hierarchy? How many of our ideas about interior space have to do with the need to maintain objects, like chairs, so that even while unused they are conveniently at hand? With a universal material, existence is defined by use: Something not being used, like a room with no one in it, will not need to be there at all.

And that's just the beginning. There is, for example, the horrifying instance in which damaged nanomachines go awry. Drexler calls these flawed machines "the gray goo." In the worst-case scenario of the gray-goo problem, lethal nanomachines will reproduce to infinity, and life on Earth will end.

To truly understand the gray-goo problem, Drexler adds, we must comprehend one of nanotechnology's greatest challenges: gearing up for mass production in the first place. Whatever nanotechnology's other advantages, it's obvious that just a single cycle of a molecular process does an incredibly small amount of work. Filling a glass of water at the rate of one water molecule a second, for instance, would take more than a billion years. This might seem like a strong argument against nanotechnology, but the problem can be dealt with:

Each day the biosphere, the aggregate of biological processes on the planet, makes hundreds of thousands of tons of biomass. Every gram is tooled out by molecular manufacturing.

Two strategies allow mass production to occur. The first strategy is hierarchical mass production: the mass production of factories, which then mass-produce products. An example of this is the body's ability to produce millions of cellular-energy factories known as mitochondria, which, over the course of a lifetime, generate molecular fuels that help the body work.

The second strategy—the hydrogen bomb of production technologies—is known as replication. In the process of replication, molecules (such as DNA) are programmed to assemble themselves and, ultimately, to reproduce. If a nanofaucet that released only one molecule of water a second could also replicate every 30 minutes, Drexler calculates, it and its progeny would fill a cup in less than two days and all the earth's oceans in less than three.

According to Drexler, most nanotechnology manufacturing facilities will come with replicability bundled in. This has several consequences. And over the three days of the retreat—walking under the great pine forest, talking over eggs at breakfast, murmuring at night from one mattress to the next—the young engineers and programmers worked them out.

Replicative cell-repair machines could generate enough units in a month to assess the health of every cell of every human alive. Replicative space probes, nibbling on asteroids and sunlight, would allow us to explore systematically every star system in the galaxy. Replicative waste processors, diffusing through the earth's crust and oceans, could search out every toxic-waste site and garbage dump in the world and detoxify anything remotely poisonous to any living thing. Replicative "miners" could inspect every cubic centimeter of the planet. And replicative nano-vacuum cleaners, programmed to gobble molecules of carbon dioxide, could—in just a few weeks—reverse the global warming trend that CO₂ will cause.

Replication would also lower the cost of manufacturing to almost nothing. A civilization that decided to buy one nanofarm—a device that could assemble any specific food [Beluga caviar, pumpernickel bread, potatoes Anna] out of sunlight, water, air, and dirt—would find thrown in at no extra cost enough food to feed everyone on or off the planet. That is fine as far as eliminating hunger goes. "But how on earth," Drexler the worrier asked, "could our economic system adjust to a manufacturing technology that destroyed the cost structure of whatever it made?"

He had concerns about the *political* ramifications, too. "Nanotechnology," he said, "would lead to surveillance technology par excellence." Tiny snoopers could follow us everywhere, even perch in our brains and look for suspicious neuron ac-

tivity. Crime could be eliminated entirely—and you don't have to be an anarchist to see what a mixed blessing that would be.

The nature of war, Drexler asserted, would change as well. Nations might try to steal one another's rare atoms, the only valuable resource left to fight over, by deploying huge fleets of concentrators through the soil. The targeted nations would presumably resist by building nanotech defense systems extending hundreds of miles down into the earth, leading to great battles deep in the lithosphere.

"We came up with a huge list of things," says Kevin Nelson, a Boston-area science educator who participated in the New Hampshire retreat. "The villains included insidious saboteur bacteria that would infect the industries of competing nations, making them slightly less efficient or more prone to breakdown; billions of replicating, flesh-eating locusts spreading over a battlefield; and behavior-modification units that would spread through the air, pass through the skin, and migrate to the brain."

But perhaps the most frightening aspect of nanotechnology was the gray goo. Suppose a little imperfection—perhaps a bug—were introduced by a terrorist at the time of manufacture. Such tampering could cause nanomachines to multiply until they had destroyed everything on Earth. "Nanoplants with leaves as efficient as solar cells could outcompete real plants, crowding the biosphere with an inedible foliage," Drexler said. "Tough, omnivorous nanobacteria could outcompete real bacteria, reducing the biosphere to dust in a matter of days."

"The people on this retreat were sober, sensible, and competent," Nelson says. "To see them all agree that this stuff was going to happen, that these problems had to be dealt with, was a powerful experience. It made it seem real."

At the end of the three days Fry put it best. "Eric," he said, "this is a terrible thing you've done, bringing us up here, telling us about all this. Now we have to do something about it."

What they did, of course, was form the Nanotechnology Study Group at MIT. The dozen or so members of the society sponsor lectures, maintain an archive of research materials, and meet twice a month to prepare for the nanorevolution to come.

And if Drexler's timetable is correct, that revolution will be here soon. "We should make the transition to the nanotechnological era in just twenty years," he says, "plus or minus ten."

We are, as an industrial society, just beginning to see benefits from such molecular technologies as genetic engineering and protein design, he says. Each new advance takes us closer to nanotechnology's goals: miniaturization and the ability to build things in the molecular realm.

Drexler is confident that progress will accelerate as each successful step down allows the construction of tools, especially research tools, to facilitate the next. "Faster

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CONTINUED FROM PAGE 62

computers will solve the engineering and design problems required to build even smaller, and therefore faster, machines. They'll also be able to simulate more complex molecular configurations, aiding advances in biotechnology. And advances in biotechnology will generate tools and enzyme probes that help researchers to understand and build ever more elaborate molecular systems," he says.

Much of the replication technology, he adds, is already in place. The molecular mechanisms installed in plants and animals might at first be used as major machine components. Genetically engineered bacteria could be used to make even more sophisticated components. In another approach high-precision fabrication tools can make the parts required to build smaller high-precision fabrication tools; and that cycle could be repeated again and again. It's even possible that minuscule needle-tip sensors, already used to "feel" surfaces at atomic resolution, can be adapted to assemble or cleave molecular machines directly.

"There's an important difference between the line of advance and the line of sight," Drexler says. "The line of sight is the most direct way of seeing that a destination exists. The line of advance is the path we will actually follow in crossing what may be a rugged, uncharted stretch. When we arrive and how we get there will depend on the underbrush and the lay of the land."

His line of sight remarkably clear, Drexler has begun to map the outback of nanoterrain. While supporting himself with various consultancies and research affiliations, he has been lecturing at forums as diverse as Mensa conferences, Naval Research Lab workshops, and meetings of the L-5 Society. He has written a few articles, and Doubleday has recently published his book *Engines of Creation*.

"I feel it's important for people to think about what will happen when nanotechnology exists," he says, "to rethink their worldview in that light."

How have things been going? "Pretty well," he says. "A lot of people have been coming around saying this makes sense."

Distinguished people, too. Freeman Dyson of the Institute for Advanced Study in Princeton, New Jersey, says that "if nature does this, we should be able to do it, too." And roboticist Marvin Minsky, Donner Professor of Science at MIT, says, "Nanotechnology could have more effect on our material existence than the replacement of sticks and stones by metals and cements, and the harnessing of electricity."

Others have responded—appropriately, perhaps—with caution. When Drexler laid out his design for a nanocomputer at Xerox's Palo Alto Research Center just recently, computer scientist Dan Russell said, "I found the theory plausible. But it

seems far off. Physics just starts to get weird at those scales."

A recent review of Drexler's book in *The New York Times* states that "it is one thing to refit a single protein and quite another to get millions of different types working together. If biology is indeed any measure, it will be a long time before scientists get nanotechnology humming. Consider that, while the earliest living cells probably had proteins much like some of our own, only after about two billion years of evolutionary trial and error did such nanomachines gather themselves into anything as complex as a nerve."

While many establishment scientists are low-key about Drexler's work, a group of younger devotees has taken his message and hit the ground running. Conrad Schneiker, a futurist and programmer at the University of Arizona, for instance, dreams of the day we combine nanotechnology with artificial intelligence. "Computers are already much faster than the human brain," he says, "and nanocomputers will be faster still. If you were to take a million such high-speed machines, which is a small population as far as nanotechnology goes, their thinking capacity would exceed in one hour that of all the scientists who have ever lived."

The members of the Nanotechnology Study Group at MIT have voyaged out even farther. After a speaker has been heard, new business disposed of, and the pizzas devoured, Fry, Kevin Nelson, Dave Forrest, and the others sit back and take the long view. Imagine, they say, what our bodies might be like if they'd been built right. Protein is fine as far as it goes, but it goes no distance at all. Everything—temperature, tensile stress, moisture, atmospheric pressure, ambient radiation intensity—has to be just so or the stuff will start to unravel, and even then its useful life is short. A creature built out of protein can live (without artificial aids) in only a fraction of natural environments, and not for long even in those. We cannot live unaided in volcanoes, on the bottom of the oceans, or in deep space.

Our brains are limited as well. One nerve cell communicates with a second through a surge of chemicals. Whatever the advantages of this system, it is necessarily slow, dependent on the diffusion of molecules through the gap between the cells. Suppose natural selection could have drawn on a more modern signal-propagation technology, like optical fibers; maybe today we would all think hundreds of times faster than we do. And suppose our muscles were made of diamond fibers; and our bones, of steel. Sooner or later, they say, we are going to transcend the flesh. Dave Lindburgh of the study group has likened that step to crawling out of the ocean all over again. That analogy, other members say, is the best we have; but it is, if anything, conservative. ☐

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