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The Nanotechnology Revolution

Adam Keiper

The English chemist John Dalton first proposed the scientific theory of the atom two hundred years ago. Since then we have seen chemists come to understand the elements and their interactions, we have seen engineers make and use new materials to improve our lives, we have seen physicists demonstrate that even atoms are divisible, and we have seen warriors unleash the power of the atomic nucleus. In these two centuries we have amassed an enormous understanding of—and wielded an increasing control over—the fundamental units of matter.

Today, in the young field of nanotechnology, scientists and engineers are taking control of atoms and molecules individually, manipulating them and putting them to use with an extraordinary degree of precision. Word of the promise of nanotechnology is spreading rapidly, and the air is thick with news of nanotech breakthroughs. Governments and businesses are investing billions of dollars in nanotechnology R&D, and political alliances and battle lines are starting to form. Public awareness of nanotech is clearly on the rise, too, partly because references to it are becoming more common in popular culture—with mentions in movies (like *The Hulk* and *The Tuxedo*), books (including last year's Michael Crichton bestseller, *Prey*), video games (such as the "Metal Gear Solid" series), and television (most notably in various incarnations of Star Trek).

Yet there remains a great deal of confusion about just what nanotechnology is, both among the ordinary people whose lives will be changed by the new science, and among the policymakers who wittingly or unwittingly will help steer its course. Unsurprisingly, some of the confusion is actually caused by the increased attention—sensationalistic reporting and creative license have done little to prepare society for the hard decisions that the development of nanotechnology will make necessary.

Much of the confusion, however, comes from the scientists and engineers themselves, because they apply the name "nanotechnology" to two different things—that is, to two distinct but related fields of research, one with the potential to improve today's world, the other with the potential to utterly remake or even destroy it. The meaning that nanotechnology holds for our future depends on which definition of the word "nanotechnology" pans out. Thus any understanding of the implications of nanotechnology must begin by sorting out its history and its strange dual meaning.

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Mainstream Nanotechnology

Nanotechnology got going in the second half of the twentieth century, although a few scientists had done related work earlier. For instance, as part of an 1871 thought experiment, the Scottish physicist James Clerk Maxwell imagined extremely tiny "demons" that could redirect atoms one at a time. And M.I.T. professor Arthur Robert von Hippel (born in 1898 and still alive today) became interested in molecular design as early as the 1930s; he coined the term "molecular engineering" in the 1960s.

Usually, though, the credit for inspiring nanotechnology goes to a lecture by Richard Phillips Feynman, a brilliant Caltech physicist who later won a Nobel Prize for "fundamental work in quantum electrodynamics." He is best remembered today for his clear and quirky classroom lectures and for his critical role on the presidential commission that investigated the *Challenger* accident. On the evening of December 29, 1959, Feynman delivered an after-dinner lecture at the annual meeting of the American Physical Society; in that talk, called "There's Plenty of Room at the Bottom," Feynman proposed work in a field "in which little has been done, but in which an enormous amount can be done in principle."

"What I want to talk about," Feynman said, "is the problem of manipulating and controlling things on a small scale. As soon as I mention this, people tell me about miniaturization, and how far it has progressed today … But that's nothing; that's the most primitive, halting step in the direction I intend to discuss."

Feynman described how the entire *Encyclopaedia Britannica* could be written on the head of a pin, and how all the world's books could fit in a pamphlet. Such remarkable reductions could be done as "a simple reproduction of the original pictures, engravings, and everything else on a small scale without loss of resolution." Yet it was possible to get smaller still: if you converted all the world's books into an efficient computer code instead of just reduced pictures, you could store "all the information that man has carefully accumulated in all the books in the world … in a cube of material one two-hundredth of an inch wide—which is the barest piece of dust that can be made out by the human eye. So there is *plenty* of room at the bottom! Don't tell me about microfilm!" He boldly declared that "the principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom"—in fact, Feynman saw atomic manipulation as inevitable, "a development which I think cannot be avoided."

In his lecture, Feynman pointed out several avenues for research that would later come to define nanotechnology, such as making computers much smaller and therefore faster, and making "mechanical surgeons" that could travel to trouble spots inside the body. Feynman admitted that he didn't have a clear conception of how such tiny machines might be used or created, but to help get things going, he offered two prizes: $1,000 to the first person to make a working electric motor that was no bigger than one sixty-fourth of an inch on any side, and another $1,000 to the first person to shrink a page of text to 1/25,000 its size—the dimension necessary to fit the *Encyclopaedia Britannica* on the head of a pin. (He awarded the former prize in 1960, the latter in 1985.)

Although Feynman's lecture is, in retrospect, remembered as a major event, it didn't make much of a splash in the world of science at the time. Research in the direction he suggested didn't begin immediately, and nanotechnology was slow to take off. Feynman himself didn't use the word "nanotechnology" in his lecture; in fact, the word didn't exist until 15 years later, when Norio Taniguchi of the Tokyo University of Science suggested it to describe technology that strives for precision at the level of about one nanometer.

A nanometer is one billionth of a meter. The prefix "nano-" comes from the Greek word *nanos*, meaning dwarf. (Scientists originally used the prefix just to indicate "very small," as in "nanoplankton," but it now means one-billionth, just as "milli-" means one-thousandth, and "micro-" means one-millionth.) If a nanometer were somehow magnified to appear as long as the nose on your face, then a red blood cell would appear the size of the Empire State Building, a human hair would be about two or three miles wide, one of your fingers would span the continental United States, and a normal person would be about as tall as six or seven planet Earths piled atop one another.

In 1981, scientists gained a sophisticated new tool powerful enough to allow them to see single atoms with unprecedented clarity. This device, the scanning tunneling microscope, uses a tiny electric current and a very fine needle to detect the height of individual atoms. The images taken with these microscopes look like tumulose alien landscapes—and researchers learned how to rearrange those landscapes, once they discovered that the scanning tunneling microscope could also be used to pick up, move, and precisely place atoms, one at a time. The first dramatic demonstration of this power came in 1990 when a team of IBM physicists revealed that they had, the year before, spelled out the letters "IBM" using 35 *individual atoms* of xenon. In 1991, the same research team built an "atomic switch," an important step in the development of nanoscale computing.

Another breakthrough came with the discovery of new shapes for molecules of carbon, the quintessential element of life. In 1985, researchers reported the discovery of the "buckyball," a lovely round molecule consisting of 60 carbon atoms. This led in turn to the 1991 discovery of a related molecular shape known as the "carbon nanotube"; these nanotubes are about 100 times stronger than steel but just a sixth of the weight, and they have unusual heat and conductivity characteristics that guarantee they will be important to high technology in the coming years.

But these exciting discoveries are the exception rather than the rule: most of what passes for nanotechnology nowadays is really just materials science.

Mainstream nanotechnology, as practiced by hundreds of companies, is merely the intellectual offspring of conventional chemical engineering and our new nanoscale powers. The basis of most research in mainstream nanotech is the fact that some materials have peculiar or useful properties when pulverized into nanoscale particles or otherwise rearranged.

Seen this way, mainstream nanotechnology isn't truly new; we've been unwitting nanotechnologists for centuries. One official from the National Science Foundation told Congress that photography, of all things, is a subset of nanotechnology—and a "relatively old" one at that! But if the term "nanotechnology" is to be used that loosely, why not reach much further back into history? Renaissance artists used paints and glazes that got their appealing color and iridescence from nanoparticles. The ancients, too, found uses for nanoparticles of soot. On and on it goes, back through the ages.

A great many of today's mainstream nanotechnologists are simply following in that tradition, using modern techniques to make tiny particles and then finding uses for them. Among the products that now incorporate nanoparticles are: some new paints and sunscreens, certain lines of stain- and water-repellent clothing, a few kinds of anti-reflective and anti-fogging glass, and some tennis equipment. Cosmetics companies are starting to use nanoparticles in their products, and pharmaceuticals companies are researching ways to improve drug delivery through nanotech. Within a few years, nanotechnology will most likely be available in self-cleaning windows and flat-screen TVs. Improvements in computing, energy, and medical diagnosis and treatment are likely as well.

In short, mainstream nanotechnology is an interesting field, with some impressive possibilities for improving our lives with better materials and tools. But that's just half the story: there's another side to nanotechnology, one that promises much more extreme, and perhaps dangerous, changes.

Molecular Manufacturing

This more radical form of nanotechnology originated in the mind of an M.I.T. undergraduate in the mid-1970s. Kim Eric Drexler was specializing in theories of space travel and space colonization in college when he first thought of using DNA to make computers. But why stop there? He soon realized that the biological "machinery" already responsible for the full diversity of life on Earth could be adapted to build nonliving products upon command. Molecule-sized machines, originally derived from those found in nature, could be used to manufacture just about anything man wished. *Anything.*

Drexler, who began to develop these theories before he'd heard of Feynman's lecture, first published his ideas in a 1981 journal article. Five years later, he brought the notion of molecular manufacturing to the general public with his book *Engines of Creation.* An astonishingly original work of futurism, *Engines* presented Drexler's nanotech theories and pointed out how nanotechnology would revolutionize other areas of science and technology—leading to breakthroughs in medicine, artificial intelligence, and the conquest of space.

At the heart of Drexler's vision for molecular manufacturing was a kind of nanomachine called an "assembler," which can "place atoms in almost any reasonable arrangement," thus allowing us to "build almost anything that the laws of nature allow to exist." It would take millions and millions of assemblers to make a product big enough for us to use—so in order for molecular manufacturing to work, assemblers must be capable of replicating themselves; as each "generation" of assemblers replicated itself, the overall number of assemblers would grow exponentially.

In one of the most striking passages of Drexler's book, he describes how molecular manufacturing could be used to build—to *grow*, really—a large rocket engine. Replicating assemblers would be pumped into a vat, and all the plans for the rocket engine would be stored on a single "seed." With the addition of fuel for the assemblers and raw materials for the construction, the engine would be completed in "less than a day" and would require "almost no human attention." The final product would be "a seamless thing, gemlike," light and strong—instead of a clunky, "massive piece of welded and bolted metal." If you wanted, you could "exploit nanotechnology more deeply" by building engines that repair themselves, or that "take different shapes under different operating conditions."

Drexler further imagined how nanotechnology could completely reshape everyday life. "It should be no great trick, for example, to make everything from dishes to carpets self-cleaning, and household air permanently fresh." Fresh food—"genuine meat, grain, vegetables, and so forth"—could be produced in the home. Suits made with nanotechnology could be used for virtual reality, simulating "most of the sights and sensations of an entire environment." And nanotechnology could make "some form" of telepathy "as possible as telephony."

Such powers seem like magic, a comparison that Drexler acknowledged: nanotechnology, he wrote, could make possible a device that "might aptly be called a 'genie machine.'" In a later book, he described in general terms how such a machine might be designed. Other writers, following in Drexler's footsteps, have imagined other grant-any-wish tools—like "utility fog," a theoretical swarm of tiny robots that could "simulate the physical existence of almost any object" and can thus "act as shelter, clothing, telephone, computer, and automobile." As envisioned by John Storrs Hall, the techie who dreamed the stuff up, the utility fog "that was your clothing becomes your bath water and then your bed."

Clearly, the Drexlerian notion of nanotechnology differs vastly from the nanotech products of today. Compare, for instance, how the two divergent visions of nanotechnology would differently affect one small aspect of human life: cosmetics. Mainstream nanotechnology will soon be used by cosmetics companies to help their current products—makeup, lotions, sunscreen, and so forth—last longer and work better. But if Drexler's version of nanotechnology were to come to fruition, the beauty industry would be revolutionized: nanomachines could precisely adjust your hair and skin color to your liking; wrinkles could be smoothed and excess fat removed; one writer suggests it would even

> become possible to mold the face and body to whatever shape might be desired. Each person who cared to could achieve his or her own ideal of physical perfection or, for that matter, whatever frightening or gruesome effect they wanted. Many who never liked their own youthful appearance will opt instead to copy some popular model or other sex symbol. It could become very confusing, with dozens of pop-idol look-alikes crowding the parks and boulevards of our future metropolis. Some may not relish the prospect, but we may never see the last of the Elvis clones.

So while mainstream nanotech gives you better eyeshadow, Drexler's nanotech gives you a whole new face—yet these two technologies of profoundly different potential share one name. "If research on waterproof fabric coatings is 'nanotechnology,' then the term has become almost meaningless," Drexler told *Wired News* in June. Drexler himself now talks about his kind of nanotech as "molecular nanotechnology" and "molecular manufacturing." Other names have been suggested, too: one observer has argued that Drexler should start using the ugly word "mechutechnology." But for most people, one umbrella term describes both the mainstream approach and Drexler's more radical vision.

But is Drexler's nanotechnology realistically possible? Will we truly be able to watch houses build themselves from the ground up, to transform garbage into steak, to populate the world with Elvis look-alikes? Drexler's book *Engines of Creation* is an extraordinary exercise in prolepsis: he meticulously refutes every technical objection he can anticipate. Will thermal vibrations make his molecular machines impossible? (No.) What about radiation? (No.) Quantum uncertainty? (No!) To shore up his technical arguments for the feasibility of his vision, he further expanded on his ideas in the world's first nanotechnology textbook. *Nanosystems* (1992), a dense volume that grew out of a class he taught at Stanford, is crammed with equations and diagrams and designs for molecular machines, and it has gone far to put Drexler's nanotechnology on sound technical footing.

To date, no scientist or engineer has been able to make a rock-solid argument showing the impossibility of molecular manufacturing as Drexler envisions it. A few critics have challenged Drexler on technical points, most prominently Richard Errett Smalley, the Rice University chemist who won a Nobel Prize for discovering the new class of carbon molecules that includes buckyballs and carbon nanotubes. In 1999, in written testimony to a congressional subcommittee, Smalley claimed that Drexler's version of nanotechnology is "just a dream" and "will always remain a fantasy" because "there are simple facts of nature that prevent it from ever becoming a reality."

When these claims were repeated in a 2001 article in *Scientific American* and again in public this year, Drexler and his allies responded with strongly worded public letters, accusing Smalley of basing his challenge on a straw man. Without getting into the technical details of the dispute, the essence of Drexler's response is devastating: If "atomically precise structures" are "fundamentally unfeasible, then so is life" itself, he wrote. Since enzymes and ribosomes and other molecular "machines" work in nature, man-made molecular machines should work, too.

Drexler and his supporters have made short shrift of other critics as well. Yet if no one has mounted a serious and sustained challenge to demonstrate a fatal flaw, or even a major error, in Drexler's vision of nanotechnology, why is it so often disparaged by those involved in mainstream nanotech? Molecular manufacturing has been called pseudoscience, science fiction, and unrealistic utopianism, and Eric Drexler himself has suffered repeated ad hominem attacks.

One reason for the animosity of the mainstreamers is their fear that Drexler's talk of the great boon and bane of nanotechnology will cast a pall over their own modest research—giving nanotech a reputation for being fantastical or hazardous.

A second explanation for why mainstream nanotech experts pooh-pooh Drexler is that they simply don't know what they're talking about. Drexler's kind of nanotechnology is so newfangled that it doesn't fit neatly into any single division of modern science or technology. (That fact actually caused difficulties when Drexler tried to obtain his Ph.D. at M.I.T.; he was eventually awarded an interdisciplinary degree—the world's first doctorate in nanotechnology.) It's difficult to find "appropriate critiques of nanotechnology designs," Drexler wrote in a 2001 article in *Scientific American*, since "many researchers whose work seems relevant are actually the wrong experts—they are excellent in their discipline but have little expertise in systems engineering. The shortage of molecular systems engineers will probably be a limiting factor in the speed with which nanotechnology can be developed."

No doubt some of the criticism of Drexler's nanotechnology is rooted in this important fact: nobody knows how to make the key component of his molecular manufacturing system, the assembler. Although Drexler and his supporters have come up with lots of designs for molecular machines and plans for how they would function, there still isn't any way to make them real. When someone figures out how to make the miniscule workhorses of molecular manufacturing—the critical moment of discovery that Drexler calls "the assembler breakthrough"—the rest may quickly fall into place, and the world could be transformed abruptly and forever.

Nanomedicine

Some people find Eric Drexler's vision of the nanotech future so compelling that they embrace it with religious fervor. This is not a new observation; a 1989 *Economist* article about Drexler spoke of his "gospel of nanotechnology." The 1995 book *Nano* by Ed Regis includes an entire chapter called "Brother Eric's Nanotech Revival," describing the sense of awe that Drexler's lectures would inspire in members of the audience: "There was a veiled feeling of being one of the Elect, the Select, the Knowledgeable, the Chosen."

A half-century ago, philosopher and technology critic Jacques Ellul argued that the rise of technology leads to the decline of traditional spirituality, as man transfers "his sense of the sacred … to technique itself." We develop a "worship of technique," Ellul said, and we associate our technology with a "feeling of the sacred." Drexler's nanotechnology is perfectly suited to arouse religious enthusiasm. It involves incredible, invisible powers. The all-important "assembler breakthrough" is akin to a Second Coming or a Judgment Day. And there's even an afterlife: cryonics.

Nanotechnology is especially appealing to those in the growing ranks of what Charles T. Rubin, in the previous issue of this journal, usefully dubbed the "extinctionist project": the transhumanists, posthumanists, extropians, and others who seek to completely remake human nature. Nanotechnology is central to their vision of a future of agelessness, immortality, and rebirth.

They place their hopes in nanomedicine, a field that would repair or improve the body from the inside out, with a precision and delicacy far greater than that of the finest surgical instruments available today. Science fiction envisioned tiny internal medical procedures long ago; in the 1966 movie *Fantastic Voyage*, a medical staff boards an experimental submarine which is then drastically miniaturized and injected into a patient in order to destroy a deadly blood clot. Of course, miniaturizing humans is preposterous, but in the 1960s it was hard to imagine any other way to make tiny machines *intelligent* enough to reach and repair damage inside the body. But nanomachines are certainly small enough, and with programmed instructions, they can be smart, too.

The world's leading expert on nanomedicine is Robert A. Freitas, Jr., a polymath with a law degree who worked on numerous space-related projects before becoming involved in nanotechnology. Currently employed as a researcher at the nanotech firm Zyvex, he is one of only a handful of people who can claim to have made major theoretical contributions to Drexlerian nanotechnology.

Freitas is currently several years into the writing of an exhaustive four-volume series called *Nanomedicine*, the first technical work on the subject. In the first massive volume (published in 1999), he offers technical speculations on how nanorobots might navigate, sense their surroundings, and move through the body; how they might detect problems and communicate with one another; and how they might change shape and obtain energy. The second volume of *Nanomedicine*, due out this year, will examine "biocompatibility"—how nanorobots might interact with the body, especially the immune system.

Many of the tools of nanomedicine could be used for either therapy or enhancement. Take, for example, the "respirocyte," an artificial red blood cell about which Freitas has theorized. Respirocytes, capable of delivering oxygen hundreds of times more efficiently than real red blood cells, would be invaluable in the treatment of various respiratory and cardiovascular disorders, or as a substitute for real blood during transfusions. But they would also have "a variety of sports, veterinary, battlefield and other applications"; they could be used to boost a mountain climber's endurance, to help a diver hold his breath for hours, or to enable a soldier to fight harder.

And the respirocyte is among the simplest medical nanomachines imaginable. Others might be able to repair cells and fix damaged DNA; to remove toxins, clean out cholesterol, and eliminate scar tissue; to destroy cancer cells and fight countless diseases. And the same nanotechnology that keeps your body healthy can indefinitely stave off senescence. The process of aging, Drexler argued in *Engines of Creation*, is "fundamentally no different from any other physical disorder," so cell repairing nanomachines should, in theory, be able to halt aging or reverse it. You can pick the age you want to be—in fact, you can play mix and match: give yourself the distinguished hairline of a fifty-year-old, the sturdy frame of a thirty-year-old, the lusty libido of a twenty-year-old, and the keen eyesight of a ten-year-old.

Even the Grim Reaper is in for tough times: Death may already be "slave to Fate, Chance, kings, and desperate men," but in the age of nanotechnology, Death will increasingly obey the whims of Tom, Dick, and Harry, too. Molecular machines will bridge the gap between living matter and nonliving matter, making the border between life and death much fuzzier. In the age of nanotechnology, a person might intentionally put himself into stasis, perhaps to "time travel" dreamlessly into the future, or to wait out a centuries-long interstellar voyage. Even today, hundreds of people of sufficient means are making plans to freeze themselves in hopes that nanotech will someday restore them; these people are willing to shell out big bucks to cryonics companies that promise to preserve their corpses, or some meaningful fraction thereof, until the prospect of reanimation becomes realistic.

There are, however, some foreseeable limits to nanomedicine. While nanomachines might one day be able to restore and maintain the body, there is no guarantee that they'll be able to keep the *mind* intact. Some brain damage can be physically fixed, but lost memories and personality—the brain's software (figuratively speaking)—will be irretrievable. If bits of your mind are lost, "repair machines could no more restore them than art conservators could restore a tapestry from stirred ash," as Drexler has said. But of course many of those engaged in the extinctionist project have a solution in the works: they seek to reduce the mind to software (literally) so the contents of your brain can be as downloadable and fungible tomorrow as digital video and music are today.

How Soon?

Estimates on how long we have to wait for major breakthroughs in nanotechnology vary greatly. Robert Freitas told one interviewer that the kind of nanomedicine he envisions is "at least 10 to 20 years away"; in a different interview he put the number at 40 years. Another nanotech expert says molecular manufacturing is 20 or 30 years away. We'll have to wait at least ten years before we can ride in "superintelligent" airplanes enhanced with nanotechnology, according to a Boeing executive. An all-purpose nanotech entertainment system could "arrive on the scene around the year 2020," according to one writer. The British Ministry of Defense says nanotech won't hit its stride any earlier than 20 or 30 years from now, but a Canadian expert says it will start to dramatically change our lives in the next 10 to 20 years. Ray Kurzweil, the technologist, predicts in his book *The Age of Spiritual Machines* that nanotech will be used in manufacturing by 2019—and that by 2049, smart swarms and nanotech food will be feasible. The U.S. government projects that the worldwide nanotechnology market will exceed $1 trillion by 2015, although one group opposed to nanotechnology puts it more ominously: by 2015, the controllers of nanotechnology "will be the ruling force in the world economy."

While there have been a few indications of progress in nanotechnology in the past two or three years, the present booming interest in all things "nano" is bound to quicken the pace of discovery. In the U.S., so many states are subsidizing nanotech research that a *New York Times* reporter whose job was to read governors' "State of the State" speeches in 2001 found herself asking: "Are there enough nanotechnological researchers to go around?" Governments in Europe and Asia are also putting money into nanotech, including Switzerland, Germany, Britain, China—and even Iran.

Businesses around the world are spending heavily on mainstream nanotech, pouring more than $3 billion into nanotech R&D this year alone, according to one estimate. A recent survey showed that "13 of the top 30 Dow component companies discuss nanotechnology on their websites." But all the nanotech buzz is destined to attract con artists and frauds, too. Some companies doing work completely unrelated to nanotechnology have incorporated "nano" into their names, in hopes of getting money from gullible investors caught up in the hype. And earlier this year, a major conference on nanotech was canceled under mysterious circumstances; it now appears that the whole thing was a scam to get money from the attendees.

If anything is likely to dampen the nanotech boom, it is the prospect of regulation. In the past year, mainstream nanotech has suddenly come under scrutiny from researchers and activists worried that nanoparticles could endanger public health or harm the environment. So far, there has been very little precautionary research on the safety of nanoparticles; indeed, when Rice University's Center for Biological and Environmental Nanotechnology conducted a survey of the scientific literature relating to nanoparticles—"a field with more than 12,000 citations a year"—they found *no* documented research on the risks of nanoparticles. Vicki L. Colvin, the Center's director, told Congress last April that the safety of nanoparticles should be determined through immediate and thorough tests. "From asbestos to DDT we have, as a society, paid an enormous price for not evaluating toxicological and ecosystem impacts before industries develop," she said. Her organization has started investigating nanoparticle safety, and in July the main U.S. lobbying group for the nanotechnology industry (the NanoBusiness Alliance) announced that it, too, would start studying the health and environmental safety of nanoparticles. Similar inquiries have begun in Britain and the European Union.

Beyond the Gray Goo

The health and environmental threats posed by mainstream nanotech are far less frightening than the hypothetical dangers of the Drexlerian flavor of nanotech. In an infamous article in *Wired* magazine in 2000, technologist Bill Joy made the case for halting nano-research because of the possibility that we might wipe out all life on Earth. Joy's article stirred up a hornet's nest of controversy, even though the idea had been around for a long time: the apocalypse he described was based on a theory that had first been suggested more than a decade earlier in *Engines of Creation.*

For molecular manufacturing to work, Drexler's assemblers would have to replicate themselves, just as tiny organisms make duplicates of themselves. But what if something went wrong—what if the replication spiraled out of control? Speed-breeding assemblers could devour all life on Earth in short order. According to *Engines of Creation*, "among the cognoscenti of nanotechnology"—presumably meaning the author and his friends—"this threat has become known as the 'gray goo problem'":

> Though masses of uncontrolled replicators need not be gray or gooey, the term "gray goo" emphasizes that replicators able to obliterate life might be less inspiring than a single species of crabgrass. They might be "superior" in an evolutionary sense … The gray goo threat makes one thing perfectly clear: we cannot afford certain kinds of accidents with replicating assemblers. Gray goo would surely be a depressing ending to our human adventure on Earth, far worse than mere fire or ice, and one that could stem from a simple labora-

> tory accident … We must not let a single replicating assembler of the wrong kind be loosed on an unprepared world.

In time, Drexler backed away from the gray goo scenario, reasoning that no one would design a self-replicating assembler capable of surviving in nature. "Consider cars," he wrote in 1990. "To work, they require gasoline, oil, brake fluid, and so forth. No mere accident could enable a car to forage in the wild and refuel from tree sap … It would be likewise with simple replicators designed to work in vats of assembler fluid"—no right-minded engineer would create replicators that could exist in the wild.

But a terrorist might. Or an enemy nation. Biosphere-destroying self-replicators may not arise as the result of an inadvertent scientific slip-up, but they might be designed intentionally by those seeking to bring destruction or wreak havoc.

In the wake of Bill Joy's screed and the gray goo frenzy it inspired, Robert Freitas, the nanomedicine expert, wrote the first serious, technical analysis of the gray goo scenario. His paper—to which he gave the whimsical title "Some Limits to Global Ecophagy by Biovorous Nanoreplicators, with Public Policy Recommendations"—made estimates and calculations relating to the speed of replication and the rate of dispersal of self-replicators in the wild. If certain unlikely conditions are arranged just right, it is theoretically possible, Freitas found, for self-replicators to destroy the planet's entire biosphere in under three hours—but such a high-speed attack would instantly cause a massive spike in temperature, alerting authorities to the situation and allowing them to respond. Conversely, it is theoretically possible for biosphere-eating self-replicators to create an almost undetectably small increase in temperature—but then it would take them twenty months to complete their task, leaving plenty of time to observe the destruction and organize a defense.

Instead of going through all the trouble of designing self-replicators that could eat everything, why not design some that could make a more focused attack? "The classic example," Freitas says, "is tire rubber and asphalt tar binder; cars, trucks and airplanes roll on roads and tarmacs worldwide." Imagine the damage to the global economy if all the world's roads became soup overnight. "Other vectors with similar properties include cotton, polyester or other uniform textiles, insulation on electrical wiring, and paper money."

And though Freitas doesn't say as much, it seems possible that self-replicating nanobots could be designed to target and destroy a specific species. Perhaps they could be tailored to attack only humans—or just specific groups of humans, or just a specific individual. Nanoweapons could be smarter than conventional biological weapons, with a more precise lethality and potential to cause diseases unlike any seen before. What's more, nanotechnology could also be used to aid in the manufacture and targeting of conventional bioweapons. (There has also been some recent speculation that nanotechnology could be combined with nuclear weaponry. Analysts at the Acronym Institute for Disarmament Diplomacy and *Jane's Chem-Bio Web* have theorized that nanotechnology could play a part in the creation of so-called "fourth-generation" nukes with small, low-yield warheads. But they apparently confuse nanotechnology with microtechnology, and they make confusing and contradictory assumptions about how the technologies needed to enable fourth-generation nukes will evolve.)

Aside from nanotech's potential as a weapon of mass destruction, it could also make possible totally novel forms of violence and oppression. Nanotechnology could theoretically be used to make mind-control systems, invisible and mobile eavesdropping devices, or unimaginably horrific tools of torture. Yes, it's true that defensive applications of nanotechnology would develop alongside offensive ones, but that hardly mitigates the potential for enormities and catastrophes.

To save the world, Bill Joy argues that we must relinquish our pursuit of nanotech knowledge. He recommends international treaties and a verification regime. But that would be exceedingly difficult, since nanotechnology isn't just a science of the small, it's also a *small science*: it doesn't require giant equipment or big laboratories or gigantic budgets, and most of the work is conducted in small labs distributed around the world rather than in a few centralized behemoth facilities. Scientists wishing to hide their nanotech research programs could easily disguise them as other projects in chemistry or physics. The allure of nanotechnology is so great that relinquishment could only work if it were enforced through "detailed, universal policing on a totalitarian scale," as Eric Drexler has worried, or if some horrible nanotech-related disaster shocked the world into giving up on nano.

No callow cheerleader for the nanotech revolution, Drexler in 1986 co-founded the Foresight Institute, a California-based nonprofit organization "formed to help prepare society for anticipated advanced technologies," especially nanotechnology. Among the Institute's projects is a set of proposed "Foresight Guidelines on Molecular Nanotechnology," first drafted in 1999. The guidelines forbid the creation of nanobots capable of "replication in a natural, uncontrolled environment," and provide several other principles for nanotechnologists. According to the Foresight website, the Guidelines "might eventually be enforced via a variety of means, possibly including lab certifications, randomized open inspections, professional society guidelines and peer pressure, insurance requirements and policies, stiff legal and economic penalties for violations, and other sanctions."

The Politics of Nanotech

So far, no nanotech businesses have adopted the Foresight Guidelines—after all, most firms are working on mainstream nanotech, not the riskier kind. Besides, nanotech companies have no motivation to regulate themselves, since it seems unlikely that they will be regulated by government any time soon. But this may change as the politics of nanotechnology begin to take shape.

Some agencies in the federal government have been involved in nanotechnology since at least the early 1980s, most notably the U.S. Naval Research Laboratory. By 1997, the federal government was annually investing $116 million in nanotech; that figure had doubled by 1999.

In 2000, the Clinton Administration pushed for more subsidies for nanotech and the creation of a National Nanotechnology Initiative (NNI) that would coordinate the nanotech work of six different agencies. President Clinton alluded to nanotechnology in that January's State of the Union Address, when he spoke of "materials ten times stronger than steel at a fraction of the weight, and—this is unbelievable to me—molecular computers the size of a teardrop with the power of today's fastest supercomputers." His administration worked hard to sell the proposal to Congress; as one official from the Clinton White House told *Scientific American*, "You need to come up with new, exciting, cutting-edge, at-the-frontier things in order to convince the budget- and policy-making apparatus to give you more money."

Congress couldn't resist, and the NNI was approved with an initial budget of $422 million. President Bush, in the first year of his administration, asked for another hundred million dollars for nanotech, and added another handful of agencies to the NNI. Bush's budget proposals for FY2003 and FY2004 further boosted the nanotech budget—despite the flagging economy and the war on terrorism. (In fact, some NNI proponents have used the war on terrorism to make the case for increasing nanotech funding; they say nanotech research can help build tools to detect weapons of mass destruction.)

Flush with nanotech cash, the National Science Foundation recently started a program to teach high school and elementary school students about nanotechnology, "with introduction to preliminary concepts as early as kindergarten," according to the *Christian Science Monitor*. "Business, industry, and higher-education leaders agree, saying early education gives students a jump on a job market many expect to blossom in the future."

Perhaps the most prominent federal entity under the NNI umbrella is the Department of Defense, which in May unveiled its new $50 million Institute for Soldier Nanotechnologies at M.I.T. The Institute, which treats soldiers as "integrated platform systems" rather than human beings, will bring together M.I.T. scientists, military officers, and researchers from private industry to develop lighter, stronger clothes and equipment for the Army. Some of the projects being suggested include an "exoskeleton" or "dynamic armor," which could become hard or soft at a soldier's command, and other clothes that could store energy—like the energy wasted in every footstep—and employ it later to give the soldier superhuman strength. All the technologies being developed at the Institute—like all other nanotech projects publicly acknowledged by the Defense Department—are essentially defensive, not offensive, in nature, so they are unlikely to incite opposition.

At the same time, because the benefits of nanotechnology are still largely uncertain, there is not yet a natural constituency for nanotech legislation—except for the nanotech companies themselves. They are represented by the New York-based NanoBusiness Alliance, a trade group founded in 2001 by F. Mark Modzelewski, who acts as the Alliance's executive director. Modzelewski, who modeled his group after the Biotechnology Industry Organization, was a low-ranking official in the Clinton Administration—which hasn't stopped him from making Newt Gingrich, that starry-eyed technophile, the Alliance's honorary chairman. Gingrich told the *Forbes/Wolfe Nanotech Report* that he believes that "those countries that master the process of nanoscale manufacturing and engineering will have a huge job boom over the next twenty years, just like aviation and computing companies in the last forty years, and just as railroad, steam engine and textile companies were decisive in the nineteenth century."

Since the politics of nanotechnology are still immature, there is no prominent opponent of nanotechnology in the nation's capital or even a unifying rationale for such opposition. The most organized opposition to nanotechnology has come from the ETC Group, a liberal Canadian environmental outfit that has published a series of harshly critical reports on nanotechnology—some of them detailed and provocative. In late July, Greenpeace issued its first report on nanotechnology, with ambiguous conclusions. A few other environmentalist groups have spoken out against nanotechnology, but there hasn't yet been any movement comparable to the massive international campaigns against genetically modified foods. It is safe to speculate that these leftist groups will in time coalesce into an anti-nanotech front, using the rhetoric of anti-corporatism and environmental extremism to make their case. They will likely be opposed by the techno-libertarian and patient advocacy groups who presently support human cloning and embryonic stem cell research, and by the mainstream political establishment, at both the national and state levels, which sees nanotech as a way to boost the economy.

Just as there is no prominent figure in Washington arguing against nanotechnology, there is currently no prominent advocate of Eric Drexler's radical vision of nanotechnology. The closest thing to such an advocate may be Glenn Harlan Reynolds, a law professor from the University of Tennessee, whose Instapundit website and online columns are read by many Washingtonians. Reynolds frequently discusses nanotechnology, and when he does, he openly supports Drexler's ideas. (He also serves on the board of the Foresight Institute.) Reynolds is one of the few writers who understands both the workings of government and the basic theories of nanotechnology, which makes him useful to readers in the nation's capital.

If still unformed, however, there is reason to believe that public debate about nanotech is about to take off—with two new nanotech organizations founded in just the past year. The Center for Responsible Nanotechnology, run by a social activist and a nanosystems theorist, has been cranking out publications since January. "What we want," says Chris Phoenix, one of the Center's founders, "is to see molecular nanotechnology policy developed and implemented with a care appropriate to its powerful and probably transformative nature." And two Washingtonians—a futurist and an antitrust lawyer—are in the process of launching the Nanotechnology Policy Forum to improve the quality of public discourse about nanotech. They intend to host events every few months, and to stay scrupulously evenhanded: the advisory panel planned for the organization will include both friends and foes of nanotech—as well as present and former congressmen.

Congress also seems slightly more attuned to the need for debate about nanotechnology. Plans are afoot in both the House and the Senate to fund studies of the social, economic, and environmental implications of nanotechnology.

Also, legislation currently wending its way through Congress would establish "grand challenges" for nanotechnology: long-term objectives akin to President Kennedy's goal of putting a man on the Moon. While it isn't at all clear at this stage that nanotechnology can capture the imagination of the public like the Moon missions did, there is one obvious goal that would make an excellent "grand challenge"—a goal presently overlooked in all the millions of federal dollars going to nanotech: the assembler breakthrough. And just as the Apollo missions to the Moon were preceded by missions with incremental goals (achieved by the Mercury and Gemini programs), an ambitious nanotechnology project aspiring to make the world's first assembler could also set intermediate goals, like the creation of a basic nanoscale computer or a nanoscale robotic arm. But the National Nanotechnology Initiative is so focused on developing mainstream nanotech that Drexler's nanotechnology has found neither a great advocate nor a great critic.

The Challenge Ahead

One Congressman, speaking on the House floor on May 7 of this year, said that nanotechnology may "create levels of intelligence that may be our protector, may be our competitor, or may simply regard us as pets. Or it may change our definition of what it is to be a human being." He said this with no indication of outrage or regret; he didn't rail against the prospect of a posthuman future; he expressed no aversion to life as a pet. Instead, he said that we need to talk about these issues, "to see how we can deal" with them, and to "get input from a wide range of society."

One proposal now under consideration is to create an advisory committee of "nonscientific and nontechnical" Americans to make recommendations about nanotechnology. This provision was inspired by the testimony of technology critic Langdon Winner before a House committee in April. "Congress should seek to create ways in which small panels of ordinary, disinterested citizens, selected in much the same way that we now choose juries in cases of law, [could] be assembled to examine important societal issues about nanotechnology," Winner said. The panels would listen to news and arguments, "deliberate on their findings, and write reports offering policy advice."

This sort of citizen panel would admittedly be an excellent gesture, a symbol of the fact that technological progress doesn't take place in a vacuum—that science and technology affect society as a whole and must remain subject to political oversight. But if the goal is really to inform the public and to get ordinary citizens to think about the implications of nanotechnology, a few citizen panels writing obscure reports won't have much effect. Nanotechnology education is most needed in newsrooms across the country and in the halls of the Capitol itself: We need reporters who know what they're talking about and who ask the right questions, and we need political leaders who can guide us through the confusing and potentially perilous times ahead.

This much seems clear: If molecular nanotechnology ever becomes a reality, we can expect massive social disruptions. As for the nature of these disruptions, we can, at best, only speculate.

First, we will hear complaints that the benefits of the new technology aren't being shared equitably; that the poor are being left out. But that problem will quickly fade away, as usually happens in our innovative market economy. (Think of the notorious "digital divide" of the 1990s, for instance; it's now all but gone.)

Second, we will reorganize our society and economy, shifting workers, eliminating jobs, and completely restructuring entire industries. We will hear questions about how our character will change: Will the abundance made possible by molecular manufacturing cause us to slip into hedonistic excess? Or might it have the reverse effect, making us *less* materialistic? Will life become so easy for us that it loses all meaning, or is it in our nature to keep seeking new challenges? (These questions may be as groundless as the "Leisure Question" that had social scientists wringing their hands a few decades ago, worrying about what we would do with all our free time in the age of automation and computers.)

Third, we will have to confront the "extinctionist" challenge and decide who we are. Nanotechnology raises many of the same ethical issues as biotechnology, and indeed the two techniques overlap. How much will we tinker with and revise our bodies? Will we choose a future as men or machines? Will we be able to use nanotechnology without drowning in nanotechnology, losing ourselves in nanotechnology, *becoming* nanotechnology?

And finally, we will be charged with rethinking our place in the universe. Our new powers of precision and perfection could lead us to a deeper appreciation for life—or they could make us lose all respect for the imperfect world we inhabit and the imperfect beings we have always been. The era of nanotechnology may be one of hubris and overreach, where we use our godlike powers to make the world anew. Is there room for wonder in a future where atoms march at our command?

Public debate about these matters will surely stay much lower to the ground—with arguments about where best to invest nanotech resources or about the quantifiable dangers of nanotechnology to the health and well-being of man and nature. Those who care about the deeper questions—about what nanotechnology means for human nature—must also master the details, both political and scientific. And they must offer not only lamentations for the disruptions and dehumanization that nanotechnology might cause, but a sensible vision of how nanotechnology might do some practical good—or even stir the very wonder that could be diminished by rearranging the smallest parts without seeing the whole.