6-2001 31 ELR 10681

ELR
NEWS & ANALYSIS

Environmental Regulation of Nanotechnology: Some Preliminary Observations

by Glenn Harlan Reynolds

The relationship between new technologies and the environment is a complex one. On the one hand, various human technologies—ranging from "low" technologies like slash-and-burn agriculture, to "high" technologies like nuclear weapons—have done more than their share of environmental harm. On the other hand, new technologies are often cleaner and safer than the older technologies they replace, and may offer ways of remedying environmental harms previously thought of as beyond help.

Both of these aspects are likely to come into play with molecular nanotechnology, a technology so new that, in truth, it barely exists yet. But though the actual accomplishments of nanotechnology at this date fall into the workbench or proof-of-concept stage, research is progressing at a speed that outpaces the predictions of the most optimistic prognosticators.[1] (Indeed, nanotechnology has received so much attention—not all of it positive[2]—that some are already pronouncing it a cliché.)[3] If researchers continue to make progress at this rate, nanotechnology will hit the marketplace more quickly than did biotechnology, a field of endeavor to which society is still adjusting. It thus seems worthwhile to begin the discussion now.

This all-too-brief essay will outline the basic nature of molecular nanotechnology. It will then discuss the likely environmental benefits (environmentalist Terence McKenna, writing in the *Whole Earth Review*, called nanotechnology "the most radical of the green visions")[4] and harms (some critics worry that rogue nanodevices will devour the planet)[5] of this technology, and at least seek to begin the discussion of how nanotechnology might be dealt with in a way that will maximize the environmental benefits—which are likely to be enormous—while minimizing the potential harms, which, if allowed to materialize, are likely to be large as well.

The Science and Technology of Nanotechnology

How Nanotechnology Works

Put simply, nanotechnology is a technology for making things by placing atoms precisely where they are supposed to go. Traditional industrial technologies operate from the top down. Blocks or chunks of raw material are cast, sawed, or machined into precisely formed products by removing unwanted matter. Results of such processes may be rather small (integrated circuits with structures measured in microns, for example) or very large (ocean liners or jumbo jets). However, in all cases matter is being processed in chunks far larger than molecular scale.[6]

We are used to this kind of top-down technology, and it is certainly capable of yielding products of fairly high precision and complexity. It is the basis of our civilization, and it has brought us the many technological revolutions described above. It is, however, something of an aberration in the natural order of things, as most products of living organisms—and those organisms themselves—are made very differently.

Rather than being produced through large chunks of material being sawed, planed, and ground to form, most such objects are constructed by tiny molecular machines, such as cells and organelles, working from the bottom up. By organizing individual atoms and molecules into particular configurations, these molecular machines are able to create works of astonishing complexity and size, such as the human brain, a coral reef, or a redwood tree.[7] This approach can produce results that would seem impossible if judged by the standards of conventional top-down production technology, but that are taken for granted in their proper context. For example, the human body begins as a single cell, a fertilized ovum. Yet a mature human being consists of approximately 75 trillion cells, complexly arranged and of many different varieties.[8] The molecular machinery responsible for this amazing, though commonplace, feat of production

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1. *See, e.g.*, Kelly Morris, *Macrodoctor, Come Meet the Nanodoctors*, 357 Lancet 778 (2001) (describing progress in medical nanotechnology); *Researchers Assemble Molecular Gear: University of Tokyo Team Scores First by Building Functional Nanodevice*, Nikkei Wkly., Mar. 19, 2001 (n.p.); Fiona Harvey, *Toughened by Nanotechnology*, Fin. Times, Mar. 15, 2001, at 14. For an extensive overview of medical nanotechnology, see Robert A. Freitas Jr., Nanomedicine Volume One: Basic Capabilities (1999).
2. Nanotechnology has already been denounced by antitechnology activists like Jeremy Rifkin and Kirkpatrick Sale. Ronald Bailey, *Rebels Against the Future: Witnessing the Birth of the Global Antitechnology Movement*, Reason Online, Feb. 28, 2001, *at* http://reason.com/rb/rb022801.html.
3. Gail Collins, *Bring on the Nanobots*, N.Y. Times, Jan. 16, 2001, at A23.
4. *Quoted in* K. Eric Drexler et al., Unbounding the Future 182 (1991).
5. *See infra* note 29 and accompanying text.
6. K. Eric Drexler, *Nanotechnology Summary*, *in* 1990 Encyclopedia Britannica Science and the Future Yearbook 162, 163-67 (describing top-down and bottom-up approaches).
7. *Id.* at 175.
8. Arthur Guyton, Textbook of Medical Physiology 2 (1986).

is capable of such dramatic results because it performs operations in parallel (that is, with many cells operating at the same time through most of the growth process), and from the bottom up.

As Eric Drexler states:

> Nature shows that molecules can serve as machines because living things work by means of such machinery. Enzymes are molecular machines that make, break, and rearrange the bonds holding other molecules together. Muscles are driven by molecular machines that haul fibers past one another. DNA serves as a data-storage system, transmitting digital instructions to molecular machines, the ribosomes, that manufacture protein molecules. And these protein molecules, in turn, make up most of the molecular machinery just described.[9]

Putting these natural molecular machines to work is nothing new, of course, as every living thing does so constantly. Nor is deliberate human programming of those machines particularly new, as it is what genetic engineering (or even selective breeding) is all about.[10] What makes nanotechnology different is that it involves the attempt to go farther than natural mechanisms permit. Using special bacterium-sized "assembler" devices, nanotechnology would permit exact control of molecular structures that are not readily manipulable by organic means (diamond, or heavy metals, for example) on a programmable basis.[11]

With nanotechnology, atoms will be specifically placed and connected, all at very rapid rates, in a fashion similar to processes found in living organisms. Trees, mammals, and far less complex organisms make use of molecular machinery to manufacture and undertake repairs at a cellular and subcellular level. The key to the application of nanotechnology will be the development of processes that control placement of individual atoms to form products of great complexity at extremely small scale.[12]

This approach was originally suggested by physicist Richard Feynman. In an article entitled *There's Plenty of Room at the Bottom*, Feynman explored the potential of atomic-scale physical manipulation of matter. As Feynman said:

> The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. [I]t would be, in principle, possible . . . for a physicist to synthesize any chemical substance that the chemist writes down. . . . How? Put the atoms down where the chemist says, and so you make the substance. The problems of chemistry and biology can be greatly helped if our ability to see what we are doing, and to do things on an atomic level, is ultimately developed—a development which I think cannot be avoided.[13]

Scientists and researchers are making progress in this direction today. Already, IBM's research division has demonstrated the ability to manipulate individual atoms by constructing a copy of IBM's logo out of individual xenon atoms, manipulated by the tip of an atomic force microscope.[14] The next step, the precise placement of atoms in combination to form stable compounds,[15] and structures, has also been achieved.[16]

Such efforts have already generated a substantial amount of theoretical literature, and considerable concrete interest. Nanotechnology has already produced a number of books and articles,[17] government reports,[18] and at least one well-established and well-funded research program—unfortunately in Japan, not the United States, though the United States is now forging ahead with its own National Nanotechnology Initiative.[19]

What Nanotechnology Can Do

Full-fledged nanotechnology promises nothing less than complete control over the physical structure of matter—the same kind of control over the molecular and structural makeup of physical objects that a word processor provides over the form and content of a text. The implications of such capabilities are significant: to dramatize only slightly, they are comparable to producing a 747 airplane or an ocean liner from the mechanical equivalent of a single fertilized egg.

9. Drexler, *supra* note 6, at 162.

10. R. Williamson, *Molecular Biology in Relation to Medical Genetics*, *in* PRINCIPLES AND PRACTICE OF MEDICAL GENETICS 17-18 (Alan Emery & David Rimoin eds., 1983).

11. K. ERIC DREXLER, NANOSYSTEMS: MOLECULAR MACHINERY, MANUFACTURING, AND COMPUTATION 10, 13, 255 (1992) [hereinafter DREXLER, NANOSYSTEMS]; Drexler, *supra* note 6, at 170.

12. *See New Technologies for a Sustainable World, Hearings Before the Subcomm. on Science, Technology, and Space, Comm. on Commerce, Science, and Transportation*, 102d Cong. 21 (1992) (testimony of Dr. Eric Drexler) [hereinafter *New Technologies Hearings*]

> The basis of this technology, as I said, is building with molecular building blocks and precise positional control. This molecule-by-molecule control can become the basis of a manufacturing technology that is cleaner and more efficient than anything we know today. It is a fundamentally different way of processing matter to make products that people want.

DREXLER, NANOSYSTEMS, *supra* note 11, at 1-5.

13. Richard Feynman, *There's Plenty of Room at the Bottom*, *in* MINIATURIZATION 282, 295-96 (H.D. Gilbert ed., 1961).

14. DREXLER ET AL., *supra* note 4, at 96-98.

15. *Id.* at 97-98.

16. *See supra* note 20 and accompanying text.

17. Books on nanotechnology include FREITAS JR., *supra* note 1; K. ERIC DREXLER, ENGINES OF CREATION (rev. ed. 1990) (the first book-length treatment of the subject) [hereinafter DREXLER, ENGINES OF CREATION]; DREXLER ET AL., *supra* note 4 (the most popularly oriented treatment); and DREXLER, NANOSYSTEMS, *supra* note 11 (the most technically oriented of the three); PROCEEDINGS OF THE FIRST FORESIGHT CONFERENCE ON NANOTECHNOLOGY (B.C. Crandall & James Lewis eds., 1991). Articles include *The Invisible Factory*, ECONOMIST, Dec. 9, 1989 (a clear, nontechnical account of nanotechnology); *Molecular Tools for Nanomanufacturing*, SCI. NEWS, Nov. 21, 1992, at 343; Christine Peterson, *Nanotechnology: Evolution of the Concept*, 45 J. BRIT. INTERPLANETARY SOC'Y 395 (1992); Ralph Merkle, *Self Replicating Systems and Molecular Manufacturing*, 45 J. BRIT. INTERPLANETARY SOC'Y 407 (1992); Paul Saffo, *Think Small; And Mechanical*, PERS. COMPUTING, Sept. 1989, at 219; Harvey Newquist, *Computers Smaller Than a Fly*, COMPUTERWORLD, Feb. 15, 1988, at 19.

18. *See, e.g.*, WHITE HOUSE OFFICE OF SCIENCE & TECH. POLICY, SCIENCE AND TECHNOLOGY: A REPORT TO THE PRESIDENT 170 (1993); U.S. CONGRESS, OFFICE OF TECH. ASSESSMENT, MINIATURIZATION TECHNOLOGIES 20-22 (1991) (both describing nanotechnology and its strategic importance).

19. *Update on Japanese Biomolecular Machine Research*, INSIDE R&D, Feb. 26, 1992, at 8 (describing Japanese research into molecular machines); Teri Sprackland, *Mini-Sensors Stake Out Mega-Markets*, ELECTRONIC BUS., Feb. 10, 1992, at 53 (reporting that Japan's Ministry of International Trade and Industry (MITI) is funding research into nanotechnology in the amount of $200 million). For some of the recent fruit of this emphasis, see *Researchers Assemble Molecular Gear*, *supra* note 1. Information on the U.S. National Nanotechnology Initiative current through the fiscal year 2001 budget cycle can be found at http://www.nano.gov.

Using nanotechnology, production would be carried out by large numbers of tiny devices, operating in parallel, in a fashion similar to the molecular machinery already found in living organisms.[20] However, these "nanodevices" would not suffer from the constraints facing living organisms—they would not have to be made of protein, or other substances readily extractable from the natural environment, nor would they have to be capable of reproducing themselves. Instead, they could be constructed of whatever material, and in whatever fashion, is most suited to their task. Known as "assemblers," these tiny devices would be capable of manipulating individual molecules very rapidly and precisely.[21] The process of using such assemblers to manufacture products may be hard for many readers to visualize; the following explains how this could work.

Nowadays, some medicines are made through biotechnological processes, for example those using recombinant deoxyribonucleic acid (DNA).[22] In essence, this means that the DNA of living creatures (usually bacteria) is altered so that the creatures are reprogrammed to produce the desired substance by assembling component atoms into the desired configurations: hydrogen here, carbon there, and so on. This approach represents a revolution in pharmaceutical technology, but has distinct limitations. Since biotechnology is based on altering the program of living organisms, only substances that can be handled by living organisms can be manufactured; only mechanisms possessed by living organisms can be used. It is as if clothing were manufactured by training spiders and silkworms to weave their product in particular patterns.

By contrast, modern textile technology represents a far more powerful, more versatile, and easier approach to manufacturing clothing. Nanotechnology represents a similar approach to the manufacture of other goods, including pharmaceuticals. Imagine the power and complexity of today's computer-driven textile looms put into machines orders of magnitude smaller than the period at the end of this sentence. Instead of weaving cloth, such machines would seize individual atoms using selectively sticky manipulator arms, then "plug" those atoms together (somewhat like assembling "lego" blocks) until chemical bonding took place.[23] By repeating these steps according to a programmed set of instructions, a nanotechnological approach would be able to produce substances that conventional biotechnology could not (say, because they are toxic to living organisms, or use elements that living organisms cannot handle efficiently) and would be able to do so with greater speed and lower expense.[24] This advantage would increase with an increase in complexity on the part of the desired molecules.

With relatively mature technology, we might expect to see general-purpose chemical synthesizers using nanotechnology. The desired molecule would be modeled on a computer screen, the assemblers would be provided with the proper feedstock solutions, and the product would be available in minutes. This application of nanotechnology would be relatively simple. More complex applications might use groups of assemblers programmed to produce molecules and then hook them together into large structures: rocket engines, computer chips, or whatever is desired.[25]

Besides allowing such efficient and powerful manufacturing capabilities, more sophisticated applications of nanotechnology would allow far more subtle applications.[26] For example, specially designed nanodevices, the size of bacteria, might be programmed to destroy arterial plaque, or cancer cells, or to repair cellular damage caused by aging, and then be injected into the body.[27] After performing their tasks, the devices may be induced to self-destruct, or remain in a surveillance mode, or, in some cases, integrate themselves into the body's cells. Such devices would have dramatic implications for the practice of medicine, and for society as a whole.

Environmental Risks and Benefits

Obviously, a technology of such capabilities offers both upsides and downsides. Some are beyond the scope of this Article: for example, Bill Joy's celebrated fear that nanotechnology may lead to superintelligent machines that will use their intelligence to achieve world domination and replace humanity.[28] (Personally, I find this unlikely. A simple glance at the headlines should be enough to dispel the belief that world domination is secured through superior intelligence. At least, if that happens, it will be the first time in human history that it has occurred that way.)

Risks

There are, however, genuine environmental risks to nanotechnology, and the nature and extent of these risks has occupied the literature in the field since the beginning. At the grossest level, there is the fear that someone will design self-replicating nanorobots, capable of making copies of

20. *See New Technologies Hearings*, *supra* note 12, at 21 ("In working with molecular building blocks, it resembles processes we see in farms and in forests and, like those processes, rather than consuming fossil fuels and emitting CO_2, it can take sunlight and CO_2 and convert them into products, acting as a net CO_2 consumer."). *Cf.* Guyton, *supra* note 8, at 35-37 (describing processes used by organic cells).

21. *See* Drexler, Engines of Creation, *supra* note 17, at 56-63, 57 (describing assemblers).

> These assemblers will work fast. A fast enzyme, such as carbonic anhydrase or ketosteroid isomerase, can process almost a million molecules per second, even without conveyors and power-driven mechanisms to slap a new molecule into place as soon as an old one is released . . . . An assembler arm will be about fifty million times shorter than a human arm, and so (as it turns out) it will be able to move back and forth about fifty million times more rapidly. For an assembler arm to move a mere million times per second would be like a human arm moving about once per minute: sluggish. So it seems a very reasonable goal.

22. *See, e.g.*, E.D.P. De Robertis & E.M.F. DeRobertis, *The Genetic Code and Genetic Engineering*, *in* Cell and Molecular Biology 522-24 (1987). Examples of such recombinant DNA products include human insulin, interferon, human growth hormone, hepatitis B vaccines, and certain coagulation factors, all of which are currently clinically available. *Id.* Indeed, such products are ubiquitous, and are regularly prescribed by physicians.

23. *See* Drexler, Nanosystems, *supra* note 11, at 181, 197-207 (discussing "chemical mechanosynthesis").

24. *See id.*

25. Drexler, Engines of Creation, *supra* note 17, at 60-62.

26. Though the implications, in terms of performance, of order-of-magnitude weight reductions in aerospace hardware are more dramatic than the simple statement might suggest.

27. Drexler et al., *supra* note 4, at 212-13, 210, 224.

28. Bill Joy, *Why the Future Doesn't Need Us*, Wired, Apr. 2000, at 238, *available at* http://www.wired.com/wired/archive/8.04/joy.html.

themselves from materials found in nature, and that those nanorobots will convert everything in the world into copies of themselves, thus wiping out the entire biosphere. In nanotechnology circles, this is known as the "gray goo" problem, after the notion that such uncontrolled replication will lead to the entire world being turned into, well, gray goo.

Such a notion is, to say the least, disturbing. While it is probably true that we already possess the capacity to substantially destroy the biosphere using nuclear weapons, or even advanced military biotechnology, the prospect of an unstoppable wave of nanorobots devouring everything in a fashion vaguely reminiscent of the science fiction movie *The Blob* seems somehow spookier and more frightening. Fortunately, further study suggests that such an event could take place only by deliberate action, not by accident.[29]

Deliberate action, however, is not impossible. More serious environmental threats involve the military or terroristic use of nanotechnology (already, the U.S. Department of Defense is one of the main sponsors of nanotechnology research).[30] Military nanotechnology is likely to be less grossly destructive than self-replicating "gray goo," but harmful enough in its own way. Early military uses of nanotechnology are likely to involve sensors and similar comparatively benign applications.[31] More advanced applications, however, are likely to be both powerful and subtle: devices that can infiltrate electronics and seize control at crucial moments, artificial "disease" agents that can rest harmlessly in victims' bodies until activated by an external signal, and so on. Some of these will have no significant impact on the nonhuman environment, but nanotechnology-based agents for crop destruction, forest-cover removal, and area-denial applications are likely to pose familiar environmental problems in a new fashion. On the more positive side, it is possible that such agents will be less persistent and less broadly destructive than, say, Agent Orange or conventional land mines.[32] Set against this possibility is the prospect that these agents will be used more broadly for that very reason, along with the possibility—impossible at this point to quantify, but irresponsible to dismiss—that they will not work as well or as "safely" as intended. Nanotechnological devices for military use also raise the issue that they do the work of chemical and biological weapons, but—at least arguably—do not fall within treaties regulating chemical and biological weapons. The argument that nanotechnological weapons—at least those of destructive, rather than surveillance, type—would be functional equivalents of chemical and biological weapons would be a strong one, and indeed destructive nanoweapons would probably achieve their effects through chemical action, though it would be mechanically initiated. Nonetheless, as the Reagan Administration's efforts to reinterpret the ABM Treaty illustrate, national governments do not require much encouragement to advance novel or disingenuous interpretations of the law where doing so serves their interests.[33]

Controlling these military applications will be difficult. Military interest in nanotechnology is already high, and an unknown, but large, amount of military nanotechnology research is going on at present; this is sure to increase as the actual application of nanotechnology becomes more feasible. It is not too early, however, to look at updating the chemical and biological warfare conventions, and other related instruments, and to explore ways in which employment of destructive nanotechnology is constrained by the laws of war.

There is also a risk that civilian applications of nanotechnology will not work as well or as cleanly as expected. This risk is almost certainly smaller than similar risks associated with military technologies, since civilian technologies tend to be more robust, and founded on a much deeper experience base than military technologies. (This characteristic is even more pronounced when the manufacturing or coding standards are open, which is why "open source" software is generally more reliable and robust than proprietary "closed source" software. This lesson has not been lost on nanotechnology enthusiasts.)[34] Nonetheless, as nanotechnology moves out of the laboratory and into the marketplace, it will be important to develop standards that ensure that its products (and byproducts, if any) do not have dangerous effects.

In many ways, these risks are likely to be lower and more manageable than those associated with biotechnology, both at military and civilian levels. Although one can imagine nanodevices of fiendish subtlety and destructiveness, it will in fact be quite some time, if ever, before it is possible to design a nanodevice that approaches the smallpox virus (even in its pristine, non-biowar form) for virulence or lethality. Despite fears of self-replicating nanodevices, the world is already full of self-replicating lethal agents that menace us on a continuous basis, and governments have been working for decades to make those agents more lethal. Most of our problems in coming decades will stem from these agents, not from conjectural nanoplagues.

29. On further examination, the "gray goo" problem turned out to be less fearsome than originally imagined: it turns out to be virtually impossible to occur by accident, and quite difficult to bring about on purpose. *See* Robert A. Freitas Jr., *Some Limits to Global Ecophagy by Biovorous Replicators, With Public Policy Recommendations*, *at* http://www.foresight.org/NanoRev/Ecophagy.html (last visited Apr. 18, 2001).

30. *See* Neil MacDonald, *DOD Plans to Award 16 Grants to Schools in Nanotechnology*, Fed. Tech. Rep., Mar. 22, 2001, at 5, 2001 WL 12451435 (describing first awards in the new Defense University Research Initiative (DURINT) program on nanotechnology). This is unclassified research, and is separate from the civilian National Nanotechnology Initiative. It is harder to pin down the extent of classified research, though rumor puts it at substantial levels. On a personal note, I have conversed with researchers from national laboratories who described their classified military nanotechnology work as sufficiently advanced and threatening that "you don't want to know." Even allowing for the inevitable hyperbole, there seems no reason to doubt the presence of significant classified military nanotechnology research.

31. *See, e.g.*, *Future Soldiers Could Get Enhanced Minds*, UPI, Mar. 19, 2001 (available on LEXIS) (describing planned use of nanotechnology to enhance soldiers' cognition and decisionmaking under stress).

32. On land mines and related technologies, see Jack H. McCall Jr., *Infernal Machines and Hidden Death: International Law and Limits on the Indiscriminate Use of Land Mine Warfare*, 24 GA. J. INT'L & COMP. L. 229, 232 (1994).

33. The ABM Treaty reinterpretation debate is discussed in GLENN H. REYNOLDS & ROBERT P. MERGES, OUTER SPACE: PROBLEMS OF LAW AND POLICY 94-101 (2d ed. 1997).

34. *See* Bryan Randolph Bruns, *Open Sourcing Nanotechnology Research and Development: Some Considerations*, Paper presented at the Eighth Foresight Conference on Molecular Nanotechnology (Nov. 3-5, 2000). Abstract available online at http://www.foresight.org/Conferences/MNT8/Abstracts/Bruns/.

Benefits

If the environmental dangers of misapplied nanotechnology are significant, the environmental benefits of nanotechnology properly employed are dramatic; it was not hyperbole when Terence McKenna called nanotechnology a radical green vision.[35] Since nanotechnology involves atom-by-atom construction, it will be able to create substances, and even finished objects, without producing the dangerous and messy byproducts that most current manufacturing processes produce. Nanodevices will operate in a liquid containing the necessary raw materials (usually carbon or silicon, with trace amounts of other elements as needed) and will simply plug the appropriate atoms in the appropriate places to produce the desired end product. Such processes should produce few byproducts, and those byproducts can be readily purified (by other nanodevices) and recycled back into feedstocks.

What is more, most products of nanotechnology will be made of simple and abundant elements: carbon, in diamond or diamondoid form, is seen as the basis of most nanomanufacturing. Products made of such materials will be very strong, meaning that smaller amounts of material can be used, and carbon is an abundant material, meaning that little in the way of exploration and extraction will be needed. Indeed, as a greenhouse remediation measure, nanodevices could even extract carbon dioxide from the air if desired.

This clean manufacturing is a significant benefit of nanotechnology, but in some sense it is less important than the economic regime that it makes possible. When materials are inexpensive, and structures of great strength and low weight can be manufactured cheaply, energy requirements for many activities drop enormously. If, for example, we can make cars that are stronger and safer than contemporary vehicles, but that weigh one-fourth (or even one-tenth) as much, electric vehicles become far more practical. Indeed, with materials of very high strength to weight, solar-powered vehicles become practical. Similarly, strong, inexpensive, energy-efficient buildings would become far more practical, further reducing energy demand. Many experts also believe that atom-by-atom manufacturing will make low-cost, high-efficiency solar cells practical. The combination of reduced energy demand and inexpensive solar power may make most of today's power generation and transmission infrastructure unnecessary. The payoff from such improvements would be enormous, not only in terms of reduced pollution from power generation, but in terms of reduced environmental impact all along the production and distribution chain: less damage from power-line construction and maintenance, less damage from transformer leakage, and, of course, less damage from coal mining, oil extraction, nuclear fuel-cycle operations, and so on.

Beyond these impacts, more advanced nanotechnology may allow active remediation of many environmental problems. For example, toxic wastes in contaminated aquifers may be neutralized by specially designed nanorobots that selectively capture undesirable molecules and then either sequester them for removal or (where the danger is chemical, not nuclear) break them down into harmless substances. While nanodevices cannot, for example, render radioactive materials nonradioactive, they could capture molecules of radioactive waste and concentrate them into a form that would be easily removed.

What to Do

At this early date, nanotechnology remains mostly a matter for laboratory work and computer simulations. That, however, makes this a good time to think about ways of regulating nanotechnology that will allow us to reap its benefits while avoiding the harms that can result from misuse. In 1999, the Foresight Institute, a Silicon Valley foundation devoted to exploring issues relating to advanced technologies, sponsored a conference intended to start the discussion on regulation of nanotechnology. Conference participants included representatives from the scientific, industrial, environmental, academic, and defense communities, and comprised a very diverse group of individuals, backgrounds, and agendas. Surprisingly, there were several areas of consensus.

The first was that simply renouncing nanotechnology—even if such a course were deemed desirable—is impossible. Unlike nuclear weapons research (which itself is poorly controlled), nanotechnology research and development does not require a large or specialized infrastructure. Indeed, the conceptual work has largely been done, and although many technical difficulties remain to be overcome, the barriers to the implementation of nanotechnology are in the nature of engineering, not basic science. In short, it was agreed that nanotechnology would be developed regardless of any efforts to suppress it, and that such efforts would only ensure that whatever research took place would do so in rogue nations, with few constraints.

The second was that proper regulation, and the use of what Arthur Kantrowitz has called "the weapon of openness,"[36] could nonetheless serve to control risks of improper use of nanotechnology. The Foresight conference produced a set of draft guidelines for research and use of nanotechnology that were designed to achieve these ends, and this draft was placed on the Foresight website for comment and critique. Many comments and criticisms were incorporated in several revisions of the draft, the current version of which is attached as an appendix to this Article. This process continues, and readers are encouraged to participate.

The third conclusion was that regulating nanotechnology will be a process, not an event. While it is not too early for thought, it is certainly too early for legislation, and an attempt to create some sort of overarching legal code for nanotechnology in advance of the facts would likely be disastrous in light of our imperfect knowledge at this point. As technology develops, and as society changes, regulatory approaches will have to keep pace. We are fortunate that we have some years—or perhaps a couple of decades—before such matters become urgent. We would be wise to make use of that time to think things through, before events surpass us.

35. For an excellent overview of nanotechnology's environmental risks and benefits, see Neil Jacobstein, *Nanotechnology and Molecular Manufacturing: Opportunities and Risks*, Presentation at Doug Engelbart's Unfinished Revolution Colloquium at Stanford University (Jan. 20, 2000), available online at: http://bootstrap.org/colloquium/session_03/session_03_jacobstein.html. This topic is also addressed at length in DREXLER ET AL., *supra* note 4, at 181-98. The following discussion draws on both sources.

36. Arthur Kantrowitz, *The Weapon of Openness*, FORESIGHT BACKGROUND NO. 4 (1990) (arguing that the maintenance of an open society is the best defense against misuse of technology). Available online at http://www.foresight.org/Updates/Background4.html.

Conclusion

This all-too-brief discussion has outlined the basic character of nanotechnology and the risks and benefits it presents. The technology of the very small poses issues sufficiently large that many minds will be required to address them. I encourage readers to add their thoughts to the process. More than most lawyers, environmental lawyers have firsthand experience with the considerations (and limitations) inherent in the application of law to advanced technologies amid conditions of technical and societal uncertainty. That expertise is likely to be helpful.

Appendix: The Foresight Guidelines

Preamble

The term "Molecular Nanotechnology" (MNT) refers to the ability to program matter with molecular precision, and scale it to three-dimensional products of arbitrary size. This developing technology presents an unprecedented new set of technical and economic opportunities. The opportunities include: the development of inexpensive and abundant diamondoid building materials with a strength-to-weight ratio 50 times greater than titanium, the possibility of widespread material abundance for all the Earth's people, the development of revolutionary new techniques in medicine, and the opening of the space frontier for development. Along with these new capabilities come new risks, and new responsibilities. The acceptance of these responsibilities is not optional. The future capabilities of MNT also raise an unprecedented set of military, security and environmental issues. Dealing with these issues proactively will be critical to the positive development of the field.

The Foresight Guidelines were developed during and after a workshop on Molecular Nanotechnology (MNT) Research Policy Guidelines sponsored by the Foresight Institute and the Institute for Molecular Manufacturing (IMM). The workshop was conducted over the February 19-21, 1999, weekend in Monterey, California. Participants included: James Bennett, Greg Burch, K. Eric Drexler, Neil Jacobstein, Tanya Jones, Ralph Merkle, Mark Miller, Ed Niehaus, Pat Parker, Christine Peterson, Glenn Reynolds, and Philippe Van Nedervelde. The resulting Foresight Guidelines ("the Guidelines") include assumptions, principles, and some specific recommendations intended to provide a basis for responsible development of molecular nanotechnology.

Continued research and education are needed to create a shared understanding and sufficient knowledge base on the entire set of MNT development and risk management issues that must be addressed. While discussion of guidelines can begin today, the scientific and technical community will continue to evolve its understanding of the issues. The Guidelines have already changed over time to reflect that dynamic understanding and input by a wider community (see Background section).

Future discussions of this subject should include detailed consideration of the economic and environmental benefits of MNT, as well as the potential problems. In particular, the need for some controls should not prevent the responsible development of the technology. Rather than have reflexive, or poorly informed controls imposed upon the MNT R&D process, the developing MNT R&D community and industry should adopt appropriate self-imposed controls, formulated in light of current knowledge and the evolving state of the art. The possibility of the necessity for additional controls remains an open question, and its resolution may depend to some extent on the success of voluntary controls.

The NIH Guidelines on Recombinant DNA technology are an example of self-regulation taken by the biotechnology community almost 25 years ago. While the kind of artificial molecular machines of primary interest for nanotechnology are expected to be very different from the kind of biological systems covered by the NIH Guidelines (just as a 747 is very different from a sparrow, even though both fly), the NIH Guidelines illustrate that advance preparations are possible and can be effective. Those guidelines were so well accepted that the privately funded research community has continued to submit research protocols for juried review, in spite of the fact that it was optional for them to do so. In addition, although the NIH Guidelines have been progressively relaxed since they were first released, they did achieve their intended effect.

Experimenters and industry should have the maximum safe opportunities to develop and commercialize the molecular manufacturing industry. In addition, MNT should be developed in ways that make it possible to distribute the benefits of the technology to the four fifths of humanity currently desperate to achieve material wealth at any environmental or security cost. Providing technical abundance alone cannot make a people wealthy and secure. This also requires education, and social arrangements described as a high-trust, civil society. However, technological abundance can alleviate many of the conflicts that stem primarily from rivalry over resources. Reducing this specific cause of conflict via molecular manufacturing could make the world more secure than it is today. In addition, the release from bare economic subsistence could enable billions of people to take advantage of the emerging global classroom over the World Wide Web. This education effect could compound the positive environmental and security benefits of MNT.

Relevant ecological and public health principles must be utilized in conducting MNT R&D. Diamondoid products may not break down easily in the natural environment. Furthermore, consumers may not at first have means readily available to recycle them. Thus, total "product lifecycle" considerations should be taken into consideration as the MNT industry develops.

Effective means of restricting the misuse of MNT in the international arena need to be developed. Adding MNT to the list of technologies covered in Chemical, Biological and Nuclear Weapons treaties might seem appropriate, but it could lead to the unintended consequence that only the U.S. and other rule following nations would be at a competitive disadvantage economically and militarily. While most nations are likely to adhere to reasonable restrictions, guidelines that are viewed as too restrictive will simply be ignored, paradoxically increasing risk. While a 100% effective ban could, in theory, avoid the potential risks of nanotechnology, a 99.99% effective ban would result in development and deployment by the 0.01% that evaded and ignored the ban. There are reasonable arguments on both sides of the treaty question. However, at this time, the Guideline participants as a group do not endorse any specific initiative to address MNT safety and security concerns through treaty arrangements.

The safe development and use of MNT depends, in part, on the good judgment of the researchers carrying out this work. The more clearly this is recognized, the more effective researchers are likely to be in avoiding and actively preventing unsafe uses of MNT and in insuring that commercial systems have built-in safeguards. The "moral repugnance" associated with biological weapons may have attenuated their development and use, in spite of the fact that they are relatively easy to make and deploy.

Eventually, MNT policy will have to balance potential risks with known benefits, and distinguish between different classes of risks. Molecular Manufacturing and nanotechnology are not one thing, but rather a spectrum of technologies, with radically different risk profiles. A substantial R&D program is needed to clarify the nature, magnitude and likelihood of the potential risks, as well as the options available for dealing with them effectively.

There are significant risks associated with failing to address ongoing economic and environmental problems that the development of MNT could help resolve. The Guidelines were not intended to cover every risk or potential abuse of the technology. People still abuse automobiles, and society has responded both by making cars safer to operate, holding drivers accountable for their actions through laws that are enforced, and requiring drivers to pay for automobile insurance. Likewise, industry and governments are held responsible for their use of technologies that have widespread impact.

The Guidelines are intended to cover most of the risks associated with normal development and use of the technology, and to mitigate, as much as possible, the risks associated with potential abuse of the technology. Informed MNT policy could accelerate the safe development of peaceful and environmentally responsible uses of the technology. This includes capturing the opportunity to develop powerful new approaches to medicine, as well as energy efficient and zero emission manufacturing and transportation technologies.

Principles

People who work in the MNT field should develop and utilize professional guidelines that are grounded in reliable technology, and knowledge of the environmental, security, ethical, and economic issues relevant to the development of MNT.

MNT includes a wide variety of technologies that have very different risk profiles. Access to the end products of MNT should be distinguished from access to the various forms of the underlying development technology. Access to MNT products should be unrestricted unless this access poses a risk to global security.

Accidental or willful misuse of MNT must be constrained by legal liability and, where appropriate, subject to criminal prosecution.

Governments, companies, and individuals who refuse or fail to follow responsible principles and guidelines for development and dissemination of MNT should, if possible, be placed at a competitive disadvantage with respect to access to MNT intellectual property, technology, and markets.

MNT device designs should incorporate provisions for built-in safety mechanisms, such as: 1) absolute dependence on a single artificial fuel source or artificial "vitamins" that don't exist in any natural environment; 2) making devices that are dependent on broadcast transmissions for replication or in some cases operation; 3) routing control signal paths throughout a device, so that subassemblies do not function independently; 4) programming termination dates into devices, and 5) other innovations in laboratory or device safety technology developed specifically to address the potential dangers of MNT. Further research is needed on MNT risk management, as well as the theory, mechanisms, and experimental designs for built-in safeguard systems.

The global community of nations and non-governmental organizations need to develop effective means of restricting the misuse of MNT. Such means should not restrict the development of peaceful applications of the technology or defensive measures by responsible members of the international community. Further research in this area is encouraged.

MNT research and development should be conducted with due regard to existing principles of ecological and public health. MNT products should be promoted which incorporate systems for minimizing negative ecological and public health impact.

Any specific regulation adopted by researchers, industry or government should provide specific, clear guidelines. Regulators should have specific and clear mandates, providing efficient and fair methods for identifying different classes of hazards and for carrying out inspection and enforcement. There is great value in seeking the minimum necessary legal environment to ensure the safe and secure development of this technology.

Development Principles

1. Artificial replicators must not be capable of replication in a natural, uncontrolled environment.
2. Evolution within the context of a self-replicating manufacturing system is discouraged.
3. Any replicated information should be error free.
4. MNT device designs should specifically limit proliferation and provide traceability of any replicating systems.
5. Developers should attempt to consider systematically the environmental consequences of the technology, and to limit these consequences to intended effects. This requires significant research on environmental models, risk management, as well as the theory, mechanisms, and experimental designs for built-in safeguard systems.
6. Industry self-regulation should be designed in whenever possible. Economic incentives could be provided through discounts on insurance policies for MNT development organizations that certify Guidelines compliance. Willingness to provide self-regulation should be one condition for access to advanced forms of the technology.
7. Distribution of molecular manufacturing *development* capability should be restricted, whenever possible, to responsible actors that have agreed to use the Guidelines. No such restriction need apply to end products of the development process that satisfy the Guidelines.

Specific Design Guidelines

1. Any self-replicating device which has sufficient onboard information to describe its own manufacture should encrypt it such that any replication error will randomize its blueprint.
2. Encrypted MNT device instruction sets should be utilized to discourage irresponsible proliferation and piracy.
3. Mutation (autonomous and otherwise) outside of sealed laboratory conditions, should be discouraged.
4. Replication systems should generate audit trails.
5. MNT device designs should incorporate provisions for built-in safety mechanisms, such as: 1) absolute dependence on a single artificial fuel source or artificial "vitamins" that don't exist in any natural environment; 2) making devices that are dependent on broadcast transmissions for replication or in some cases operation; 3) routing control signal paths throughout a device, so that subassemblies do not function independently; 4) programming termination dates into devices, and 5) other innovations in laboratory or device safety technology developed specifically to address the potential dangers of MNT.
6. MNT developers should adopt systematic security measures to avoid unplanned distribution of their designs and technical capabilities.

Background

The idea of guidelines for the safe development of MNT (Molecular Nanotechnology) has been discussed within the Foresight community for over a decade. It is inevitable that any guidelines put forth today will be further discussed and perhaps substantively changed; but the dialog on specific proposals must begin somewhere.

In spite of the diversity of briefing materials and views represented at the Monterey workshop in February of 1999, the participants managed to discuss the technical and policy issues with both intensity and civility. While any one participant might have preferred more or less emphasis on a particular issue, the group was able to converge on a common set of draft guidelines for the development of MNT.

The group agreed to review the Guidelines among themselves, discuss them in wider Foresight meetings during 1999, and then release them on the WWW for review by the larger community. The goal was to get the Guidelines endorsed and adopted by organizations sponsoring MNT research and development projects, and to inspire effective self-regulation wherever necessary and possible.

Another goal of the Workshop members was to educate MNT researchers about the potential benefits and risks of the technology. The long-term goal was to eventually produce a dialog and set of Guidelines that would be useful to policy makers, the public, and the MNT research and development community.

The Foresight Guidelines were intended as a living document, subject to modification and revision. Early drafts have been reviewed and revised several times since the Monterey workshop, including during Foresight/IMM sponsored discussions led by Neil Jacobstein in May and November of 1999. They were also provided in the attachments to Ralph Merkle's June 1999 Congressional testimony on MNT [available at http://www.merkle.com/papers/nanohearing1999.html and http://www.house.gov/science/merkle_062299.htm], and referenced in Neil Jacobstein's presentation on Nanotechnology and Molecular Manufacturing: Opportunities and Risks at Stanford University's Colloquium for Doug Engelbart in January of 2000 [available at http://bootstrap.org/colloquium/session_03/session_03_jacobstein.html]. The Workshop participants debated whether the Guidelines were sufficiently developed for widespread publication, when Bill Joy's article: "Why the Future Doesn't Need Us" [available at http://www.wired.com/wired/archive/8.04/joy.html] was published in the April 2000 issue of *Wired* Magazine. This article raised public awareness of the potential dangers of self-replicating technologies, including nanotechnology.

Since that time, the Guidelines were reviewed critically by Robert Freitas, and revised by Ralph Merkle and Neil Jacobstein. Version 3.6 of the Guidelines was discussed in a May 2000 Foresight workshop session led by Neil Jacobstein. Bill Joy was invited to participate in this discussion. He made several constructive suggestions, including one that outlined a guideline on closing the economic incentives loop via an insurance policy requirement for developers. Jacobstein incorporated the feedback from this and subsequent discussions into version 3.7 of the Guidelines, and they were then published for open review on the web.

Version 3.7 of the Guidelines are available at the Foresight web URL: http://www.foresight.org/guidelines/. This text, like most web text, can be annotated using software called Crit, which enables in-line comments to be made using a web browser. Information about the use of Crit can be found at http://crit.org. We encourage your ideas and constructive criticism about how to improve the Guidelines.

Eventually, the Guidelines need to become sufficiently specific that they can form the basis for a legally enforceable framework within which MNT development can be safely pursued. Future versions of the MNT 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. Enforcement will be inherently imperfect, but the deterrent effect of unpredictable inspection, combined with predictable and swift consequences for violations, may prove preferable to the available alternatives.

Care must be taken that future revisions of the Guidelines do not become so restrictive that they simply drive MNT research and development underground. This could expose compliant countries to the increased risks associated with decreased technical, economic, and military capabilities. It would also sacrifice the many significant economic, environmental, and medical benefits of MNT that counteract serious and certain risks that society now faces in industrialized countries and particularly in the developing world.