Harvard Journal of Law & Technology
Volume 17, Number 1 Fall 2003

NANOTECHNOLOGY AND REGULATORY POLICY: THREE FUTURES

*Glenn Harlan Reynolds**

TABLE OF CONTENTS

---

* Beauchamp Brogan Distinguished Professor of Law, University of Tennessee College of Law. J.D., Yale Law School, 1985; B.A., University of Tennessee, 1982. An earlier version of this Article was published by the Pacific Research Institute. GLENN HARLAN REYNOLDS, FORWARD TO THE FUTURE: NANOTECHNOLOGY AND REGULATORY POLICY (2002), *at* http://www.pacificresearch.org/pub/sab/techno/forward_to_nanotech.pdf.

I. INTRODUCTION

"THESE GUYS TALKING HERE ACT AS THOUGH THE GOVERNMENT IS NOT PART OF THEIR LIVES. THEY MAY WISH IT WEREN'T, BUT IT IS. AS WE APPROACH THE ISSUES THEY DEBATED HERE TODAY, THEY HAD BETTER BELIEVE THAT THOSE ISSUES WILL BE DEBATED BY THE WHOLE COUNTRY. THE MAJORITY OF AMERICANS WILL NOT SIMPLY SIT STILL WHILE SOME ELITE STRIPS OFF THEIR PERSONALITIES AND UPLOADS THEMSELVES INTO THEIR CYBERSPACE PARADISE. THEY WILL HAVE SOMETHING TO SAY ABOUT THAT. THERE WILL BE A VEHEMENT DEBATE ABOUT THAT IN THIS COUNTRY." LEON FUERTH, FORMER NATIONAL SECURITY ADVISOR TO VICE PRESIDENT ALBERT GORE, JR.[1]

The conversation that Leon Fuerth called for is now underway. Molecular nanotechnology is a technology so new that, in truth, it barely exists. Although the actual accomplishments of nanotechnology at this date tend to fall into the workbench or proof-of-concept stage, research continues to progress at a speed that outpaces the predictions of the most optimistic prognosticators.[2] Indeed, nanotechnology has received so much attention — not all of it positive[3] — that some are already pronouncing it a cliché.[4] If the rapid pace of research continues, however, nanotechnology will hit the marketplace more quickly than did biotechnology, a field of endeavor to which society is still adjusting.

1. Leon Fuerth, Remarks at the Foresight Senior Associate Gathering (Apr. 28 2002), *quoted in* Ronald Bailey, *What's the purpose of life?: Nanotechnology Might Provide the Answer*, REASON ONLINE, ¶ 19 (May 1, 2002), *at* http://reason.com/rb/rb050102.shtml.

2. *See, e.g.*, Philip Ball, *DNA Construction Business: DNA Could Help Build NanoMachines Made of DNA,* NATURE SCI. UPDATE (May 1, 2002), *at* http://www.nature.com/nsu/020429/020429-5.html (describing nanostructures and motors built with DNA); Kelly Morris, *Macrodoctor, Come Meet the Nanodoctors*, 357 LANCET 778 (2001) (describing progress in medical nanotechnology); *see also Researchers Assemble Molecular Gear: University of Tokyo Team Scores First by Building Functional Nanodevice*, NIKKEI WKLY., Mar. 19, 2001, at 11; Fiona Harvey, *Toughened by NanoTechnology,* FIN. TIMES (London), Mar. 15, 2001, at 15. For an extensive overview of medical nanotechnology, see ROBERT A. FREITAS JR., NANOMEDICINE, VOLUME I: BASIC CAPABILITIES (1999). Indeed, nanotechnology's importance to medicine is such that *The Lancet* is publishing a special issue devoted to the topic. *See Nanomedicine: Grounds for Optimism, and a Call for Papers*, 362 LANCET 673 (2003). Military nanotechnology is also of growing interest to the Pentagon. *See* Chappell Brown, *Nanotech Goes to War,* ELECTRONIC ENGINEERING TIMES, Aug. 25, 2003, at 18.

3. Nanotechnology has already been denounced by anti-technology activists such as Jeremy Rifkin and Kirkpatrick Sale. *See* Ronald Bailey, *Rebels Against the Future: Witnessing the Birth of the Global Anti-Technology Movement*, REASON ONLINE, ¶ 2 (Feb. 28, 2001), *at* http://reason.com/rb/rb022801.html. The debate over nanotechnology has also figured in the Michael Crichton novel, *Prey*. MICHAEL CRICHTON, PREY (2002). For a skeptical review of Crichton's nano-villains, see Freeman J. Dyson, *The Future Needs Us!*, N.Y. REV. BOOKS, Feb. 13, 2003, at 53.

4. *See* Gail Collins, *Bring On the Nanobots*, N.Y. TIMES, Jan. 16, 2001, at A23.

The "vehement debate" that Leon Fuerth predicted has just now begun. The time where nanotechnology was seen as too exotic for general discussion has passed, and a number of significant leaders, including Britain's Prince Charles, have expressed growing concerns over nanotechnology, "grey goo," and the future of humanity.[5] The evolving discussion over nanotechnology mirrors the current debate over cloning, a technology considered pure science fiction a short time ago. As the cloning debate has taught us, the discussions over nanotechnology should begin sooner rather than later, because as the debate grows more intense and as the science approaches feasibility, it becomes more difficult to think carefully about the issues involved.

This Article outlines the basic characteristics of nanotechnology as it is currently understood and will briefly describe some of the technical — and social — consequences likely to arise as nanotechnology matures. Next, it examines three potential approaches for regulating nanotechnology and the likely consequences of each. The Article concludes with suggestions for further study, as well as a list of "dos" and "don'ts" for regulating nanotechnology.

II. A BEGINNER'S GUIDE TO NANOTECHNOLOGY

A. How Nanotechnology Works

Put simply, nanotechnology is the science and technology of building things from the bottom up — one atom or molecule at a time. In contrast, 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 until only the desired configuration remains. Results of such processes may be rather small (e.g., integrated circuits with structures measured in microns) or very large (e.g., ocean liners or jumbo jets). However, in all top-down processes, matter is being processed in chunks far larger than molecular scale.[6]

This top-down technology is familiar to most people and is certainly capable of yielding products of fairly high precision and complexity. This method does differ, however, from the natural processes of the world, since most products of living organisms — to say nothing of those organisms themselves — are produced in a far different manner.

---

5. *See* Mark Welland, *Don't Be Afraid of the Grey Goo*, FIN. TIMES (London), Apr. 30, 2003, at 21; *see also infra* text accompanying note 37.

6. *See* K. Eric Drexler, *Nanotechnology Summary in* 1990 ENCYCLOPEDIA BRITANNICA SCIENCE AND THE FUTURE YEARBOOK 162, 163–67 (describing top-down and bottom-up approaches).

Rather than being produced through the shaping and molding of large chunks of material, most objects on Earth 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 can create objects of astonishing complexity and size, such as the human brain, a coral reef, or a redwood tree.[7] This approach produces results that would seem impossible if judged by the standards of conventional top-down production technology (e.g., no one could "build" a tree using top-down methods). Despite this discrepancy, most bottom-up processes are taken entirely for granted. For example, the human body begins as a single cell, a fertilized ovum, but evolves into a mature human being consisting of approximately 75 trillion complexly-arranged cells.[8] The molecular machinery responsible for this amazing, though commonplace, feat of production is capable of such 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. This process thus serves as a kind of "existence proof" for nanotechnology. 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]

Of course, putting these natural molecular machines to work is nothing new, as every living thing does so constantly. Nor is deliberate human programming of those machines particularly new, as this forms the basis of genetic engineering.[10] What differentiates nanotechnology is its attempt to go beyond the capabilities of natural mechanisms. Using special bacterium-sized "assembler" devices, nanotechnology permits exact control of molecular structures that are not readily manipulable by organic means (e.g., diamond or heavy

---

7. *See id.* at 175.
8. ARTHUR C. GUYTON, TEXTBOOK OF MEDICAL PHYSIOLOGY 2 (7th ed. 1986).
9. Drexler, *supra* note 6, at 162.
10. *See* R. Williamson, *Molecular Biology in Relation to Medical Genetics*, *in* 1 PRINCIPLES AND PRACTICE OF MEDICAL GENETICS 16, 17–18 (Alan E. H. Emery & David L. Rimoin eds., 1983).

metals) on a programmable basis.[11] As Rice University nanotechnologist Vicki Colvin notes:

> Nanomaterials are different. Because of their small size, we are able to get them into parts of the body where typical inorganic materials can't go because they're too big. There is an enormous advantage to using nanoparticles if you're engineering, for example, drug delivery systems or cancer therapeutics.[12]

More advanced plans involve going beyond nanomaterials to nanodevices. With nanotechnology, atoms will be specifically placed and connected, all at a rapid pace, in a manner 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 future of nanotechnology depends on the development of processes that can control placement of individual atoms to form products of great complexity on an extremely small scale.[13]

This approach was originally suggested by physicist Richard Feynman. In an article entitled *There's Plenty of Room at the Bottom*, Feynman explores the potential of atomic-scale physical manipulation of matter.[14] As Feynman writes:

> 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

---

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

12. David Rotman, *Measuring the Risks of Nanotechnology,* TECH. REV., Apr. 2003, at 71.

13. *See New Technologies for a Sustainable World: Hearing Before the Subcomm. on Science, Technology and Space of the Senate Comm. on Commerce, Science, and Transportation*, 102d Cong. 21 (1992) (testimony of Dr. Eric Drexler) [hereinafter *New Technologies Hearing*] ("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."); *see also* DREXLER, NANOSYSTEMS, *supra* note 11, at 1–5.

14. Richard P. Feynman, *There's Plenty of Room at the Bottom*, *in* MINIATURIZATION 282 (Horace D. Gilbert ed., 1961).

> level is ultimately developed — a development which I think cannot be avoided.[15]

Scientists and researchers continue to make progress in this direction. By the early nineties, IBM's research division had already demonstrated the ability to manipulate individual atoms, using the tip of an atomic force microscope to construct a copy of IBM's logo out of xenon atoms.[16] The next step, the precise placement of atoms in combination to form stable compounds and structures,[17] has also been achieved.[18]

Such efforts have already generated substantial theoretical literature and considerable scholarly interest. Nanotechnology has produced a number of books and articles,[19] government reports,[20] and at least one long-established and well-funded research program — unfortunately in Japan[21] rather than the United States. However, the United States is now forging ahead with its own National Nanotechnology Initiative.[22]

---

15. *Id.* at 295–96.

16. *See* K. ERIC DREXLER ET AL., UNBOUNDING THE FUTURE: THE NANOTECHNOLOGY REVOLUTION 96–98 (1991).

17. *See id.* at 97–98.

18. *See* Ball, *supra* note 2.

19. *See, e.g.*, ROBERT A. FREITAS JR., NANOMEDICINE VOLUME ONE: BASIC CAPABILITIES (1999); K. ERIC DREXLER, ENGINES OF CREATION (rev. ed. 1990) (the first book-length treatment of the subject); DREXLER ET AL., UNBOUNDING THE FUTURE, *supra* note 16, (the most popularly-oriented treatment); K. ERIC DREXLER, NANOSYSTEMS: MOLECULAR MACHINERY, MANUFACTURING, AND COMPUTATION (1992) (the most technically-oriented of the three Drexler books); PROCEEDINGS OF THE FIRST FORESIGHT CONFERENCE ON NANOTECHNOLOGY (B.C. Crandall & James Lewis eds., 1991). Articles include *The Invisible Factory*, ECON., Dec. 9, 1989, at 91 (a clear, nontechnical account of nanotechnology); E. Pennisi, *Molecular Tools for Nanomanufacturing*, SCI. NEWS, Nov. 21, 1992, at 343; Christine L. Peterson, *Nanotechnology: Evolution of the Concept*, 45 J. BRIT. INTERPLANETARY SOC. 395 (1992); Ralph Merkle, *Self Replicating Systems and Molecular Manufacturing*, 45 J. BRIT. INTERPLANETARY SOC. 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.

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

21. Japan's program is very long-established indeed. *See* 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 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 2.

22. *See* NATIONAL NANOTECHNOLOGY INITIATIVE, *at* http://www.nano.gov (last visited Nov. 20, 2003). Furthermore, at the time of this writing, a bill authorizing nearly $3.7 billion for nanotechnology research and development is awaiting signature by President Bush. 21st Century Nanotechnology Research and Development Act, S. 189, 108th Cong. (2003); *see also* Jeff Karoub, *U.S. House Sends Nanotechnology Bill to Bush for Expected Signature*, SMALL TIMES (Nov. 20, 2003), *at* http://www.smalltimes.com/document_display.cfm?document_id=6981.

B. 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 or an ocean liner from piles of the most basic materials (e.g., raw iron) and the mechanical equivalent of a single fertilized egg.

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.[23] 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, the nanodevices 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 rapidly and precisely.[24] Since the process of using such assemblers to manufacture products may be difficult for many readers to visualize, I have formulated an example of how this technology could work.

Currently, scientists produce certain medicines through biotechnological processes, such as those using recombinant DNA.[25] In essence, this means that the DNA of living creatures (usually bacteria)

---

23. *See New Technologies Hearing, supra* note 13, 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 CO2, it can take sunlight and CO2 and convert them into products, acting as a net CO2 consumer."); *cf.* GUYTON, *supra* note 8, at 35–37 (describing processes used by organic cells).

24. As Eric Drexler describes them:

> 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.

DREXLER, ENGINES OF CREATION, *supra* note 19, at 56–63.

25. *See, e.g.*, E.D.P. De Robertis & E.M.F. De Robertis, Jr., *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. *See id.* Indeed, such products are ubiquitous and are regularly prescribed by physicians.

is altered so that the creatures are reprogrammed to produce the desired substance. This approach represents a revolution in pharmaceutical technology, but has distinct limitations. Since biotechnology operates by altering the program of living organisms, only those substances that can be handled by living organisms can be manufactured, and only those mechanisms possessed by living organisms can be used. To understand this limitation, imagine that clothing could only be manufactured by training spiders and silkworms to weave their product in particular patterns. By contrast, modern textile technology provides 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 many times 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.[26] By repeating these steps according to a programmed set of instructions, a nanotechnological approach would be able to synthesize materials at greater speed and lower cost.[27] Also, such an approach would produce substances that conventional biotechnology could not — because they either are toxic to living organisms or are comprised of elements that living organisms cannot handle efficiently.[28] As the molecules desired grew more complex, the advantage gained by their use would continue to increase.

With relatively mature technology, one 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 raw materials, and the product would be available in minutes. 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 else may be desired.[29]

Besides allowing such efficient and powerful manufacturing capabilities, more sophisticated applications of nanotechnology would allow far more subtle applications. For example, specially designed nanodevices, the size of bacteria, might be programmed to destroy arterial plaque, or fight cancer cells, or repair cellular damage caused by aging.[30] After performing their tasks, the devices could be induced

---

26. *See* DREXLER, NANOSYSTEMS, *supra* note 11, at 181, 197–207 (discussing "chemical mechanosynthesis").

27. *See id.*

28. *See id.*

29. *See* DREXLER, ENGINES OF CREATION, *supra* note 19, at 60–62.

30. *See* DREXLER ET AL., UNBOUNDING THE FUTURE, *supra* note 16, at 210, 212–13, 224.

to self-destruct, or remain in a surveillance mode, or, in some cases, integrate themselves into the body's cells.[31]

In addition to treating diseases, there is no reason why nanotechnology could not integrate networks of distributed sensors into the human body, providing drastically enhanced mental, physical, and sensory abilities. In addition, substantial changes in human morphology would be possible for practical purposes (e.g., greatly enhanced musculature and height or underwater breathing[32]) or for more whimsically cosmetic purposes (e.g., ornamental wings or decorative tails). Some experts believe that highly intelligent nanodevices distributed throughout the brain may permit copying of thought patterns — in essence, mind uploading — so that a copy of a person's personality and memories could be placed in storage, or even run as a form of naturally-created artificial intelligence.[33]

As Leon Fuerth notes in the passage quoted at the beginning of this Article, such capabilities would undoubtedly lead to considerable discussion and calls for regulation. The remainder of this Article will examine potential regulatory environments and the consequences associated with each.

III. REGULATORY RESPONSES

Technologies with dramatic societal implications tend to generate strong pressures for some degree of regulation. Currently, controversial technologies such as genetic engineering and cloning exemplify the heightened debate surrounding new technologies.[34] While nanotechnology may not generate the same passionate debate of these other technologies, it has been — as previously mentioned — been the target of a number of anti-technology activists.[35] As nanotechnology continues to advance and expand into the mainstream, an increasing number of people can be expected to show interest in its regulation.

---

31. *See id.* at 209.

32. *See* ROBERT A. FREITAS, JR., A MECHANICAL ARTIFICIAL RED CELL: EXPLORATORY DESIGN IN MEDICAL NANOTECHNOLOGY (speculating about oxygen-storing "respirocytes" that would permit extended underwater stays without scuba equipment), *available at* http://www.foresight.org/Nanomedicine/Respirocytes.html (last visited Nov. 20, 2003).

33. *See* ROBERT A. FREITAS, JR., MIND UPLOADING (collecting list of papers and links on the topic), *available at* http://www.foresight.org/Nanomedicine/Uploading.html (last visited Nov. 20, 2003); *see also* Raymond Kurzweil, *Live Forever*, PSYCHOL. TODAY, Jan./Feb. 2000 (predicting that "[w]ithin 30 years, we will be able to scan ourselves — our intelligence, personalities, feelings and memories — into computers"), *available at* http://www.psychologytoday.com/htdocs/prod/ptoarticle/pto-20000101-000037.asp.

34. *Compare* FRANCIS FUKUYAMA, OUR POSTHUMAN FUTURE: CONSEQUENCES OF THE BIOTECHNOLOGY REVOLUTION (2003) (generally negative view) *with* GREGORY STOCK, REDESIGNING HUMANS: OUR INEVITABLE GENETIC FUTURE (2002) (generally positive view).

35. *See* discussion *supra* note 3.

Regulatory responses to nanotechnology could fall along a broad spectrum, ranging from complete relinquishment or prohibition, to permissible use only in military programs, to more moderate regulation, to *laissez-faire*. As discussed below, each approach presents its own difficulties for implementation, and its own likely consequences for the future of nanotechnology.

A. "Relinquishment" and Prohibition

Some anti-technology activists may already believe that the risks posed by nanotechnology — either in terms of physical harm or in terms of societal change — are sufficiently great that we should pursue a Barney Fife regulatory strategy: "nip it in the bud."[36] Only by preventing any nanotechnology research at the outset, they argue, can the consequences that they regard as undesirable be prevented. This approach will most likely appeal to opponents of technological development in general, as well as to others who believe that once nanotechnology appears likely to produce substantial social benefits, it will become more difficult to stop.

Though, as discussed further below, such an approach seems plainly unworkable, the concerns that motivate calls for prohibition do have some rational basis. The potential beneficial uses of nanotechnology could also be manipulated for malicious purposes. The same technology that could selectively destroy cancer cells could instead target immune or nerve cells, producing death or further debility. Self-reproducing robots ("replicators") could turn everything else in the world into copies of themselves (the so-called "grey goo" problem), thus ending life as we know it.[37] Nanotechnology, while having the potential to dramatically increase computing power, might, therefore, also give rise to artificial intelligence that could threaten humanity.

1. The Case for Prohibition: Children of Our Minds

This latter fear has been examined, with differing degrees of concern, by Sun Microsystems's Chief Scientist, Bill Joy, in his essay, *Why the Future Doesn't Need Us*,[38] and by Ray Kurzweil in his book,

---

36. *See generally* Bailey, *supra* note 3. *See also* TV LAND, CITIZENS OF MAYBERRY, *at* http://www.tvland.com/shows/griffith/citizens/index.jhtml (last visited Nov. 20, 2003).

37. On further examination, the "grey goo" problem appears 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 (2000), *at* http://www.foresight.org/NanoRev/Ecophagy.html.

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

The Age of Spiritual Machines.[39] Kurzweil views the prospect of human-like, and human-superior, artificial intelligence with equanimity. In his book, a person traveling into the future checks in with a woman over a period of several decades, only to find her growing more and more indistinguishable from the machines that are her servants.[40] At the end, she seems to have blended with them in a fashion that she, at least, finds entirely acceptable.[41] Just as we are, in some sense, commensal organisms formed by the blending of many prehistorically independent entities (e.g., the mitochondria in our cells), she has become a new kind of organism, synthesizing human and machine. Kurzweil's future is alien, but it is not, at least in his view, entirely dystopian.[42]

Joy, who gained inspiration from Kurzweil's work, sees the future in less felicitous terms.[43] He fears that intelligent machines will, as a consequence of their greater intelligence, become competitors of humanity, and by virtue of their intelligence, outcompete us into extinction.[44] Joy concludes that we may have to "relinquish" research in some areas in order to prevent such an outcome, even if this means condemning some people to deaths that could have been prevented through more advanced technology.[45]

It is not obvious, however, that intelligence has much to do with world domination. Certainly, those currently ruling the world did not attain their positions by virtue of their intelligence, and it may be that, like James Branch Cabell's eponymous protagonist Jurgen, superintelligent machines would find that "cleverness was not at the top of things, and never had been."[46] While scientists and computer experts,

---

39. RAY KURZWEIL, THE AGE OF SPIRITUAL MACHINES: WHEN COMPUTERS EXCEED HUMAN INTELLIGENCE (1999).

40. *See id.*

41. *See id.*

42. *See id.*

43. *See* Joy, *supra* note 38.

44. *See id.*

45. *See* Richard Scheinin, *Guiding Science: Technologist Bill Joy Leads a Debate Over How Far We Should Go With New Machines,* SAN JOSE MERCURY NEWS 1F, ¶¶ 1, 3 (Feb. 17, 2001) ("Perhaps science should stop manipulating genes, [Joy] suggested, even if new gene therapies might save a child from incurable cancer. . . . 'I could imagine letting someone suffer to protect the group.'").

46. JAMES BRANCH CABELL, JURGEN: A COMEDY OF JUSTICE 332 (1934). In the text, Jurgen has just met Koshchei the Deathless, "who made things as they are." *Id.* The full passage reads:

> And of a sudden Jurgen perceived that this Koshchei the Deathless was not particularly intelligent. Then Jurgen wondered why he should ever have expected Koshchei to be intelligent? Koshchei was omnipotent, as men estimate omnipotence: but by what course of reasoning had people come to believe that Koshchei was clever, as men estimate cleverness? The fact that, to the contrary, Koshchei seemed well-meaning, but rather slow of apprehension and a little needlessly fussy, went far toward explaining a host of matters which had long

whose chief pride (as with Jurgen) lies in their intelligence, would tend to regard superior intellect as the *sine qua non* of power, this view can be quickly dispelled by a glance at the headlines.

2. Problems with Turning a Blind Eye

Regardless of these quibbles, however, Joy's proposal, and in particular his suggestion that we may need to relinquish certain lines of research entirely, has received a great deal of attention. Though Joy may have backtracked somewhat,[47] others have taken up his call for limits on scientific research. Yet, if anything about the future of technology — or for that matter, its past — is clear, it is that such an approach cannot possibly work, even if, as it must, it moves from a voluntary program of "relinquishment" to a draconian program of prohibition.

The relinquishment approach was originally taken by nanotechnology pioneer K. Eric Drexler, whose first reaction when considering the implications of nanotechnology was guarded silence, for fear that it could potentially lead to great dangers.[48] Drexler, however, soon recognized that if he could think of such an idea, others could as well. (Indeed, Drexler later discovered that the basic principles of nanotechnology had been anticipated by Richard Feynman decades earlier.)[49] Thus, Drexler concluded that the only responsible approach was to guide the inevitable development of nanotechnology in constructive directions.[50]

The basic ideas of nanotechnology are now in general circulation. A ban on nanotechnology could thus only be accomplished by banning research and development, rather than discussion. To have any chance of success, such a ban would have to be comprehensive and draconian. However, even then it would face at least four insuperable problems: definition, concealment, bureaucracy, and perfection.

The first problem would be in formulating an exact definition of nanotechnology. At present, researchers in search of funding have tended to define "nanotechnology" rather broadly, including such things as molecular electronics and even high-resolution photolitho-

---

> puzzled Jurgen. Cleverness was of course, the most admirable of all traits: but cleverness was not at the top of things, and never had been.

Id. Jurgen, who has always prided himself on his cleverness, learns much from this encounter.

47. According to reports in October 2000, Joy qualified somewhat his calls for a relinquishment of research. *See* Patrick McGee, *Bill Joy Hopes Reason Prevails*, WIRED NEWS (Oct. 30, 2000), *at* http://www.wired.com/news/technology/0,1282,39864,00.html. On the other hand, more recent accounts suggest that he is calling for such a relinquishment, after all. *See* Scheinin, *supra* note 45, at 1F.

48. *See* ED REGIS, NANO 58–62 (1995).

49. *See id*.

50. *Id.* at 90–91.

graphy. Nanotechnology generally consists of the mechanical manipulation of atoms and molecules at a nanometer scale, but the term as generally used in nanotechnology circles has become more specified, and usually includes only particular methods of manipulation done with particular goals in mind.

Yet, a nanotechnology-prohibition regime that banned only the construction of, for example, assembler devices, would exempt from regulation huge amounts of research that could be readily translatable into such devices. The resulting prohibition regime would merely drive the final stages of nanotechnology work underground.

On the other hand, a broader regime of nanotechnology regulation would encompass everything from high-precision chip manufacturing to many aspects of biotechnology, creating enormous barriers to progress across a wide range of technical fields. While Luddites[51] might view such side effects as beneficial, rather than detrimental, society as a whole is unlikely to agree.

A second problem with a prohibitionist approach is the ease with which nanotechnology research can proceed using inconspicuous tools in concealable locations. In fact, the current tools-of-choice for nanotechnology research are computers, as well as Scanning Tunneling Microscopes and Atomic Force Microscopes, which are inexpensive and are often homemade within laboratories doing the research.[52] Thus, there are no large fuel-enrichment facilities (as with nuclear weapons research), no unusual chemical precursors or feedstocks (as with chemical weapons), and not even any odd organisms or nutrients (as with biotechnology research) for investigators to discover in searching for rogue labs.

Such signature items will naturally appear once nanotechnology research and development advances sufficiently. However, by that time it would be too late for a prohibitionist approach to have any credibility. At present, and for some time, a nanotechnology research program could easily be concealed within a wide range of electronic or biotechnology-related projects, with no apparent giveaways. In the absence of giveaway signature technologies, the only way in which a prohibitionist approach is likely to succeed is if it (1) covers a broad range of potentially nanotechnology-related fields, and (2) subjects

---

51. Luddism has been defined as "intense dislike of or opposition to technological innovation." 9 OXFORD ENGLISH DICTIONARY 86 (2d ed. 1989).

52. *See, e.g.*, Mitch Jacoby, *STM: An All-In-One Tool*, 77 CHEMISTRY & ENGINEERING NEWS 48, at 9–10 (Nov. 29, 1999) (describing homemade Scanning Tunneling Microscopes), *available at* http://www.physics.uci.edu/~wilsonho/c&en112999.html; Metin Sitti & Hideki Hashimoto, *Controlled Pushing of Nanoparticles: Modeling and Experiments,* 5 IEEE/ASME TRANSACTIONS ON MECHATRONICS 199 (June 2000) (describing homemade Atomic Force Microscope system), *available at* http://robotics.eecs.berkeley.edu/~sitti/papers/mechat_00.pdf.

work in those areas to in-depth surveillance and regulation. Such efforts, however, are unlikely to be well-received.

A third difficulty is that, at the very least, a prohibition regime is likely to create sizable bureaucratic demands for pre-approval of any research that borders on the prohibited. The resulting bureaucratization of research and development will likely slow technical progress substantially. Nonetheless, given the concealable nature of nanotechnology, as described above, it would be largely ineffective in preventing illicit research.

The biggest problem with a prohibitionist approach, however, is that it must be both universal and perfect to be any good. Obviously, a prohibitionist approach that successfully prevents all nanotechnology research will prevent all harms that result from such research. However, a prohibitionist approach that prevents only 99.999% of nanotechnology research, while allowing a few underground projects sponsored by rogue states to slip through its net, would likely do just as much harm with no corresponding benefits. Indeed, it would only make things worse, because those rogue states would then have a monopoly on a powerful technology, while the civilized world would lack the wherewithal to deploy countermeasures.[53]

Calls for a moratorium on nanotechnology research face similar problems. Such calls for voluntary relinquishment are mostly attention-getting devices (as even their proponents admit[54]), and are unlikely to promote the regulation of the technology. It is conceivable that a moratorium on some specific aspects of nanotechnology that raise particular questions might be appropriate at some time in the future — as it was with early biotechnology research[55] — but at this point a research moratorium would more likely keep us in the dark than keep us safe.

The prohibitionist approach is unlikely to carry the day. The drawbacks are too great, the advantages too few, and the difficulties too involved.[56]

---

53. *Cf.* DANIEL R. HEADRICK, THE TOOLS OF EMPIRE (1981) (describing the role of key technologies in ensuring European military supremacy).

54. Barnaby J. Feder, *From Nanotechnology's Sidelines, One More Warning*, N.Y. TIMES, Feb. 3, 2003, at C1 (quoting moratorium proponent as saying "it gets people's attention").

55. *See infra* Part III.C.1.

56. This Article does not address the constitutional problems with such regulation — both in terms of the First Amendment, and in terms of limitations on Congressional power over things that are not clearly interstate commerce. *See, e.g.*, United States v. Morrison, 529 U.S. 598 (2000) (lack of power under Commerce Clause for challenged Congressional legislation); United States v. Lopez, 514 U.S. 549 (1995) (same). For more on this topic, see Glenn H. Reynolds & Brannon P. Denning, *Lower Court Readings of* Lopez*, or What if the Supreme Court Held a Constitutional Revolution and Nobody Came?*, 2000 WIS. L. REV. 369. *See also* John A. Robertson, *The Scientist's Right to Research: A Constitutional Analysis*, 51 S. CAL. L. REV. 1203, 1217–18 (1977).

B. Restriction to the Military Sphere

One regulatory approach short of outright prohibition is to keep nanotechnology research within the classified military realm. Such an effort might consist of:

- Large amounts of classified research, which would tend to draw nanotechnology researchers into the military sphere;
- Legislation, somewhat like the Atomic Energy Act,[57] making private research cumbersome and difficult, and specifying that some sorts of nanotechnology would be "born classified" regardless of source; and
- The use of informal guidance, export control laws, government contracting, and other measures to retard the growth of the civilian nanotechnology sector relative to the military nanotechnology sector — as has been done in the past for areas such as encryption[58] and certain telecommunications technologies.[59]

1. The Case for "Painting It Black"

The government might choose to pursue a strategy of classification because the stakes are high and it might work for a time. In the nineteenth century, technologies like steam navigation, repeating firearms, and high explosives gave the Western powers virtually unchallenged supremacy throughout the rest of the world.[60] Nanotechnology could play a similar role in the twenty-first century. Thus, it is easy to see why such a role might appeal to military planners and, perhaps, to those worried about the social implications (e.g., extended lifespans or drastic body modifications) of civilian nanotechnology.

The military uses of nanotechnology are likely to be plentiful and important. Nanotechnology might permit devices ranging from pervasive, hard-to-detect battlefield sensors,[61] to brain modifications that enhance soldiers' cognitive skills,[62] to artificial "disease" agents that could hide undetected in the bodies of enemy populations or leaders

---

57. 42 U.S.C. §§ 2011–2281; *see also infra* text accompanying notes 65–68.

58. *See* Vandana Pednekar-Magal & Peter Shields, *The State and Telecom Surveillance Policy: The Clipper Chip Initiative*, 8 COMM. L. & POL'Y 429 (2003) (discussing federal government's attempt to use a combination of purchasing and regulatory power to prevent spread of unsanctioned encryption technology).

59. *See id*.

60. *See generally* HEADRICK, *supra* note 53.

61. *See* Scott Pace, *Military Implications of Nanotechnology,* FORESIGHT UPDATE 6, Aug. 1, 1989, at 2 ("In low-intensity warfare, intelligent sensors and barrier systems could isolate or channel guerrilla movements depending on the local terrain."), *available at* http://www.foresight.org/Updates/Update06/Update06.2.html.

62. *See, e.g.*, Kelly Hearn, *Future Soldiers Could Get Enhanced Minds,* UPI, Mar. 19, 2001, LEXIS, Nexis Library, UPI File (describing planned use of nanotechnology to enhance soldiers' cognition and decision-making under stress).

until triggered by external stimuli. Indeed, sophisticated nanodevices could even manipulate neurotransmitter levels within the brains of individuals or populations, producing the ultimate weapon in psychological warfare. Israelis and Palestinians might be induced to love one another like brothers, but populations might similarly be induced to love Big Brother. Furthermore, military nanotechnologies are particularly appealing because they may be cleaner, safer, and less likely to cause collateral damage than current technologies.[63]

2. Problems with Military Classification

The promise of such technologies is surely hard for military planners to resist. This also means that military planners will want to deny access to potential adversaries. In practice, given the tendency of technology to spread, this means denying it to almost everyone outside the military. For example, the military and intelligence establishment has tried for decades to limit the availability of encryption technology to non-military entities and individuals.[64]

Similarly, in atomic weapons technology, some information is described as "born classified," meaning that disclosure is forbidden from the moment of discovery.[65] For example, consider the following anecdote, which demonstrates how troublesome such an environment can be:

> A small company that had never had any involvement with the atomic energy program, nor any government contracts at all, sought to patent an invention. . . . The company's executives were stunned to learn that their invention included a

---

63. *See* Pace, *supra* note 61 (describing the potential relative advantages of nanotechnology and "smart munitions" in various forms of warfare). Pace observes that:

> Rather than requiring nuclear weapons to attack massive conventional forces or distant, hard targets, nanotechnology enhancements to cruise missiles and ballistic missiles could allow them to destroy their targets with conventional explosives. Conventional explosives themselves might be replaced by molecular disassemblers that would be rapidly effective, but with less unintended destruction to surrounding buildings and populations. . . . Nanoweapons could lower the cost of meeting aggression (in both dollars and lives) in tactical applications while preserving strategic deterrence without nuclear weapons.

Id.

64. Indeed, similar efforts continue. *See* Dan Froomkin & Amy Branson, *Deciphering Encryption*, WASHINGTONPOST.COM (describing law enforcement restrictions against exporting encryption technology), *at* http://www.washingtonpost.com/wp-srv/politics/special/encryption/encryption.htm (last updated May 8, 1998).

65. *See generally* Richard G. Hewlett, *'Born Classified' in the AEC: A Historian's View,* BULL. ATOM. SCIENTISTS, Dec. 1981, at 20–27 (pointing out that this policy became more problematic when American companies wanted to start research into gas centrifuge processes that European companies had already begun).

> highly classified concept critical to the production of fissionable material. They were equally stunned to learn that the Atomic Energy Act prohibited their continued access to their own invention unless all relevant personnel were investigated and cleared.[66]

And, in a similarly curious incident:

> In late 1953, the Atomic Energy Commission general manager received a letter from a prominent scientist who had been an important figure in the wartime atomic bomb project. The letter stated that the writer had been out of the atomic energy program since 1948, but had been doing some calculations concerning nuclear weapons in his own laboratory. He was certain, he said, based on his knowledge of the atomic weapons program, that his calculations had produced information that would be highly classified had it been developed within the government program. Accordingly, he was asking the Commission to provide him with a security-approved, three-way combination safe in which he could store the sensitive information he had created so as to protect it against leakage to unauthorized persons.
>
> This letter threw the Commission and the Department of Justice into turmoil, because the scientist did not have security clearance and, therefore, it was unlawful for him to have created Restricted Data or to have access to the data. Moreover, the situation could not be remedied since he was regarded as "unclearable."[67]

The difficulties created by such a regime are rather obvious, and they would be more serious in the current context of nanotechnology because of the lower threshold for experimentation, the more widespread nature of the technical knowledge, and the greater sensitivity these days toward scientific freedom and free speech generally.

While the Atomic Energy Act was an extreme case, it was not the only means by which the federal government attempted to limit the spread of scientific and technical knowledge. During the Cold War, other "sensitive" technological information was subjected to stringent

---

66. Harold P. Green, *"Born Classified" in the AEC: A Legal Perspective*, BULL. ATOM. SCIENTISTS, Dec. 1981, at 29.

67. *Id.*

restrictions such as pre-publication review requirements and limitations on international data-sharing.[68]

Were such efforts successful? Given that we won the Cold War, much has been forgiven, but as recently as the 1980s most scientists believed controls on scientific information were overly strict and were doing more harm than good.[69] Even some military experts fear that keeping nanotechnology under wraps via military classification would be a mistake. Not only would it undermine the civilian economy, but it would push research underground. As Admiral David Jeremiah writes:

> Somewhere in the back of my mind I still have this picture of five smart guys from Somalia or some other nondeveloped nation who see the opportunity to change the world. To turn the world upside down. Military applications of molecular manufacturing have even greater potential than nuclear weapons to radically change the balance of power. In anticipation of that possibility the uninformed policymaker is likely to impose restrictions on development of technology in such a way as to inhibit commercial development (ultimately beneficial to mankind) while permitting those operating outside the restrictive bounds to gain an irrevocable advantage.[70]

In terms of undesirables developing a secret technological advantage, the comparative risk is admittedly less under the military classification regime than under the outright prohibition regime (i.e., "mere" disadvantage in the former versus utter helplessness in the latter), but the remaining risk is clearly still significant.

Also, there is the risk that military nanotechnologies, by their very nature, will be more dangerous than civilian nanotechnologies, since civilian technologies tend to be more robust and founded on a much deeper experience base than military technologies.[71] A civilian nanotechnology sphere will allow many bugs to be worked out in the

---

68. For a concise history, see Edward Gerjuoy, *Controls on Scientific Information Exports*, 3 YALE L. & POL'Y REV. 447 (1985).

69. *See id.*

70. David E. Jeremiah, Nanotechnology and Global Security, Presentation at the Fourth Foresight Institute Conference on Molecular Nanotechnology (Nov. 9, 1995), *available at* http://www.zyvex.com/nanotech/nano4/jeremiahPaper.html.

71. 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. *See* BRYAN BRUNS, OPEN SOURCING NANOTECHNOLOGY RESEARCH AND DEVELOPMENT: SOME CONSIDERATIONS, *at* http://www.foresight.org/Conferences/MNT8/Papers/Bruns/index.html (last visited Nov. 1, 2003).

open, and permit more safety oversight than a classified military program. Thus, classification of all nanotechnology research is likely to make military nanotechnology both more dangerous and less reliable than would otherwise be the case.

Military monopolization of nanotechnology also poses political risk. Nanotechnology is likely to have dramatic nonmilitary applications, ranging from enhanced computing power to a cure for cancer and old age. A military monopoly on nanotechnology would either cause society at large to forego those benefits, or — perhaps worse — place those benefits under the control of Pentagon bureaucrats. Given that the "military-industrial complex" already wields significant power via purchasing and pork,[72] do we want it to be able to offer political supporters access to secret age-reversing treatments or disease cures? Though such prospects might sound like the plot to a best-selling techno-thriller, a military monopoly on nanotechnology might make them a reality or, at the least, give rise to fears and rumors that might prove equally destructive to democracy.

C. Modest Regulation and Robust Civilian Research

If nanotechnology is not outlawed altogether or limited to military applications, then we must look to other models. Some research, of course, is largely unregulated except with regard to generally applicable laws having to do with safety (e.g., research into laser technology). Nanotechnology regulation could follow the same idea, but its potential dangers make such an approach politically unlikely, regardless of its merits.[73]

A more plausible alternative is a modest form of regulation coupled with robust civilian research — an approach that has been applied successfully to biotechnology, or "recombinant DNA" research, as it used to be called. Though some have criticized the regulatory regime governing biotechnology as overly intrusive, it has largely prevented misuse, maintained public confidence, and allowed science to proceed (yielding many new drugs and treatments). In fact, it has also created an entirely new high-technology industry sector.[74] As one might expect, this approach is championed by those who believe the benefits of nanotechnology justify development in the field (e.g., scientists, advocates for the seriously ill, et cetera).

---

72. *See* GORDON ADAMS, THE POLITICS OF DEFENSE CONTRACTING: THE IRON TRIANGLE (1981) (describing mutually-reinforcing relationship among Congress, the Pentagon, and defense contractors).

73. *See supra* Part III.A.1.

74. *See generally* Joseph M. Rainsbury, *Biotechnology on the RAC — FDA/NIH Regulation of Human Gene Therapy*, 55 FOOD & DRUG L.J. 575 (2000); Charles Weiner, *Is Self-Regulation Enough Today?: Evaluating the Recombinant DNA Controversy*, 9 HEALTH MATRIX 289 (1999).

1. Early Biotechnology Regulation

In the early 1970s, when it became apparent that genetic modifications were becoming feasible, some scientists became worried about the potential dangers. Scientist Paul Berg began doing research involving tumor viruses and *E. coli* that some feared might conceivably create infectious forms of cancer.[75] Others began to discuss the risks posed by transfering genes across species lines.[76] Berg agreed to defer his experiment until the questions were addressed.

Over 100 scientists met and discussed these issues at the "Asilomar I Conference" in 1973.[77] Later that year, at the Gordon Research Conference, several leading scientists agreed that the issue deserved more attention and drafted a letter to the National Academy of Sciences ("NAS") and the National Institute of Medicine; soon after, the letter was published in the journal *Science.*[78] Subsequently, in a press conference held at NAS headquarters, scientists agreed that research in certain potentially dangerous areas should not progress until the subject had been studied. This was followed by another letter to *Science* (and to the British journal *Nature*) explicitly calling for a moratorium on experiments that might develop deadly bacteria or viruses.[79]

The moratorium was generally observed until the scientists met again in 1975 at "Asilomar II" to develop more detailed guidelines,[80] which later became official government regulations covering biotechnology research funded by the National Institutes of Health ("NIH").[81] These guidelines have been modified as experience demonstrated that concerns about safety were generally overblown.[82] However, they remain sufficiently prestigious that many companies voluntarily sub-

---

75. *See* MATT RIDLEY, GENOME: THE AUTOBIOGRAPHY OF A SPECIES IN 23 CHAPTERS 244-45 (1999); *see also* DONALD S. FREDRICKSON, THE RECOMBINANT DNA CONTROVERSY, A MEMOIR: SCIENCE, POLITICS, AND THE PUBLIC INTEREST 1974–1981 (2001); Judith P. Swazey et al., *Risks and Benefits, Rights and Responsibilities: A History of the Recombinant DNA Research Controversy*, 51 S. CAL. L. REV. 1019 (1978).

76. *See* RIDLEY, *supra* note 75.

77. For a good, near-contemporaneous summary of these events, see Swazey et al., *supra* note 75. *See also* FREDRICKSON, *supra* note 75 (providing a more recent overview).

78. Maxine Singer & Dieter Soll, *Letter to the Editor: Guidelines for DNA Hybrid Molecules*, 181 SCIENCE 1114 (1973).

79. Paul Berg et al., *Letter to the Editor*, 185 SCIENCE 303 (1974); *see also* Swazey, *supra* note 77, at 1022–26.

80. *See* Swazey et al., *supra* note 77, at 1025–36; *see also* Roger B. Dworkin, *Science, Society and the Expert Town Meeting: Some Comments on Asilomar*, 51 S. CAL. L. REV. 1471 (1978).

81. Decision of the Director, National Institutes of Health To Release Guidelines for Research on Recombinant DNA Molecules, 41 Fed. Reg. 27,902 (July 7, 1976).

82. *See* Weiner, *supra* note 74 (describing confidentiality issues raised by widespread voluntary compliance and general fading of safety concerns with experience).

ject their work to NIH guidelines and review,[83] and standard licensing agreements even call for such voluntary compliance.[84]

2. Evaluating the Biotechnology Model

Overall, it is fair to call the regime for regulating civilian biotechnology a success. First, of course, the horrible scenarios envisioned by early critics (e.g., epidemics of cancer-bearing *E. coli*) have neither materialized nor turned out to be a real threat.[85] Second, the biotechnology industry has grown and flourished, and although industry members no doubt would prefer less regulation, it has not been strangled in its crib.

That success, of course, has its downsides, as some writers have observed, because it has limited public discussion:

> Perhaps as a result of the success of industry self-regulation of rDNA, there was very little public discussion of GM [genetically modified] products in the 1980s and early 1990s. . . .
>
> Measurable public concern about the technology did not emerge in the United States until the late 1990s — well after varieties of soy, cotton, and corn had been introduced into American agriculture — and only after the issue had become a political force in Europe.[86]

The result, interestingly, was that the lobby opposing genetically modified foods was able to capitalize on the lack of public discussion

---

83. *See id.*

84. *See, e.g.*, 3 ROBERT GOLDSCHEIDER, ECKSTROM'S LICENSING IN FOREIGN AND DOMESTIC OPERATIONS: THE FORMS AND SUBSTANCE OF LICENSING § 12:2 (2003) (calling for licensee to comply with NIH guidelines).

85. For a discussion of how early critics' fears have failed to materialize, see Glenn Harlan Reynolds, *Research and Risks*, TECH CENT. STATION (July 31, 2002), *at* http://www.techcentralstation.com/073102B.html. For example, while the then-mayor of Cambridge, Massachussetts, once expressed apprehension that genetic engineering would lead to "Frankenstein-type microbes coming out of the sewers," such early concerns today "seem almost quaint [since] even high school biology classes . . . do the same gene combining experiments that once struck fear into the hearts of public officials and private citizens." *Gene Therapy: Medicine for Your Genes* (National Public Radio broadcast, 1998) (transcript), *available at* http://www.dnafiles.org/PDFs/therapy.pdf.

86. Emily Marden, *Risk and Regulation: U.S. Regulatory Policy on Genetically Modified Food and Agriculture*, 44 B.C. L. REV. 733, 743 (2003); *see also* D.L. Uchtmann, *Starlink™: A Case Study of Biotechnology Agricultural Regulation*, 7 DRAKE J. AGRIC. L. 159 (2002).

and seize the initiative, something that probably harmed the future of many biotechnology-related products.[87]

In addition, self-regulatory regimes — just like government-run regulatory regimes — require modification to stay up to date. It is likely that new developments will require a second look at the regime for biotechnology regulation as the technology advances and as tools become cheaper. For example, it is now possible for scientists to synthesize viruses, whether beneficial or dangerous, in ordinary laboratories using off-the-shelf technology,[88] and the dangers posed by this development are, perhaps, even more immediate than those posed by nanotechnology.[89] Fortunately, however, the same technological developments are likely to make the countering of such threats easier. One expert summed it up as follows: "This kind of knowledge is really going to generate all kinds of benefits, but I also think the bioscience community is going to have to take responsibility for creating and maintaining institutions for responsibly managing this knowledge."[90]

In any case, the drawbacks sketched out here are less significant for our purposes since (a) nanotechnology is *already* being — and seems unlikely to stop being — hotly debated in public fora, and (b) nanotechnology is still in its infancy — or, at most, only toddling. Therefore, the modest regulatory regime, which has successfully allowed biotechnology to thrive in its early stages without realizing a parade of horribles, seems to provide, in contrast to the two regulatory possibilities previously considered,[91] the most promising model for nanotechnology regulation.

IV. Lessons for Nanotechnology

As should be clear by now, even though outlawing nanotechnology is likely to prove impossible and counterproductive, lawmakers need not be resigned to inaction. Indeed, the biotechnology experience suggests that a combination of self-regulation combined with government coordination and monitoring can answer legitimate safety

87. *See* Marden, *supra* note 86 at 753–58.

88. *See Scientists Synthesize New Organism*, WASH. TIMES, Nov. 14, 2003, *available at* http://www.washingtontimes.com/upi-breaking/20031113-124041-8941r.htm (describing synthesis of a phage, a benign virus that infects only bacteria).

89. *See* Rick Weiss, *Researchers Create Virus in Record Time: Organism Not Dangerous to Humans*, WASH. POST, Nov. 14, 2003, at A10 (quoting Eckard Wimmer, the scientist who "painstakingly stitched together" the polio virus two years ago, as saying that "[y]ou could use [this new] technology to make HIV in two weeks." (internal quotation marks omitted)), *available at* http://www.washingtonpost.com/wp-dyn/articles/A38211-2003Nov13.html.

90. *Id*. (quoting Tara O'Toole, Director of the University of Pittsburgh Medical Center's Center for Biosecurity, in Baltimore, Maryland) (internal quotation marks omitted).

91. *See supra* Part III.A (prohibition); *supra* Part III.B (classification).

concerns while allowing research to flourish. In fact, proper regulation offers the prospect of minimizing nanotechnology's risks, while maximizing its potential benefits. There are several key areas of regulation, each with its own appropriate regime.

A. Research

Regulation of research might be justified on two grounds. First, some might advocate regulating nanotechnology research for fear of the knowledge that might result — a suggestion already put forth by Bill Joy.[92] Such regulation is unlikely to succeed, not only for lack of consensus on what kinds of knowledge are undesirable, but also for fairly obvious First Amendment reasons.[93] While the degree of First Amendment protection enjoyed by scientific research as such is not entirely clear, regulation of research solely in order to ban the acquisition of knowledge seems rather dubious. In regulating research in order to forbid knowledge, after all, the government is really aiming at knowledge itself.[94]

The second ground for regulating research, however, is stronger. Regardless of the knowledge that it may or may not yield, the government can certainly regulate research for safety.[95] For nanotechnology, this chiefly means ensuring that research with self-replicating systems (replicators) is conducted under conditions that ensure none will escape the laboratory, and that if such escape did occur, the replicators would be unable to reproduce in the wild. Aside from obvious containment measures, such safety regulations might specify, for example, that important parts of the replicators' blueprints for reproduction depend on elements not found in the natural environment. Such an approach, in fact, is consistent with the "physical containment" and "biological containment" approaches taken to the regulation of biotechnology.[96]

---

92. *See* Scheinin, *supra* note 45, at 1F (noting that "[Joy] said *not* knowing everything there is to know 'may have group benefit as well'").

93. U.S. CONST. amend. I.

94. *See generally* Steven Goldberg, *The Reluctant Embrace: Law and Science in America*, 75 GEO. L.J. 1341 (1987). *See also* Steven Goldberg, *The Constitutional Status of American Science*, 1979 U. ILL. L.F. 1 (1979) (arguing that Constitution protects scientific research); Richard Delgado & David R. Millen, *God, Galileo and Government: Toward Constitutional Protection for Scientific Inquiry*, 53 WASH. L. REV. 349 (1978) (same); Robertson, *supra* note 56 (same). *But see* Stephen L. Carter, *The Bellman, the Snark, and the Biohazard Debate*, 3 YALE L. & POL'Y REV. 358, 369–73 (1985) (questioning whether the First Amendment protects research).

95. *See* Valerie M. Fogleman, *Regulating Science: An Evaluation of the Regulation of Biotechnology Research*, 17 ENVTL. L. 183, 185–87 (discussing regulatory and First Amendment issues).

96. "Physical containment" means precautions against escape from laboratories; "biological containment" involves ensuring that organisms used for research cannot survive outside the lab. *See* Swazey et al., *supra* note 77, at 1044–45.

B. Beyond the Lab

The real problem with nanotechnology, however, is not accident, but abuse.[97] Thus, regulation of nanotechnology must focus more on preventing deliberate destructive uses of nanotechnology rather than preventing accidents. This is likely to involve several complementary approaches.

1. Access Limitation

One approach, employed in other areas, would be to only allow licensed dependable professionals to work with nanotechnology, or at least those nanotechnologies deemed particularly risky (e.g., general-purpose self-replicating devices, which might be easier to reprogram in destructive ways[98]). Such an approach parallels the treatment of explosives and toxic substances and might offer some benefits, but at best the protection would be incomplete.[99] Just as restrictions on high explosives are evaded through the use of expedients like fuel-oil/fertilizer mixes, or through theft, bribery, and blackmail, restrictions on nanotechnology access can be evaded or neutralized by more-than-casual offenders.

2. Export Controls

Similarly, one might attempt to limit the spread of nanotechnology to hostile or irresponsible nation-states through export controls, an approach that has proven modestly effective in some areas. Nuclear programs, in particular, are easy to control because they require a large and conspicuous physical plant, need significant quantities of rare fissionable materials, and make use of equipment that was, until recently, specialized in nature and easy to control.[100] Nanotechnology does not possess these characteristics to nearly as great a degree,[101] and may be compared more accurately to less-conspicuous biological programs.

---

97. *See* DREXLER ET AL., UNBOUNDING THE FUTURE, *supra* note 16, at 254.

98. Being more flexible, they would be analogous to personal computers, which are more susceptible to backing and reprogramming than specialty "embedded" systems like those in automobile engines or toasters.

99. *See generally* Alan Calnan & Andrew E. Taslitz, *Defusing Bomb-Blast Terrorism: A Legal Survey of Technological and Regulatory Alternatives*, 67 TENN. L. REV. 177 (1999).

100. However, this approach has not stopped North Korea, India, and Pakistan from developing nuclear weapons programs. *See* FED. OF AM. SCIENTISTS, STATES POSSESSING, PURSUING OR CAPABLE OF ACQUIRING WEAPONS OF MASS DESTRUCTION, *at* http://www.fas.org/irp/threat/wmd_state.htm (last updated July 29, 2000).

101. *See supra* text accompanying note 52.

3. Professional Ethics

The single most successful example of technology control in the last century was the regulatory regime established for biotechnology.[102] What is interesting about this approach is that it was largely "soft law," more the product of professional self-regulation, culture, and expectations than of harsh regulatory systems. Applying this approach to nanotechnology has a number of advantages. First, if the nanotechnology community in general can be imbued with positive values, this approach produces a large number of "regulators" who can identify and respond to improper conduct that governmental authorities would be unlikely to notice. Second, if such an approach is regarded as morally binding by large numbers of people in the field, it is likely to be obeyed even under circumstances where formal legal controls would be unable to operate.[103] Third, such attitudes are likely to be self-reinforcing, spreading from those initially adopting the attitude to coworkers. In total, while this approach is not sufficient in itself, it appears to offer many advantages.

4. Inherent Safety

The various implementations of nanotechnology could be required to be inherently safe (i.e., resistant to accident, misuse, and abuse). For example, the "genome" of replicating nanodevices might be encrypted to make reprogramming more difficult and to ensure that "mutations" would lead to nonsense instructions; there might be limitations on the number of generations that a device could reproduce; software could be configured so that changes would produce an audit trail; and certain types of programming or operations might be prohibited. If such protections are built into the most basic elements of nanotechnology, they would probably be effective at preventing accidents, and helpful (though not insuperable) in preventing abuse. Furthermore, as previously suggested, an open source approach to nanotechnology architectures might be helpful in producing systems that are robust and resistant to abuse,[104] though this may conflict to some degree with other control approaches.

C. Evaluating the Options

In evaluating these and other regulatory approaches, it will be important to maintain a proper perspective. Many of the gross dangers

102. *See supra* Part III.C.1–2.

103. Such cultural norms, or "soft law," are, for example, why we wash our hair and mow our lawns, and are likely more effective than formal laws at ensuring such behavior.

104. *See* discussion *supra* note 71.

posed by nanotechnology (e.g., the runaway proliferation of hostile self-replicating devices) will not really be all that new. Disease organisms, after all, are hostile self-replicating devices, and we have been dealing with their threat — and with the threat of deliberate human modification of such organisms to enhance their deadliness — for some time. Indeed, crude biological weapons (and some that are not so crude) have been possessed by many nations for decades without being put into significant military use. This should be comforting.

Moreover, it is important to recognize that the choice is not simply between stepping on the accelerator or on the brake. Stopping nanotechnology through regulation is effectively impossible.[105] The choice is not "will this technology be developed at all?" but rather "what can we do to ensure that this technology develops in a benign fashion?" Regulators must exercise as much care against unintended consequences as scientists, because in actual experience, regulation leads to Frankensteinian results far more often than does science.[106]

Scholars of administrative law have long recognized the existence of what Cass Sunstein calls "paradoxes of the regulatory state."[107] Such paradoxes occur when regulation is self-defeating, something that happens more often than is generally understood. The following are a few examples of this phenomenon that may be particularly applicable to the regulation of nanotechnology.

1. Overregulation Produces Underregulation

When regulations are especially aggressive, administrators will tend not to enforce them; when statutes require especially stringent regulations, administrators will tend not to issue regulations at all. For example, extraordinarily strict rules on workplace toxins have have led the Occupational Safety & Health Administration ("OSHA") to fail in addressing all but a tiny minority of suspected toxic chemicals.[108] The burden on OSHA, and the industry, would simply be too great if more suspected toxins were controlled. In general, "[a] crazy

---

105. *See supra* Part III.A.

106. For example, the Environmental Protection Agency's requirement of MTBE as a fuel additive to promote clean air has led to serious groundwater pollution problems. CONG. RESEARCH SERV., MTBE IN GASOLINE: CLEAN AIR AND DRINKING WATER ISSUES (2001), *available at* http://cnie.org/NLE/CRSreports/Air/air-26.cfm. Similarly, as Malcolm Gladwell has reported, the decision to require airbags in passenger vehicles was driven more by regulatory ideology than by science and, though expensive to implement, it may well have cost more lives than it has saved. Malcolm Gladwell, *Wrong Turn: How the Fight to Make America's Highways Safer Went Off Course*, NEW YORKER, June 11, 2001, at 52–61. Other examples follow in the text.

107. Cass J. Sunstein, *Paradoxes of the Regulatory State*, 57 U. CHI. L. REV. 407, 407 (1990).

108. *See id.* at 414 ("Of the many toxic substances in the workplace, OSHA has controlled only ten.").

quilt pattern of severe controls in some areas and none in others is the predictable consequence of a statute that forbids balancing and tradeoffs."[109]

2. Stringent Regulation of New Risks Can Increase Aggregate Risk Levels

New technologies are usually safer than old ones, but for political reasons it is easier to impose regulations on new technologies rather than on entrenched industries. Paradoxically, this can actually make things more dangerous. Requiring that new automobiles be much cleaner, and thus more expensive, has the effect of encouraging people to drive old environmentally-unfriendly automobiles longer. As Professor Sunstein notes:

> The strategy of imposing costs exclusively on new sources or entrants . . . will discourage the addition of new sources and encourage the perpetuation of old ones. The problem is not merely that old risks will continue, but that, precisely because of regulatory programs, those risks will become more common and last longer than they otherwise would.[110]

3. To Require the Best Available Technology Is to Retard Technological Development

If the government requires companies to employ the best available technology, it creates a disincentive for companies to develop new technologies, because they will be forced to adopt the results whether they want to or not. "Perversely, requiring adoption of the [best available technology] eliminates the incentive to innovate at all, and indeed creates disincentives for innovation by imposing an economic punishment on innovators."[111]

These paradoxes of regulation suggest some specific regulatory approaches that should be avoided. Generally, they caution regulators to move incrementally, lest they aggravate the problems they are trying to address. Experience certainly demonstrates that such unintended consequences are not to be dismissed.[112]

---

109. *Id*. at 416.
110. *Id.* at 417.
111. *Id.* at 420.
112. *See* discussion *supra* note 106.

D. The Foresight Guidelines on Molecular Nanotechnology

With these sorts of concerns in mind, and with the Asilomar experience as a guide, the Foresight Institute conducted a workshop in the spring of 1999 aimed at drafting a set of guidelines for the ethical use of nanotechnology.[113] The conference, including individuals from the scientific, defense, environmental, and legal communities, undertook considerable discussion of the proper approach for nanotechnology regulation before producing the draft guidelines. Since its development, the draft has been subject to criticism and revision in an effort to identify flaws and reach consensus. The Guidelines draft is available on the Foresight Institute's website, which also provides information on how to comment and propose revisions.[114]

The Foresight Guidelines are consciously modeled on the successful experience of biotechnology regulation.[115] Like the biotechnology guidelines,[116] they will no doubt be modified as experience and scientific knowledge dictate. Indeed, the Foresight Guidelines are more like guidelines for formulating regulations than regulations themselves. The philosophy of the Guidelines is that the process of regulating nanotechnology should be Hippocratic in nature ("first, do no harm"), and that regulation should be incremental and based on experience whenever feasible. If possible, self-regulation and culture should be used in place of law, as those tools are more pervasive and flexible in their application.

Thus, the Guidelines include the following principle:

> People who work in the MNT [molecular nanotechnology] 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.[117]

In addition, the Foresight Guidelines include some more specific development principles:

---

113 *See* John Carroll, *Nanotech's Dark Side Debated in the Aftershock of Sept. 11*, SMALL TIMES, Nov. 2, 2001, at http://www.smalltimes.com/document_display.cfm?document_id=2485 (describing Monterey conference); Kenneth Chang, *Can Robots Rule the World? Not Yet*, N.Y. TIMES, Sept. 12, 2000, at F1 (describing Guidelines).

114. *See* FORESIGHT INST., FORESIGHT GUIDELINES ON MOLECULAR NANOTECHNOLOGY (2000), *at* http://www.foresight.org/guidelines/current.html.

115. Biotechnology regulation was successful because, as described above, it has allowed great technical progress without significant dangers to public safety. *See supra* Part III.C.2.

116. *See supra* note 81.

117. FORESIGHT INST., *supra* note 114.

> 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.[118]

These guidelines and principles are, obviously, only a start (just as the guidelines produced by the Asilomar conferences were only a start), but they do point the way toward a promising regulatory approach — an approach that will avoid the dangers of prohibition, and the political difficulties of a *laissez-faire* regime.

Their existence is valuable not only as guidance, but also as innoculation. Historically, Congress tends to "discover" a new technology in response to hyperbolic media attention, often moving rapidly (but injudiciously) in response to perceived public pressure.[119] The

---

118. *Id*.

119. For example, one study — purporting to analyze pornography on the internet — later became the basis for a sensational *Time* magazine cover story. *See* Philip Elmer-DeWitt, *On a Screen Near You: Cyberporn*, TIME, July 3, 1995, at 38 (discussing Marty Rimm, *Marketing Pornography on the Information Superhighway: A Survey of 917,410 Images, Descriptions, Short Stories, and Animations Downloaded 8.5 Million Times by*

presence of widespread forethought on the subject will help to ensure that, should such a spasm of regulatory interest appear, it will be constrained and informed by a well-developed base of knowledge and reflection.

The good news is that people are thinking ahead. Even some environmental groups recognize that efforts to ban nanotechnology are a bad idea. Greenpeace recently commissioned a study by researchers at Imperial College in London that, in fact, characterizes a nanotechnology moratorium called for by other groups as "unpractical and probably damaging."[120] The report also warns (in my view, correctly) that such a moratorium may nonetheless be imposed if the sort of self-regulation described in the Foresight Guidelines does not take place.[121]

Nanotechnology researcher Vicki Colvin of Rice University recently made a similar point in her Congressional testimony:

> In fact, I argue that the lack of sufficient public scientific data on GMOs [genetically modified organisms], whether positive or negative, was a controlling factor in the industry's fall from favor. The failure of the industry to produce and share information with public stakeholders left it ill-equipped to respond to GMO detractors. This industry went, in essence, from "wow" to "yuck" to "bankrupt." There is a powerful lesson here for nanotechnology.
>
> In contrast, the Human Genome Project provides a good model for how an emerging technology can defuse potential controversy by addressing it in the public sphere. Mapping of the human genome carries with it many of the same potential concerns as do other fields of genetic research. The increased availability of genetic information raises the potential for loss of privacy, misuse by the police and insurance

---

Consumers in Over 2000 Cities in Forty Countries, Provinces, and Territories, 83 GEO. L.J. 1849 (1995)). Even though Rimm's study was later discredited, the *Time* story is generally regarded as providing the impetus for passage of the Communications Decency Act. *See* Heather L. Miller, *Strike Two: An Analysis of the Child Online Protection Act's Consitutional Failures*, 52 FED. COMM. L.J. 155, 156 (1999).

120. *See* ALEXANDER H. ARNALL, FUTURE TECHNOLOGIES, TODAY'S CHOICES: NANOTECHNOLOGY, ARTIFICIAL INTELLIGENCE AND ROBOTICS; A TECHNICAL, POLITICAL AND INSTITUTIONAL MAP OF EMERGING TECHNOLOGIES 44, *at* http://www.greenpeace.org.uk/MultimediaFiles/Live/FullReport/5886.pdf (2003) (report for the Greenpeace Environmental Trust). The other groups include the Canadian ETC Group, whose moratorium call is discussed in the Greenpeace report. *Id*.

121. *See id.*

> companies, and discrimination by employers. The founders of the Human Genome Project did not try to bury these legitimate concerns by limiting public discourse to the benefits of this new knowledge. Instead, they wisely welcomed and actively encouraged the debate from the outset by setting aside 5% of the annual budget for a program to define and address the ethical, legal and other societal implications of the project.[122]

Both the Greenpeace report and Colvin are right: discussion *now* prevents problems *later*. Although there is a natural tendency among the research and business communities to avoid the spotlight and discourage public discussion, experience suggests that such an approach is generally misguided.

V. CONCLUSION

As nanotechnology continues to develop, it is likely that the debate over regulation will also evolve. Experience with biotechnology indicates that early concerns about safety are likely to be overblown and that an effective regulatory regime can be based on consensus and self-regulation. Though there are likely to be some calls for a complete ban on nanotechnology, such a strategy will not succeed. Its unworkability means that such calls will probably come from anti-technology groups who command little political support. Similarly, efforts to limit nanotechnology to military applications alone are likely to face serious social, technical and political hurdles, as knowledge diffuses and as the public seeks access to potentially life-saving technologies.

However, there will also be more responsible calls for regulation. The conscientious commentators' concerns can be met through a regulatory approach that will not stifle the development of nanotechnology. Let us hope that the political system will approach these questions with wisdom, rather than arrogance.

122. *Nanotechnology Research and Development Act of 2003 before the House Comm. on Science*, 108th Cong. (2003) (statement of Vicki Colvin, Director, Center for Biological and Environmental Nanotechnology), *available at* http://www.house.gov/science/hearings/full03/apr09/colvin.htm.