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## *INTRODUCTION*

1959 was an eventful year for science and technology. The Soviet spacecraft Lunik II became the first manmade object to reach the moon; Japanese scientists discovered that resistance to antibodies is carried from one bacterium to another by plasmids; Ochoa and Kornberg won the Nobel Prize for Physiology for the artificial production of nucleic acids with enzymes; Ford, Jacobs, and Strong showed that certain syndromes are caused by sex-chromosome defects; the first Xerox copier was introduced; and De Beers manufactured the first artificial diamond.

At the very end of the decade, on December 29, 1959, at the California Institute of Technology in Pasadena, California, Richard Feynman (who would win the 1965 Nobel Prize in Physics) gave a talk to the American Physical Society, "There's Plenty of Room at the Bottom." The talk outlined the possibility of using DNA for computers and the potential ability to "use living organisms to build tiny machinery, not just for information storage but for manipulation and manufacturing" (Gleick, 1992, p. 355). Feynman envisioned billions of what he called 'tiny factories' making copies of themselves as well as manufacturing all manner of things. To prove his point, that such advances could really be achieved, Feynman offered a pair of one-thousand-dollar prizes. The first prize was for anyone who could produce a readable book page reduced 25,000 times in each direction (the equivalent in size of printing the entire Encyclopedia Britannica, pictures and all, on the head of a pin.) The other prize would go to the first person to manufacture an operating electric motor no larger than a 1/64th-inch cube (Feynman, 1959). With mixed feelings (elation over the accomplishment and regret at the expense), he found himself writing a check for the motor the same year. He awarded the prize for the mini-sized book page in 1985 (Gleick, 1992, p. 356). More recently, the Foresight Institute has given $5,000 annual awards in Feynman's name and in 1996 announced a $250,000 "Feynman Grand Prize" for the first person to design and build two nanotechnology devices - a nano-scale robotic arm and a computing device that demonstrates the feasibility of building a nanotechnology computer (see the chronology in Appendix A.)

Since 1959, many scientists and technologists have been inspired by Feynman's ideas and have attempted to implement them in an emerging capability for molecular manufacturing — what we now call molecular nanotechnology. The results show impressive progress to-date but the most optimistic applications are still speculative. Globally, more than one billion dollars are spent each year by governments and other institutions on nanotechnology research (Nelson & Shipbaugh, 1995, p. 25). While some governments have formal policies for managing this potentially important R&D effort, the government of the United States has none.

The potential scope and formulations for such a policy encompass a wide range of potential strategies, extending from a total ban on nanotechnology research—similar to the one proposed for human cloning—to undertaking a fully coordinated national nanotechnology initiative. Although neither of these polar options is likely or desirable, a review of the field suggests that there is reason to explore the question of a national nanotechnology policy.

In this paper, I will review current U. S. science and technology (S&T) research in nanotechnology, describe the field's accelerating results, and ask what issues policymakers should consider in addressing a national nanotechnology program. Through the lens of multidisciplinary Science and Technology Studies (STS), I will review the potential risks and rewards of success (or failure) from the perspectives of policymakers, S&T practitioners, and the public in an externalist expanded study of a technology in the making (Staudenmaier, 1989).

According to some policy analysts who have expressed interest in the field, the status quo of nanotechnology policy in the United States is inadequate (Nelson & Shipbaugh, 1995). In their view, nanotechnology research efforts are disjointed, uncoordinated, and funded under the auspices of too many federal agencies and commercial firms. There are few controls or information mechanisms to provide synergy and avoid waste and duplication. Consequently, in this view, nanotechnology will take longer to come to fruition than is necessary. The RAND Corporation, the Department of Defense, and the National Academy of Sciences have issued papers recommending a more unified approach to nanotechnology research than now exists and the National Science Foundation is about to release a report with a similar conclusion.

From another viewpoint, maintaining the status quo is better than directing research into selected organizations, adding more structure or managing the funding process more carefully. To do any of these would–result in "monocropping" or "putting all one's eggs in one basket" (Bennett, 1995). From this perspective, the current, multiform approach funded by a profusion of sources works well, and one or more initiatives might be successful even if most others are not. Proponents of this policy believe that nanotechnology will most likely flourish if as many interested parties as possible invest their time, effort, and money.

In emerging technologies with potential for great good or harm—such as nanotechnology—the ways by which research resources are allocated and prioritized bear further examination. It is only in the last few years that American S&T policy analysts have looked closely at nanotechnology, and there has effectively been no top-level policy assessment.

I come to this research site as one who is intrigued by the possibilities of molecular nanotechnology. I do not, however, have "faith" that nanotechnology will bear fruit. The technical problems are not insignificant. The political and financial barriers may be insurmountable—and the full measure of the risks is not yet known—but it seems likely to many, myself included, that our best and brightest scientists and technologists will find a way to make it work. Its proponents, among them several Nobel Laureates, allege that no new scientific breakthroughs are necessary, that we need only to improve our proficiency in working with smaller pieces of matter (i.e., individual molecules) and to create more sophisticated methods of communications and computing. I share, with many who are interested in nanotechnology, a desire for technological solutions, as opposed to deprivation-based solutions, to the global issues of growth and sustainability. Scientists and technologists tend to be optimists by their nature (at least regarding their own work) and mankind has been optimistic enough to strive throughout the ages to better his condition through the science of the times.

In today's research environment, based on the scientific disciplines as they are currently defined, most nanotechnology research is conducted by scientists working on small subsets of the conventional interests of their disciplines. These projects sometimes harmonize—mostly by coincidence—with the works of others in different disciplines to advance the field.

In this paper, I hope to give policymakers a framework for deciding whether this work merits continuation, reduction, expansion, or closer management. The intended audience for this analysis includes policymakers, researchers, and students of STS. In the tradition of "practicing what you preach," I have attempted to draw from the policy, research, and STS communities to create a synergy more valuable than a detailed but isolated view from any one of the individual fields.

## *Chapter I — What is Molecular Nanotechnology?*

### *Background and Definitions*

Eric Drexler, the Chairman of the Board of the Foresight Institute, is fond of saying that a new idea is declared to be impossible until the day it is declared to be obvious. Nanotechnology is a relatively new idea and it has not yet been declared obvious. It has grown, however, from the barest conceptual germ to a multi-billion dollar research site with hundreds of investigators in dozens of countries sponsored by scores of funding agencies. On a regular basis, new issues of *Science*, *Nature*, and other refereed journals publish papers describing progress in the field. It is time to take a close look at nanotechnology from a policy perspective asking: “Why is it important? Where is it now? What should society do about it?” This chapter will provide an historical perspective on this emergent, multidisciplinary field.

There is no single definition of molecular nanotechnology that will satisfy all. There are boundary issues among the proponents and between the proponents and those who think nanotechnology to be a waste of valuable resources. For example, Nobel Laureate Richard Smalley disagrees with molecular modeler Ralph Merkle about when (and even whether) a remotely controllable self-assembler will be available (Lewis, 1997). The members of the National Academy of Sciences’ (NAS) panel on Biomolecular Self-Assembling Materials (NRC, 1996) cite many of the sources you will see in this paper but they do not cite Eric Drexler. (I will later discuss why not). Reporter Gary Stix chose to disparage the entire field in a hotly contested *Scientific American* article in 1996 (Stix, 1996).

Professional relationships among researchers who are interested in nanotechnology are just beginning to develop. There are different sets of experiences and different expectations of the right approaches. In short, there is no current, universally accepted, nanotechnology research paradigm. Yet nanotechnology research is achieving many successes (see Appendix A) in the absence such generally accepted conventions about what constitutes a field and what approaches might be the most productive.

There is some difference of opinion about the very term *nanotechnology*. According to the Foresight Institute, it is

> “an anticipated technology giving thorough control of the structure of matter at the molecular level. This involves molecular manufacturing, in which materials

> and products are fabricated by the precise positioning of molecules in accord with explicit engineering design" (Drexler, 1992b, p. 1).

Others define nanotechnology much more narrowly. They include in their definition only the capabilities that represent an expansion of the current state of microminiaturization. This paper is not about a miniaturization policy. Standard S&T practices are eminently capable of dealing with marginal improvements to the existing state-of-the-art. This paper is concerned with the more ambitious view that includes future software control over self-assembling devices.

Drexler, a member of *Newsweek* Magazine's "Century Club" of 100 people to watch in the next century (Newsweek, 1997), described his view of nanotechnology in *Unbounding the Future,*

> "Technology-as-we-know-it is a product of industry, of manufacturing and chemical engineering. Industry-as-we-know-it takes things from nature—ore from mountains, trees from forests—and coerces them into forms that someone considers useful. Trees become lumber, then houses. Mountains become rubble, then molten iron, then steel, then cars. Sand becomes a purified gas, then silicon, then chips. And so it goes. Each process is crude, based on cutting, stirring, baking, spraying, etching, grinding, and the like.
>
> Trees, though, are not crude: To make wood and leaves, they neither cut, grind, stir, bake, spray, etch, nor grind. Instead, they gather solar energy using molecular electronic devices, the photosynthetic reaction centers of chloroplasts. They use that energy to drive molecular machines—active devices with moving parts of precise, molecular structure—which process carbon dioxide and water into oxygen and molecular building blocks. They use other molecular machines to join these molecular building blocks to form roots, trunks, branches, twigs, solar collectors, and more molecular machinery. Every tree makes leaves, and each leaf is more sophisticated than a spacecraft, more finely patterned than the latest chip from Silicon Valley. They do all this without noise, heat, toxic fumes, or human labor, and they consume pollutants as they go. Viewed this way, trees are high technology." (Drexler, 1986, p. 19)

Molecular nanotechnology as we will discuss it, refers to attempts to emulate this natural "high-tech" system of manufacture. There are several potential approaches to this goal. The web site at Rice University's Center for Nanoscale Science and Technology, headed by Richard Smalley, describes three approaches to nanotechnology (Cole, 1995):

- 'Wet' nanotechnology is the study of biological systems that exist primarily in a water environment. The functional nanometer-scale structures of interest here are genetic material, membranes, enzymes, and other cellular components. The success of this nanotechnology is amply demonstrated by the existence of living organisms whose form, function, and evolution, are governed by the interactions of nanometer-scale structures.

- ‘Dry’ nanotechnology derives from surface science and physical chemistry, focuses on fabrication of structures in carbon (e.g. fullerenes and nanotubes), silicon, and other inorganic materials. Unlike the ‘wet’ technology, ‘dry’ techniques admit use of metals and semiconductors. The active conduction electrons of these materials make them too reactive to operate in a ‘wet’ environment, but these same electrons provide the physical properties that make ‘dry’ nanostructures promising as electronic, magnetic, and optical devices. Another objective is to develop ‘dry’ structures that possess some of the same attributes of the self-assembly that the wet ones exhibit.
- Computational nanotechnology permits the modeling and simulation of complex nanometer-scale structures. The predictive and analytical power of computation is critical to success in nanotechnology: nature required several hundred million years to evolve a functional ‘wet’ nanotechnology; the insight provided by computation should allow us to reduce the development time of a working ‘dry’ nanotechnology to a few decades, and it will have a major impact on the ‘wet’ side as well.”

It is too early to tell whether any or all of these approaches will be successful or to what degree. There are many in the field who think that the most likely scenario is that success will come from a combination of these approaches. For example, Bruce Smith—formerly of Wolfram Research and now establishing his own nanotechnology firm—is programming a DNA sequence (wet nanotechnology) to force molecules into very specific areas, allowing covalent bonds (dry nanotechnology) to occur only in very specific ways. The resulting shapes could be engineered to allow positional control and fabrication of nanostructures. Ned Seeman at NYU is working on a hybrid that uses DNA to make scaffolding for the structures (Seeman, 1988, p. 997).

Biological systems have the capability of creating huge volumes of very complex materials in very short times (for example, trees.)

> "A gene is a molecular device that directs the synthesis of proteins. The ability to add or remove a gene from a chromosome involves manipulation on a nanometer scale. An enzyme is a whole chemical factory on a nanometer scale. In this view, both dry and wet forms of nanotechnology can be intentionally engineered, and they can even be used in combination" (Olson et al., 1997, p. 1-5).

Few practitioners in the field are completely comfortable with the calculus of purely mechanical methods and most insist that success will be dependent upon a cross-disciplinary approach because no single discipline has within it all of the needed tools (Whitesides, Mathias, & Seto, 1991).

However it is achieved, these authors agree that nanotechnology will involve humans manufacturing molecule-sized devices that can replicate themselves and make other things in quantity. It is intended that these "assemblers" will be able to make anything we can design, to make it quickly and inexpensively, to make it from plentiful molecules such as carbon, and to make at least some of it software-controllable.

### *Potential benefits of nanotechnology (if it is realized)*

Richard Feynman described the use of small hands to make smaller hands, to make even smaller hands, etc. in order to create the tiny devices he hypothesized. He used hands because that was an explainable method of input, output, and control. We have other ways of manipulating things in environments unsuitable for our hands. We operate in space with satellites, undersea with submersibles, on computer disk drives with read/write heads and lasers. Operating at the molecular level is not conceptually different from these other environments. Drexler theorizes the use of what are, in essence, molecule-sized Lego's to make programmable robots that are smaller by far than human cells, to accomplish the task of molecular manipulation. Seeman and others would use DNA not only to program, but also to form the structure of, molecular machines.

Molecular nanotechnology has the potential to generate innumerable (and to a great degree, unforeseeable) benefits and risks for mankind. The potential benefits might fall into three categories. First are the benefits that could come just from doing nanotechnology research whether it ever meets it full potential or not. Researchers are trained, lessons are learned, institutions are funded, vendors make profits, etc. In this sense, the topic of the research is less important than the fact that there is a research endeavor. Even “failed” experiments and disproved theories instruct us and improve the general store of knowledge. Nanotechnology research, in that it impacts and crosses-over so many fields, offers as much in this respect as other emerging fields and therefore merits investment insofar as proposals are competitive and pass peer review requirements.

Secondly, even if nanotechnology never progresses beyond the microminiaturization stage, the benefits are thought likely by some to far outweigh the research costs. The expected benefits that may come from microminiaturization are the reason IBM and its competitors are investing in the field. Heinrich Rohrer of IBM’s Zurich research facility gave a lecture on nanotechnology at the National Science Foundation in 1997 (Smith, 1997). Although Rohrer discussed the assembly scenario, he spent much more of his time talking about miniaturization (Smith, 1997 and Chong, 1997). He said that companies that manufacture computers and the organizations that use them would have no choice but to invest in the miniaturization aspects of nanotechnology because conventional lithography has just about reached its limits. Competition and increasing energy requirements alone would be sufficient to force improvement to continue at a “Moore’s Law” pace—that is that the number of transistors that can fit on a chip doubles every 18 months (Smith, 1997).

Besides chip density, we could reasonably expect other benefits from intermediate success in nanotechnology research. These include such properties as greatly improved coatings, higher strength and hardness for materials, greater ductility and toughness, better efficiency in optics, improved catalysis, and novel magnetic properties. The benefits also include biomaterials and sensors of many types, the merger of biology and electronics, increased functionality per weight or volume unit, smart weapons, agent detection and remediation (Siegel et al., 1998). It is now the “conventional wisdom” that nanotechnology research is cost-effective and likely to bear economic fruit according to a report sponsored by the National Science Foundation (NSF), the Air Force’s Office of Scientific Research (AFOSR), the Office of Naval Research (ONR), the Department of Commerce (DOC), the Department of Energy (DOE), the National Institute of Standards and Technology (NIST), the National Institutes of Health (NIH), and the National Aeronautics and Space Administration (NASA) (Siegel et al., 1998). All of these potential benefits would make it desirable to continue and expand research in the field, all other things being equal.

Finally, the benefits that could come from a full implementation of molecular nanotechnology and molecular manufacturing are remarkable. The most optimistic proponents project such capabilities as cell repair at the genetic level. This could, they hold, allow the end to disease processes as we know them, and an end to the aging process (Drexler, Pergamet, & Peterson, 1991, p. 215, 224). This potential benefit has long been attractive to many. Twenty-four years before *Unbounding the Future* suggested the possibility, Weinberg wrote,

> "Of all the sciences, the biomedical sciences are the only ones specifically aimed at, and relevant to, alleviation of man's elementary sufferings, disease and premature death. There is urgency of the most excruciating kind in getting on with this job. The assault on human disease, insofar as it may result in alleviation of immediate everyday human suffering, has an urgency comparable to the urgency with which a nation prosecutes a war" (Weinberg, 1967, p. 101-104).

President Clinton, in his 1999 budget package, asked Congress to increase the NIH budget by 50% over the next five years (Clinton, 1998). Some advocates claim that nanotechnology, in its most advanced form, could do more to advance medical practice than any other proposed capabilities now on the horizon.

MIT's Marvin Minsky, in his foreword to *Engines of Creation*, recounted other examples of social benefits that could derive from nanotechnology. We could, he said,

> "manufacture assembly machines much smaller even than living cells, and make materials stronger and lighter than any available today. Hence, better spacecraft. Hence, tiny devices that can travel along capillaries to enter and repair living cells. Hence, the ability to heal disease, reverse the ravages of age, or make our bodies speedier or stronger than before. And we could make machines down to the size of viruses; machines that would work at speeds which none of us can yet appreciate. And then, once we learned how to do it, we would have the option of assembling these myriads of tiny parts into intelligent machines, perhaps based on the use of trillions of nanoscopic parallel-processing devices which make descriptions, compare them to recorded patterns, and then exploit the memories of all their previous experiments" (Minsky, 1986, p. vi).

Another set of best case benefits includes the theoretical ability to manufacture virtually anything at practically no materials' cost. This would include food, houses, cars, computers, and practically anything else one can imagine. Hard goods could be made of "diamondoid" materials allowing previously unknown strength and durability. Space travel could be facilitated by strong materials reducing the weight of payloads and launch vehicles. There is even work on the drawing boards for self-assembling launch platforms that could grow high enough to reduce the impact of gravity on launches.

Even those who care very much about making these best case scenarios happen do not know whether they are possible. Nevertheless, if any of it is possible, then much or all of it is possible. The common key to the best case scenarios is precise control of the placement of molecules into machinery that can respond to external programming—tiny robots if you will. These nanomachines would assemble many copies of themselves that would, in turn, assemble the desired finished products. As far as process is concerned, it matters very little whether the desired product is a hamburger or a bowling ball as long as the raw molecular materials are available and the software is sufficiently robust to handle the complexity of the manufactured product. This is certainly not something we could do today, nor can we extrapolate recent progress to predict that it will happen. But it is perhaps no more removed from our current capabilities than landing a robot on Mars was removed from the capabilities of Goddard's generation.

### ***Potential risks of nanotechnology***

The potential risks of nanotechnology are as frightful as the potential benefits are wonderful. If it were developed in secret and without societal controls, nanotechnology could be dangerous beyond precedent. Ralph Merkle of Xerox's Palo Alto Research Center describes some of the dangers of uncontrolled nanotechnology,

> "Self-replicating systems pose two major risks. One is that a self-replicating system will continue to replicate unchecked. The other is that during replication there will be changes or alterations in the self-replicating system that will allow mutations that lead to some sort of evolutionary process" (Merkle, 1992, p. 290).

We have a model for dealing with this kind of risk that has worked for nearly three decades—the kinds of controls that were applied to recombinant DNA research (Krimsky, 1983). In the early 1970's, researchers were actively pursuing advances in this new "biotechnology." In 1971, concern developed about the potential hazard of the proposed insertion of DNA from a monkey tumor virus into E. Coli bacteria. Experimentalists were encouraged not to pursue this course but many continued their early-stage work. In 1973, such safety issues were discussed at the Gordon Research Conference. A group of scientists led by Paul Berg of Stanford sent a letter to the National Academy of Sciences (NAS) requesting the appointment of an advisory committee. The next year, NAS committee members wrote letters to *Science* and *Nature* asking for a temporary worldwide moratorium on certain types of research and calling for an international conference. They also asked NIH to set up an advisory committee to promulgate guidelines and, consequently, the Recombinant DNA Advisory Committee (RAC) was established.

In 1975, at an international meeting at Asilomar, California the RAC recommended that recombinant DNA research should continue with appropriate physical and biological containment. During the next four years, the scientific community policed itself, instituted a self-imposed moratorium, and established peer review procedures to insure safe containment. Though the recombinant DNA risk management process could instruct the nanotechnology field, clearly we needed to look more closely at the issue.

As with any new knowledge, nanotechnology poses numerous potential risks—some foreseeable, some not. Among the foreseeable risks is that of malfunctioning prototypes. If working assembler/disassemblers are successfully created, then the primary essential variables will be the availability of raw materials and the reliability of software. The assemblers themselves and the software to program them, initial versions as well as later iterations, will be subject to typical new product prototyping errors. If the next version of Microsoft® Windows is flawed, it probably will not be fatal to anyone. However, a flawed assembler or flawed assembler software might be fatal to many—a run-away assembler could, in worst-case theory, use *any* matter, including everything in the biosphere, as raw materials.

There are tools such as “design-ahead” software that can allay this kind of risk. Dodge advertises that before they made a single part for their Intrepid, they built the entire car digitally—digital model, virtual test track, resulting in thousands of errors and millions of dollars saved. Modelers are working on the same kinds of tools for nanotechnology. But the consequences of significant errors are such that the use of the appropriate precautions must somehow be guaranteed. A primary concern with the current lack of oversight is that someone who is talented enough could create an assembler without sufficient social safeguards.

There are other serious potential risks—among them the twin risks of nano-weapons and biowarfare. As many have noted, the possibility of using nanotechnology for aggressive purposes is very frightening. If nanotechnology has the potential to meet the expectations of its most optimistic proponents, it could also have the consequences that are most feared. Not only is there the potential ability for small organizations and sub-national entities to build powerful weapons quickly, but the weapons could be self-assembling, allowing for explosive proliferation and even programmable ‘germ’ nanomachines for warfare (Wisz, 1995).

We could be facing a world where molecular nanotechnology allows such capabilities as the creation of artificial viruses for which there would be no natural immunity, or invisible devices that could find specific human targets, sample their DNA, and create “designer weapons” on the spot. DARPA already has an extensive counter-biological warfare program. None can doubt the need for such a program in today’s environment, and it would be even more necessary in a nanotechnology-capable world.

Another risk category is that of unexpected risk. Just as we cannot predict the future benefits, we cannot predict all of the risks that might be inherent in such new and potentially revolutionary capabilities. Nanotechnology, as any such new technology, will have unforeseen and unforeseeable consequences (Bauer, 1990), some of which could be universally negative and some of which could be positive for some and devastating for others.

Given the kind of capability that nanotechnology could place in the hands of political, religious, or economic terrorists, it would be surprising in the extreme if our military is not already investigating the possibilities. Any such program would by necessity be secret and outside the purview of this paper. Since the U. S. military is by far the biggest spender of R&D money, yet it is very low on the list of nanotechnology funding sources, I suspect that such an activity is underway. It would seem only prudent that the government take the highest interest in a technology with this degree of negative potential. At present, there is no unclassified effort to monitor progress in the field from a risk perspective.

### ***Nanotechnology research since 1959***

It is incumbent on anyone who would inform policy in a given field to have some knowledge of the state of that field. To provide a representative sampling of the significant events in the history of molecular nanotechnology across many different disciplines, I undertook a literature search, concentrating on refereed journals such as *Science* and *Nature*. I emphasized these journals in my research because, as Alvin Weinberg said, “The ‘refereed’ literature, by means of which scientists criticize each other and maintain the standards of science, is one of the most important means of maintaining science as a responsible undertaking” (p. 59).

The results of this search can be found in their entirety in Appendix A of this paper[1]. They show substantive and accelerating efforts—mostly over the last decade and a half—in nanotechnology-related research. The chronology represents findings, discoveries, and achievements by individuals, U. S. government agencies, foreign governments and investigators, private funding organizations and firms, and academic institutions. The researchers come from around the world and from many different scientific and technological disciplines.

This “discipline-boundedness” is significant. Many of the investigators listed in the chronology are unlikely to have ever heard of each other because they work in different circles. This issue was clearly articulated by the leaders of the 1998 WTEC Workshop — Global Assessment of R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices (Siegel, 1998). Computer scientists tend not to understand the nuances of physics, physicists tend not to know biology very well, biologists know something about chemistry but do not use the terminology used by chemists, chemists do not do a great deal in the area of mechanical engineering, and mechanical engineers do not often work with individual molecules. The importance of this disciplinarity issue and how it effects money, institutions, and the peer review cycle will be amplified in Chapter V.

### *Nanotechnology progress highlights*

Highlights from the chronology[2] are presented in the figures that follow, one for each of six time frames. Nanotechnology research began slowly in the 1960’s through the mid-1980’s, began to grow between 1986 and 1988, and picked-up steam between 1989 and 1991. The field became more respected and thereby attracted more investigators between 1992 and 1994. It started to show signs of congealing into more of a combined discipline in 1995 and 1996, and began to receive substantial funding from the U. S. government in 1997. The rate of publications

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[1] I hope not to give the impression that this data is less significant by virtue of its placement outside of the main body of the paper. I suggest a thorough reading of the appendix to anyone who wants to seriously consider a case for cross- and multi-disciplinary treatment of nanotechnology research or the possibility of a new paradigm emerging.

[2] Full citations are found in Appendix I.

has increased as funding sources have expanded and as researchers in the field have begun to receive prestigious awards, including several Nobel prizes.

**Nanotechnology Research — 1959 to 1985**

During the period from 1959 through 1985, nanotechnology concepts were just beginning to take shape in the minds of a few researchers. A number of events took place that were not nanotechnology per se, but that helped to set the stage conceptually and technically.

- Richard Feynman gave his original “Plenty of Room at the Bottom” talk and awarded two $1,000 prizes.
- NobuhikoTaniguchi coined the term “nanotechnology”.
- Researchers described the rotation of a bacterial flagellar motor, the computer modeling of protein folding and engineering, the chemical synthesis of DNA, the characteristics of RNA catalysts, and the concept of molecular engineering.
- Computer science made significant strides in speed, storage, and memory density.
- Rohrer and Binnig built the first Scanning Tunneling Microscope (STM).
- Richard Smalley discovered Buckminsterfullerene.
- The last two achievements would result in Nobel Prizes in physics and chemistry.

**Figure 1 Nanotechnology — 1959 to 1985**

**Nanotechnology Research — 1986 to 1988**

Nanotechnology research began to take shape, with clearer definition and breakthroughs in some nanotechnology-enabling capabilities.

- Drexler published *Engines of Creation*, the first multidisciplinary, long-range explication of the potential of nanotechnology.
- Researchers made progress in biological constructs, protein engineering, selective binding molecules and molecular recognition (another Nobel), self-replicating molecules, nano-effector designs, molecular transistors, applying engineering principles to cellular biology, a molecular on-off switch, optical “tweezers”, and molecular-sized computer memory storage devices.
- MIT held its first Nanotechnology Symposium.
- Japan launched a $6 billion Human Frontier Science Program, including nanotechnology research.
- The Office of Technology Assessment (OTA) published its report on “Advanced Materials by Design” including a section on nanotechnology.

**Figure 2 Nanotechnology — 1986 to 1988**

### Nanotechnology Research — 1989 to 1991

- Progress was made in miniature medical robotics, the organic chemistry of molecular machinery, DNA structures, treating proteins as modular devices, and cellular conveyor systems.
- Investigators designed and built primitive replicators and programmable assemblers.
- Others described atomic-scale and bacterial flagellar motors and enzymes with bendable and foldable hinges.
- Buckytubes were manufactured for the first time.
- AAAS published a special nanotechnology issue of *Science*.
- Nadrian (Ned) Seeman of NYU announced plans to build three-dimensional structures out of DNA segments, then to hook proteins to the resulting framework.
- The first Foresight Conference on Nanotechnology was held "to promote understanding of nanotechnology and its consequences."
- The Institute of Physics published issue #1 of a new refereed journal, *Nanotechnology*.
- Japan's MITI announced that it would spend some $171 million over the next ten years to study "microtechnology" and Germany announced plans to devote some $255 million over four years to similar research.

**Figure 3 Nanotechnology — 1989 to 1991**

### Nanotechnology Research — 1992 to 1994

- Drexler's *Nanosystems—Molecular Machinery, Manufacturing, and Computation* was named the outstanding book in computer science for 1992.
- Researchers planned to study molecular interactions by fusing proteins to the structural components of viruses.
- Others used Atomic Force Microscopes to perform machining and cutting operations, and designed a prototype molecular switch based on organic molecules for use in optical computing.
- Researchers started to apply for patents for fullerene-based products and capabilities—there were nine patents awarded in 1992, twenty-four in 1993, and sixty-one in 1994.
- Scientists demonstrated room temperature quantum effect integrated circuits, made self-assembled polymer, peptide, and lipid nanotubes, and single-molecule logic gates. Others worked on "directed evolution" PCR, atomic resolution mapping, and using SPM's to position molecular building blocks.
- Progress was made in understanding mitochondrial rotary engines, using nanotubes as ion channels, creating simulations of atomically perfect fullerene gears, software to fold amino acid sequences, and using an STM to fabricate semiconductor nanostructures.
- During this period, the Defense Advanced Projects Agency (DARPA) began its ULTRA Project to create computers 100 times faster than current systems.
- Rice University announced a Nanotechnology initiative with researchers in chemistry, physics, biochemistry, and chemical engineering directed by Nobel Laureate Smalley.

**Figure 4 Nanotechnology — 1992 to 1994**

## Nanotechnology Research — 1995 and 1996

Advances were made in the many separate fields that were now beginning to appear (to some) like a nanotechnology field.

- A firm developed a new capability to "cut and paste" DNA.
- There was modeling work on molecular "steam engines," and on buckytubes as conveyors, molecular bearings, simulated motors, and simulated diamondoid bearings.
- Covalent chemistry was used to freeze self-assembled structures in place.
- Researchers used heat and light as a signaling mechanism for molecular devices.
- Others made progress in gene sequencing and the design of biologically based structures.
- One multi-university team built a "Nanomanipulator" that coupled an STM to a virtual-reality interface that operates over a scale difference of a million to one.
- Smalley's group made progress in the creation of ropes of single-wall nanotubes.
- MacDonald of Cornell's National Nanofabrication Facility announced a silicon-tipped micro-electromechanical STM with a tip that works in three dimensions.
- Scientists moved and precisely positioned individual molecules at room temperature.
- Researchers demonstrated that single molecules can act as molecular wires to conduct electricity, fabricated functioning molecular-scale circuit elements using chemical self-assembly, and made nanometer-scale wireless electronic switches out of quantum dots.
- A software entrepreneur announced the formation of a company for building the first assembler to prove that nanotechnology is possible in the next 10 years.

Government and policy activities also began to accelerate during this period.

- The NSF Directorate for Biological Sciences issued a report on "The Impact of Emerging Technologies on the Biological Sciences."
- The Hughes Aircraft Company Studies and Analysis Group published a government-funded report on the impact of technology on military planning that pointed out the potential importance of the "increasingly fine control of matter" including biotechnology, molecular modeling, scanning probe microscopy, molecular computing, and digital material processing.
- Former Chairman of the Joint Chiefs of Staff, Admiral David E. Jeremiah, USN (Ret) spoke on "Nanotechnology and Global Security."
- Ned Seeman won the Foresight Institute's Feynman Prize for his work on DNA to make structural objects.
- Globus and Levit of NASA's Ames Research Center began funded work in computational nanotechnology.
- The Japanese government's investments in nanotechnology efforts were estimated to be in the hundreds of millions of dollars each year.
- A multidisciplinary NAS panel with expertise in the physical sciences, the life sciences, and engineering issued its report, *Biomolecular Self-Assembling Materials*.
- There were thirty-four patents applications for fullerene-based products and capabilities in 1995, and twenty-one in 1996.

**Figure 5 Nanotechnology — 1995 and 1996**

**Nanotechnology Research — 1997**

In S&T:

- Functional proteins were attached to a DNA backbone.
- A nanostructure was constructed out of polymers with atomically precise molecular substructures.
- A biological motor an order of magnitude smaller than a bacterial flagellum was built, and a working nano-sized biosensor was demonstrated.
- Researchers used recombinant DNA to create “molecular gatekeepers” that can be switched to open or closed positions, allowing the passage of predetermined molecules for “smart” drug delivery, chemotherapy, and configurable biosensors.
- Ned Seeman (who created cube-shaped DNA objects in 1991) and Jim Gimzewski of IBM (who designed the molecular abacus) were named *Discover’s* Emerging Technology Winners for 1997.
- *Newsweek* named Drexler to its “Century Club”—the one hundred people to watch in the next century.
- Thirty-six fullerene patents were issued in 1997.

In policy and government areas:

- The Department of Defense Task Force on the future of military healthcare (MHSS2020) formed a working group on Nanotechnology and Biotechnology and later issued its report to the Deputy Assistant Secretary of Defense for Policy and Planning Coordination.
- An international conference on Biomolecular Motors and Nanomachines was held “to start a free flow of information and opinion about how nature has designed macromolecular and supermolecular machines and to explore how or whether these principles might apply to nano-engineering.”
- The National Science Foundation announced the completion of a study entitled, “Nanoparticles, Nanostructured Materials, and Nanodevices.”
- NASA’s Ames Research Center and NSF issued requests for proposals for funded molecular nanotechnology research projects.

**Figure 6 Nanotechnology — 1997**

The progress shows no sign of abating. Researchers announced in January of 1998 that a protein called melanopsin enables light to set the biological clocks that tell frogs when to perform a host of basic functions. Although they do not suggest the possibility, if this protein is controllable (as are many proteins) this could be used as a signaling/communications method with nanomachines. In March of 1998, twenty-nine years after Feynman’s “There’s Plenty of Room at the Bottom” talk, the American Physical Society featured sessions on nanotechnology at its annual meeting. In a press release, Dr. Michael Rourkes of Caltech said, “When we get there, nanotechnology will provide techniques for the mass production of tiny functional machines assembled, atom-by-atom, with perfect precision. This happens every day, in nature, within us, and in the truly miraculous living organisms around us. But right now, Mother Nature is really the only true nanotechnologist." The press release continued that the overall goal of researchers in the field is to expand knowledge about nature's functions and processes at the nanoscale, to allow the artificially engineering of those processes and create entirely new types of ultra-miniature machines (Enright, 1998).

In addition, the U. S. military is beginning to take a much greater interest in nanotechnology than before. Not only was it a participant in the World Technology Evaluation Center (WTEC) study (Siegel et al., 1998) but, along with NSF, the U.S. Army Soldier Systems Command (SSCOM), the Army Research Office (ARO), and the Army Research Laboratory (ARL) sponsored the 1998 "Nanotechnology for the Soldier System Conference" in Cambridge, Massachusetts (SSCOM, 1998).

***Where we are on the path to nanotechnology***

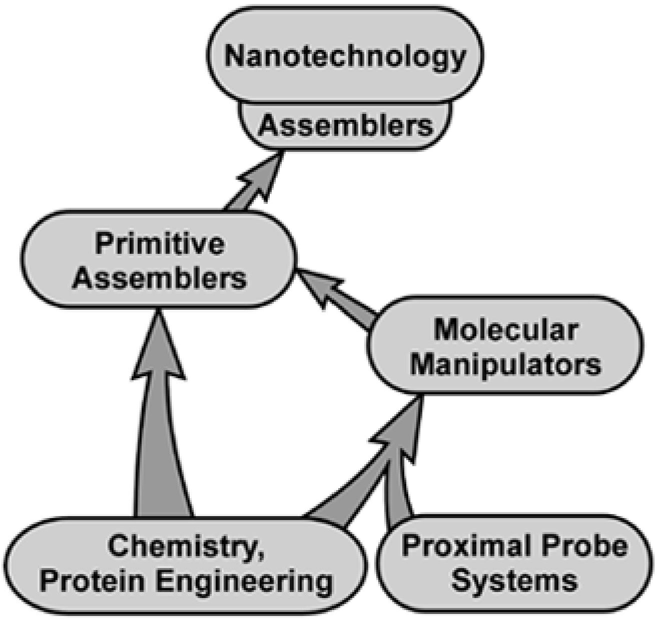

**Figure 7 Nanotechnology Development Flow Chart**
(Drexler et al., 1991)

In *Unbounding the Future,* published in 1991, Drexler discussed the most logical pathway from what was the then-current state of the art to molecular nanotechnology with computer driven assemblers. See Figure 7, above. Nanotechnology research has progressed since its publication to encompass significant improvements in chemistry, protein engineering, proximal probe systems, and to a somewhat lesser degree, molecular manipulators. Though no one has yet demonstrated an assembler, there has been substantial progress in assembler design, molecular modeling, and assembler communications and programming theory.

There appears to be acceleration in both the number and the breadth of refereed journal articles about nanotechnology-related discoveries and announcements. There also seems to be a type of “halo effect” brought about by the acceptance of nanotechnology as a research field by recognized scientists. When nanotechnology researcher Richard Smalley, as the head of a multidisciplinary team, won the Nobel Prize for chemistry, nanotechnology research became more acceptable to scientists than it had been. When the Foresight Institute featured an article on Heinrich Rohrer’s NSF talk (Smith, 1997), in its September 30, 1997 issue, it was because Rohrer was a Nobel Laureate and thereby the owner of credibility. Nanotechnology has begun to appear less outrageously optimistic in the last several years and therefore it has become more likely to attract serious researchers and to obtain funding. While this trend will take more time to establish, it is anecdotally demonstrated by the issuance of Requests for Proposals (RFP’s) for nanotechnology research by NASA and the NSF in late 1997 (see Appendix D.)

The plausibility of nanotechnology used to be highly questionable, therefore many investigators either avoided the field or identified their work as something other than nanotechnology. This certainly is not a new phenomenon, Thomas Kuhn described it in *The Structure of Scientific Revolutions* when he said

> “To a great extent these {seemingly plausible ideas} are the only problems that the community will admit as scientific or encourage its members to undertake. Other problems, including many that had previously been standard, are rejected as metaphysical, as the concern of another discipline, or sometimes as just too problematic to be worth the time” (Kuhn, 1962, p. 37).

Over the last several years—as measured by such metrics as the number of refereed journal articles and the government funds invested—the common perception of nanotechnology has been progressing from implausible, scientifically unworthy, overly optimistic and pseudo-scientific to respected, promising, and well-funded.

Although reports in the lay press are less convincing and less precise than reports in refereed journals, they are often better situated in context and can therefore help point out trends. So it is interesting that nanotechnology-related articles appear more and more frequently in the national press—from “Making Something Out of Nothing” in *Newsweek* (Rogers, 1997, p. 14) to “Nanotech: Bigger Isn’t Better” (Wu, 1997, p. S14) in *Science News*. This increasing coverage by the press does not make nanotechnology either substantive or more likely. It does, however, show a reduction in the general level of public skepticism that parallels the growing acceptance among scientific communities.

Nanotechnology is also becoming a more frequent subject matter for science fiction writers from Kim Stanley Robinson’s *Red Mars*, a positive representation of nanotechnology as an enabler of longer life-spans and planetary terraforming, to the latest X-Files book, *Antibodies* (Anderson, 1997), a story about nanomachines run amok and acting like man-made, Ebola-like viruses. Nanotechnology is a critical feature in the thought-provoking “didactic fiction” of James Halperin, author of *The Truth Machine* (Halperin, 1996) and *The First Immortal* (Halperin, 1998). While science fiction is rarely a good predictor of future breakthroughs, it can sometimes catch the fancy of future scientists, influencing them into (or out of) a field. It often reflects “outside the box” thinking that can help serious scientists and policymakers think about what they ought to think about.

Current press, science fiction, and current events notwithstanding, there is no pre-determinable path in technology (Rosenberg, 1994, p. 10) and no one can demonstrate where nanotechnology research will lead. We can see an accelerating trend through the technological trajectory in the chronology in Appendix A but it proves nothing. This apparent acceleration seems likely to continue—especially if respected scientists continue to enter the field. If other technologies provide a reliable model, the same forces of inertia and momentum that operated to slow early work in the field will operate to keep the current activity at a high level (Constant, 1989, p. 229) and (Bijker, Hughes, & Pinch, 1989, p. 176).

There is, however, a counterbalancing influence in play. The lack of a common set of terminology and experience has some dampening effect on research in the field. Although many investigators are involved, they remain involved primarily within their own disciplines and tend not to be aware of the work being done by investigators in other disciplines even when there is potential synergy in the research. Many analysts have discussed this limitation, including Phillip

Schewe (Schewe, 1997), Evelyn Hu (Siegel, 1998), Henry Bauer (Bauer, 1990), and Daryl Chubin and Edward Hackett (Chubin & Hackett, 1990) and several government studies (NSF et al., 1995) and (NRC, 1994). I will return to this important theme in Chapter V.

All of the nanotechnology research in the United States as described here has occurred without a formal national nanotechnology policy of any kind. The extent and apparent acceleration of research activity may indicate that there is a need for policymakers to pay more attention. If nanotechnology researchers are getting closer to proving the feasibility of self-assembling or self-replicating devices, then there is more risk and, perhaps, more reward than strategic planners and policymakers might previously have thought. In the next chapter, I will discuss current technology innovation policy in the United States and who (individually and organizationally) could give attention to the policy questions that may need to be addressed.

## *Chapter II — U. S. Technology Innovation Policy*

In the previous chapter, we established that nanotechnology research has been accelerating over the last decade and gives many signs of continuing to do so. These advances, although many have been made at U. S. taxpayer expense, have been made in the absence of any comprehensive nanotechnology policy[3]. While it is certainly possible that this laissez faire approach could continue, the magnitude of the investment and the potential risks and rewards suggest that there should at least be a policy review of some kind. This chapter will examine how various factors are typically assessed by policymakers to make decisions on the funding and management of innovative S&T and how these policies might serve to improve safe research into molecular nanotechnology.

Modern U. S. research policy began with the formation of the Office of Scientific Research and Development (OSRD) during World War II. Since that time, it has been the stated policy of our government not only to encourage, but also to actively sponsor innovative S&T research (Branscomb & Florida, 1997, p. 13). The roots of this policy were perhaps best articulated by OSRD Director Vannevar Bush in his report to President Truman, *Science, the Endless Frontier,* in 1945.

> “It has been basic United States policy that Government should foster the opening of new frontiers. It opened the seas to clipper ships and furnished land for pioneers. Although these frontiers have more or left disappeared, the frontier of science remains” (Bush, 1945, p. 6).

There are some critics (Sarewitz, 1996) who believe Bush’s approach to be outdated and others believe that industrial entities rather than the government should be the loci of S&T decisions and funding. Most policymakers, however, still agree that the pursuit of new scientific knowledge and the development of new technology is a proper, in fact a necessary role for the federal government. In order to remain competitive with other nations, and to insure the future well being of our citizens, the government must make substantial investments (Branscomb, Florida, Hart, Keller, & Boville, 1997, p. 2).

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[3] Although this paper is concerned with public policy, a thorough review of the policy process itself is outside its purview. The concepts used herein derive generally from much more in-depth views of policy and policy-making in Public Policy Analysis (Dunn, 1981), Understanding Public Policy — 8th Edition (Dye, 1995), and Policy Analysis by Design (Bobrow and Dryzek, 1987).

Science policy is not made by scientists alone but by those who allocate research and development funding. Scientists can influence policy, but they do not control it. This can be problematic because scientists and politicians or bureaucrats do not tend to have the same motivations or to use the same terminology. In fact, they often do not trust each other to make the best choices (Press, 1994, p. 18). Formulating policy for an emerging field such as nanotechnology is particularly challenging because it can also involve communities of scientists from many fields.

The NAS Report *Allocating Federal Funds for Science and Technology* (Press, 1995) offers a framework for discussing the distribution of resources for S&T. “Basic research” creates new knowledge; is generic, non-appropriable, and openly available. It often has no specific application in mind and requires a long-term commitment by the sponsors and practitioners. “Applied research” has a specific purpose and attempts to produce knowledge relevant to a technology. It can be short-term or long-term. Nanotechnology research most closely fits a third category, “Fundamental technology development (FTD),” which develops prototypes uses research findings to develop practical applications and is of general interest to many. FTD results in returns that cannot be captured by any one company. It is usually short- but can be long-term. It is not developed for one identifiable commercial or military product; and it often makes use of new knowledge from basic or applied research.

Science policy is most often concerned with the allocation of resources. The S&T budget of the United States is not really managed as a system, but rather the money is accounted for mostly after the fact (Press, 1995, p. 3). As the NAS report states, de facto priorities are established as issues arise, but at the broadest level, no one really coordinates the efforts. This is not a problem for “normal” science, which has developed internal mechanisms for setting research agendas (Kuhn, 1962). However, in the case of a nascent field such as nanotechnology, it can lead to far less efficient use of resources.

The budget process covers a broad range of issues, interactions, and conflicts. Because of this complex set of interactions, de facto priorities emerge. Those priorities reflect contending goals, different actors and funding agencies, and all of the competing jurisdictions. Given the sometimes radically different perspectives and motivations of the competitors, making de facto policy, is a challenging task (Gibbons, 1997d, p. 3). Policymakers and budgeters must question the costs, benefits, and risks of various strategies and tactics. These factors must be judged through political, financial, and scientific lenses. Individual policymakers will derive answers and, from them, they will create a baseline for their thinking. From this starting position, they later filter all of the new data they receive, and it is on the basis of these filters that they make policy and funding decisions.

Thus, one who wishes to understand and/or influence policy must know which actors can secure and influence changes and what kinds of factors enter their minds. Who are the players and what makes them tick? “What are the roles of the various stakeholders in technology policy—states, universities, national labs, federal agencies, and industry? What are the institutional mechanisms through which technology policy can be managed” (Branscomb & Keller, 1997, p. 1)? Let us briefly review these institutional structures as they could relate to nanotechnology policy.

### ***Strategic policymaking structure***

The strategic policymaking entities in the United States are the Executive Office of the President (including the Office of Science and Technology Policy, the Office of Management and Budget, and other Executive Branch policy structures) and the Congress. Each of these is heavily influenced by various scientific and industrial interest groups. With this is mind, let us look at each policymaking stratum in turn, beginning at the top.

### ***Executive Office of the President***

The White House policy structure includes the Office of Science and Technology Policy (OSTP) and its subsidiary organs, the National Science and Technology Council (NSTC) and the President's Committee of Advisors on Science and Technology (PCAST). These organizations help the President coordinate science, space, and technology policy and programs across the federal government. The following organization chart from the OSTP web site shows the organization including the PCAST, the NSTC, and the Science (SCI), Technology (TECH), Environment (ENV), and National Security and International Affairs (NSIA) Divisions.

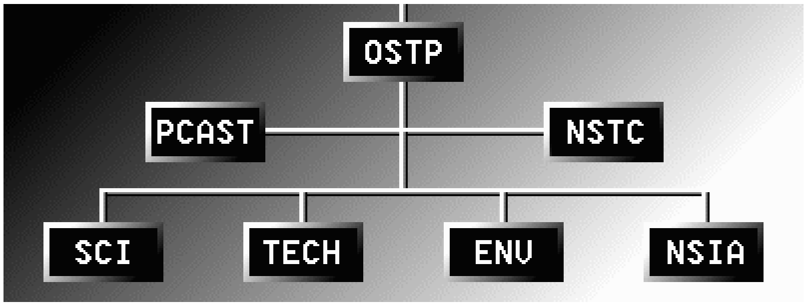

Figure 8 Office of Science and Technology Policy Organization Chart Source: “OSTP Organization” <http://www1.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Info.html>

The PCAST, whose members are drawn from non-government institutions in industry, education, and the research community, is the highest level private sector S&T advisory group for the President. It “provides feedback about Federal programs and actively advises the NSTC about science and technology issues of national importance.” (Gibbons, 1997a) The PCAST, which replaced the discontinued President’s Science Advisory Committee (PSAC), is currently co-chaired by John Gibbons, Assistant to the President for Science and Technology and Director of OSTP, and John Young, former Hewlett Packard CEO. PCAST concentrates on giving advice in areas of strategic scientific importance and has no budgetary or legislative power (Congress, 1991a, p. 76). However, as a staff organization with the power to decide what alternatives to present, it has more than a little influence.

The National Science and Technology Council (NSTC), chaired by the President, consists of the Vice President, the Assistant to the President for Science and Technology, cabinet secretaries and agency heads with significant S&T responsibilities, and other White House officials. It helps the President coordinate science, space, and technology policy and programs across the federal government by planning coordinated R&D strategies and making budget recommendations. It therefore has a great deal of influence over S&T priorities.

OSTP Chairman John Gibbons describes the role of the NSTC as follows:

> “The NSTC acts as a ‘virtual’ agency for science and technology to coordinate the diverse parts of the Federal research and development enterprise. An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in areas ranging from information technologies and health research, to improving transportation systems and strengthening fundamental research. The Council prepares research and development strategies that are coordinated across Federal agencies to form an

> investment package that is aimed at accomplishing multiple national goals" (Gibbons, 1997b, p. 1).

The strategic importance of the OSTP cannot be understated. While it does not become involved in the day-to-day management of S&T, it has the very powerful responsibility to pose the questions that will dominate the scientific agenda. Gibbons describes the OSTP this way:

> "In accordance with the National Science and Technology Policy, Organization, and Priorities Act of 1976, the Office of Science and Technology Policy (OSTP) prepares a biennial report to the Congress on science and technology. This report addresses the President's policy for maintaining the Nation's international leadership in science and technology; developments and Federal actions of national significance in science and technology; currently important national issues that are affected by science and technology; and opportunities for using science and technology and associated human resources to achieve Federal program objectives and national goals. OSTP advises the President of the United States on policy and budget formulation in all matters in which science and technology are important elements. OSTP also coordinates the development and implementation of the Administration's domestic and international science, research, and technology policies, programs, and budgets in support of the President's goals for strengthening the economy and creating jobs, improving education and health care, enhancing the quality of the environment, harnessing information technology, and maintaining national security. OSTP also fosters strong partnerships among Federal, State, and local governments and the scientific communities in industry and academia" (Gibbons, 1997b; Gibbons, 1997c, p. 1).

To date, neither the OSTP, the PCAST, the NSTC, nor any of their subsidiary agencies or boards has looked closely at nanotechnology.

### *The Office of Management and Budget*

The Office of Management and Budget, which is part of the Executive Office of the President, prepares the administration's budget. In doing so, it assesses competing funding demands among agencies, adjudicating among the thousands of program managers who are vying for increasingly limited funds. The OMB evaluates agency programs, policies, and procedures, and sets funding priorities. In addition to its significant administrative and procurement oversight functions, the OMB has six budget divisions, several of which have primary impact on science—particularly the Division of Natural Resources, Energy, and Science that monitors, among other agencies, the National Science Foundation. As former National Science Advisor, D. Allan Bromley once said, "if you can control the budget, you control public policy. This is one of the facts of life that a science advisor must learn, that OMB is a tough player and not necessarily sympathetic" (Congress, 1991a, p. 77).

Unlike the OSTP, the OMB typically works at the tactical (financial) level with much more concern over individual S&T programs. Many scientists, including those whose projects have not been funded, believe that OMB budget examiners have an unwarranted degree of control over priorities and agendas. The OMB also occasionally comes under fire due to the non-public nature of its deliberations. Like the OSTP and other higher-level strategic policy planning organizations, the OMB has not yet paid any attention to nanotechnology research. As the sums spent for federally sponsored nanotechnology research grow for individual programs and in the aggregate, the likelihood of OMB attention grows. There is no fixed lower limit to describe just when the OMB should become aware, but the current rate of spending (in excess of $150M per year) may be enough.

### *Other Executive Branch Policy Structures*

Another significant player in the S&T policy community is the Department of Commerce. Commerce has been under fire recently from those in Congress who would disband it (Knezo, 1997). At this writing, the department's Technology Administration is the home of three major agencies, the National Institute of Standards and Technology (NIST), the National Technical Information Service (NTIS) which is primarily an information resource for industry, and the Office of Technology Policy (OTP).

In addition to its responsibilities in the area of standards development and measurement, NIST, the former Bureau of Standards, is charged with helping private industry develop new technologies, improve product quality, modernize manufacturing processes, and improve product reliability. One of its most important goals is to facilitate rapid commercialization of products based on new scientific discoveries. It is in this role that NIST has invested, and is continuing to invest, in molecular nanotechnology development. This will be discussed further in Chapter III.

The Advanced Technology Program (ATP) at NIST is one of the most active institutions funded by the U. S. government in the area of novel technologies. "The ATP is a unique partnership between government and private industry to accelerate the development of high-risk technologies that promise significant commercial payoffs and widespread benefits for the economy" (Powell, 1997, p. 1). Its policy of working with (mostly) small and for-profit firms through the vehicle of competitive awards serves to diminish its efforts in the newest of technologies. Since according to the rules of the program there must be a short-term payoff for the sponsored firm, any technology as long-range and speculative as nanotechnology would not be a viable candidate for many of its programs.

The Commerce Department’s Office of Technology Policy (OTP) considers itself to be “the only office in the federal government with the explicit mission of developing and advocating national policies that use technology to build America's economic strength” (Powell, 1997, p. 1). OTP is very active in such areas as the competitive needs of industry, rapid commercialization, industry-wide and international competitive analyses, and the removal of regulatory barriers. It is also active in the growing and important telemedicine and environmental management technologies. Although OTP has a stated goal of promoting private sector innovation, little that it does would lend itself to the kinds of long-range, high technology innovation discussed in this paper.

NSF, DoD, DARPA, and NIH are not at the pinnacle of strategic S&T policymaking. They do, however, make tactical policy by spending enormous amounts of money and thereby influencing the behaviors of industry and academia. Because of their ability to spend money that they often have much more practical power than organizations higher up the ladder.

All these agencies have invested in nanotechnology research. Aside from the de facto policy created when an agency invests, none of these agencies has attempted to create any strategic nanotechnology research policy, and each continues to fund research on a project-by-project basis. The total dollars expended by these agencies on nanotechnology is growing rather substantially — federal investment in nanotechnology research was $116M in FY97 (Siegel et al., 1998) and since NSF, DoD, NASA, and NIH have nanotechnology as an area of research focus in FY99, the rate of increase in the corresponding research will be higher than the average (Roco, 1998). One could conclude that there is an *effective* policy if not a stated one. We will discuss these investments in more depth in Chapter III.

### *The Legislative Branch*

There are over a hundred different congressional committees with some jurisdiction over scientific and technological research (Congress, 1991a, p. 82). There have been no bills introduced in Congress to create any strategic nanotechnology policy or funding nanotechnology research. Hearings were held in the Senate in 1992 with testimony by Eric Drexler (Drexler, 1992b) but no legislation resulted. While there have been fifteen bills introduced in the 105th Congress about cloning, there have been none regarding nanotechnology.

The legislature appropriates the funds spent by the executive branch. However, many believe that at the legislative level "we have no coherent science *policy*" (Press, 1995, p.3). It is probably not productive at this time to look for policy guidance from this branch of government. Even when not overwhelmed by partisan politics, the Congress is not organized in a manner conducive to making strategic policy.

> "Overlapping committee jurisdictions can slow and even stall policy development and send mixed signals to the executive branch and lower levels of government. Committees that try to develop comprehensive research policies are often frustrated by the vested interests of their sister committees, executive branch agencies, and various research communities" (Congress, 1991a, p. 83-84).

Virtually all members of Congress say that they care about progress in S&T. Some members have confidence in the power of the free market and competition to drive research in the right directions. Others insist that science is better left in the hands of government and academia. Some support federal research and development only to produce military systems (Branscomb & Florida, 1997, p. 5). However, almost all support R&D in their congressional districts. The temptation to use public R&D funds for partisan political purposes is often too great for most elected (and up-for-reelection) politicians.

Much of the money spent on S&T is not appropriated as the result of hearings and debate but rather as the result of "earmarking" favored congressional projects. This creates support for projects, not based on a concept of the broad, national public good, but often on grounds that are much more parochial. When one analyzes political support for a scientific program, the science may not be much of a factor. This practice, known by many as "pork barrel" has a longstanding tradition, not successfully challenged until the line item veto was approved. The line-item veto has since been struck-down by a federal district court, and may or may not survive in the Supreme Court. "Pork" may continue to be a rich source of funds for science projects. To date, there have been no congressional sponsors of earmarked nanotechnology projects. Nanotechnology research is expensive, but it comes in small bites. There have not yet been enough big, expensive projects or enough new jobs created in one place, to interest any representatives.

Not all congressional S&T policy activity occurs in committee rooms or on the floor of the House and Senate. There are also the Congressional Budget Office and the Library of Congress, which serve as resources for legislators and their staffs. Congress was previously served by the Office of Technology Assessment (OTA) which was terminated several years ago.

The OTA was created in 1972 to provide Congress with unbiased assessments of emerging technologies and the technical expertise to evaluate complex legislation on S&T issues. The OTA (which reported on nanotechnology in 1991) enjoyed bipartisan support over the years and its work was well known in the research and engineering communities but it was disbanded in 1995, as part of an effort to cut government spending and trim $19 million per year from the deficit. In their paper "Congressional Management of National Research Priorities" published in the 1994 AAAS Science and Technology Policy Yearbook just before OTA's termination, John Brademus and Davis Robinson strongly suggested that the OTA was an integral part of the Congress' ability to judiciously shape policy. They pointed out that the Carnegie Commission on Science, Technology, and Government had recommended that the OTA should "expand its capabilities and cooperate more closely with the Congressional Research Service of the Library of Congress, the GAO, and the Congressional Budget Office" (Brademus & Robinson, 1994). The formation of and justification for the OTA are discussed in depth in "Politics by the Same Means: Government and Science in the United States" (Bimber & Guston, 1995, p. 560-571). To date, the OTA has neither been reestablished nor replaced by a comparable capability and "a large gap remains in the area of informed policy assessment" (Branscomb & Keller, 1997, p. 11).

### *Interest groups*

Congressmen and administrators often seek the advice of external experts in making choices from among all of the myriad programs and policies vying for their support. There is a network of lobbyists and special interest groups who provide decision-makers with data and rationales to help them make informed choices. Examples include such general scientific organizations as the American Association for the Advancement of Science (AAAS); private non-profit societies such as the National Academy of Sciences (NAS); disciplinary science groups such as the American Physical Society (APS) and the American Chemical Society (ACS); think tanks including the Brookings Institution, the Center for Policy Research on

Science and Technology, and the RAND Corporation; and many single or special interest organizations.

There are also numerous firms that have no scientific expertise but nonetheless specialize in lobbying (some only to earn a fee) for specific projects. As is always the case when the sums of federal funds in question are large, these interest groups often tend to provide information that supports the positions of their clients or constituents. Scientific lobbyists sometimes have an immense influence on the prioritization of science projects.

Harvey Averch, in his still timely A Strategic Analysis of Science & Technology Policy, looked at the question from a historical perspective. “Although the Eisenhower, Kennedy, and Johnson administrations had all sought methods for ordering priorities among fields in basic research, no credible methods existed then (nor do they now).” The priorities were “set by history, by the political weight of particular scientific constituencies, and by bargaining and lobbying” (Averch, 1985, p. 23). Science policy and research funding decisions result from a complex set of social negotiations, and since there is never any completely correct answer to such complex questions, the lobbyists and interest groups who provide information, whether they are altruistic or self-serving, will play a major role. Throughout academia and in industry (Stephan & Levin, 1992, p. 166), scientific research always tends to follow the funding.

There are numerous active, vocal and visible advocacy groups supporting various scientific “causes” such as cancer and AIDS research, the space program, improvements in agriculture, etc. Programs supported by these groups often receive more support than programs with as much scientific merit but less political support. Aside from the Foresight Institute, the primary focus of which is to enhance knowledge and promote critical discussion, there are no advocacy groups pushing for nanotechnology research. This could change over time, of course, but at present, nanotechnology does not offer any current capability or solve any current problem. It suggests many possible, future capabilities and solutions. As these become closer (e.g., as quantum effect computing becomes the only way for computer manufacturers to continue to improve performance) one could expect to find more political lobbying for nanotechnology R&D funds.

### *Big Science, Little Science*

All of this raises the question of how these diverse entities in our government manage to sort out priorities in order to make policy. To address this, we need to consider the concept of "big science." Most strategic policy-making work involves expensive and politically visible projects. Small projects and emerging technologies, that is to say, projects without substantial political or financial constituencies, do not normally receive broad political attention, and they are not individually affected by broad, strategic policies. Their participants can obtain small grants and go about their research unfettered. Ambitious science—whether big individual projects or assemblages of smaller projects that add-up to big programs—live or die by politically made policies.

Some scientists began calling for a unified effort to unravel the genetic code in 1986. They were convinced that success in that endeavor would allow a revolution in the war against disease. It took five years from the beginning of concerted lobbying and activist efforts until the Human Genome Project was formally established in 1991 with oversight in two large federal agencies, the Department of Energy and the National Institutes of Health (Cook-Deegan, 1994). Over the fifteen-year project life, total expenditures are expected to exceed $3 billion. There was therefore a huge financial and political constituency to satisfy.

In comparison, as reported in his remarks at the World Technology Evaluation Center (WTEC) Conference by NSF's Eldon Marsh, all U.S. agencies are expected to spend approximately $153 million in the aggregate in 1998 for nanotechnology research (Marsh, 1998). Because the federal government spends so much money on science (between $35 billion and $40 billion) (Press, 1995, p. 51), the relatively insignificant amount spent each year for nanotechnology, spread over many line items and in many different budgets, is not likely to be noticed by strategic policymakers. Coupled with the lack of a political constituency seeking any change in policy, this lack of financial consequence lessens the likelihood that a strategic policy of any kind will be initiated by policymakers in the near future. The size of a budget, the amount of an investment, should be important factors in deciding whether a program merits oversight and continued funding. Nevertheless, there must be a better way than measuring the potential financial and/or political impact to decide which S&T efforts deserve policy planning.

What kinds of science projects should qualify for the attention of policymakers? Is a "big science" approach likely to produce better, more efficient, or faster results? Not necessarily. "Big science" can mean large and expensive facilities, multidisciplinary team efforts with cooperative planning where individual scientists must sacrifice some freedom in choosing goals and methods (Congress, 1988b). On the other hand, it can imply bureaucratic central management by government administrators with all of the inherent penalties that derive from being treated as big science—"politicization, bureaucratization, high risk, and the loss of autonomy" (Smith, 1992, p. 185).

In his treatise on "big science," Alvin Weinberg asked the basic question "Can we allocate resources rationally between competing branches of science? Can we adjudicate rivalries between different scientific institutions, all of which are supported by the same government (Weinberg, 1967, p. 39-40)?" He proposed that our strategic policymakers attempt to do this using the criteria of technological merit, scientific merit, and social merit and he said, "Once we have decided, one way or another, that a certain technological end is worthwhile, we must support the scientific research necessary to achieve that end" (p. 72-77).

In the case at point, nanotechnology, technological merit is effectively decided by industry which invests (or not) based on their strategic and profit plans. Scientific merit is decided by peer review. Policymakers decide, in the aggregate, how much money is available for the peers to allocate. Both technological and scientific merit are evaluated by people as a part of an institutional social process. Albeit sometimes based "more on faith than on validated strategies with robust predictive capabilities," (Averch, 1985, p. 2) those processes are somewhat objective.

The job of strategic policymakers is to allocate funding broadly and to set strategies broadly. Unless a project is very big and very expensive—or serves as a big and expensive class of projects like the human genome project or cancer research—there is small likelihood that strategic policymakers will play much of a role in resource allocation. Nanotechnology is not yet big enough or expensive enough to warrant such attention.

At the tactical level, within the organizations and infrastructure involved in funding S&T, nanotechnology research receives, in the aggregate, significant but uncoordinated funding. The status quo is not unattractive for nanotechnology researchers. Although more funding might produce quicker or better results, with high-profile political support comes high-visibility. Visibility would likely produce demands for immediate results. Researchers in molecular nanotechnology are well funded for now, and neither micro-managed or nor politicized. They can work towards incremental improvements in this rapidly evolving field, following breakthroughs in neighboring fields as appropriate.

At the strategic policy level—in the administration and in the Congress—the issues are broader, the politics are critically important, and most financial decisions (except for congressionally earmarked funds) are dealt with at the most generic level. There is currently no debate on nanotechnology policy at this level. A more strategic policy seems to make sense. The potential risks of nanotechnology are great, the potential benefits are substantial, and the investment is consequential. Technical progress in the field is tangible. However, the variety and extent of R&D achievements in nanotechnology since 1959 have gone mostly unnoticed by all but a few, because most scientists, technologists, and policymakers tend only to pay attention in their own areas of disciplinary interest.

It may be appropriate for someone in government to brief the OSTP, the PCAST, and the Congress on nanotechnology—what it is, what it means, what can be done to make it happen, what it will cost, what can be done to make it safe. The best office to do this may be that of the Director of NSF. Since NSF will spend over $90M dollars for nanotechnology efforts in FY 1999, NSF might be a good place to “catalyze a national endeavor in nanotechnology” (Siegel et al., 1997, p. 1).

In summary, many government agencies could be involved in nanotechnology policy but none currently are. S&T policy is politically and socially constructed by policymakers—no rules of science make any specific allocation decisions inherently better than any others. Since nanotechnology is nascent and emerging, there is no definitive locus for a national policy, and although nanotechnology research lacks the political support and funding that accrue to some “big science” programs, it is attaining substantial results without them. In the next chapter, we will explore the infrastructure of this tactical level and how research funds are allocated and spent.

## *Chapter III — Current U. S. Research Infrastructure for Nanotechnology*

Chapter II dealt with policy organizations and strategies. Now we turn to a discussion of the research organizations that determine policy at the tactical level by deciding resource allocations, specifically the current U. S. research infrastructure that supports nanotechnology. I will survey the relationships among government agencies, universities, industrial organizations, and individual scientists specifically involved in nanotechnology.

### *U. S. research infrastructure in general*

In the United States, basic research is predominantly conducted by federal government agencies, by self-directed but federally-funded universities, and by some private organizations. The government agencies that control most of the research funds are the DoD (with some spending not identified to the public), the NSF, and the NIH with its 24 separate and distinct Institutes, Centers, and Divisions.

In general, there is little coordination among research funding agencies except when an extraordinary circumstance (e.g. the AIDS crisis) triggers a reallocation of funds to a small number of agencies. The norm is that each Executive Branch agency submits an annual budget based, for the most part, on an inflationary increase from the previous year's budget. These budgets are typically modified by the legislative branch as influenced by the public sector. The agencies then manage the appropriated research dollars in keeping with their mission statements and they expend resources along the well-defined scientific lines they have traditionally followed. The R&D budgets of these agencies often overlap. For example, research into histocompatability can be found in DoD agencies and armed services branches, in the NSF and its beneficiaries, in the NIH and its supported organizations, in other government-funded academia, and in government-assisted private industry.

The following NSF table reflects how U. S. research funds were allocated in Fiscal Years 1995-97 by budget function:

## Table 1 U. S. R&D by Function

Table 1. Federal R&D Budget Authority by Budget Function:
Fiscal Years 1995-97

[In millions of current dollars]

| | ---------Administration's Proposal--------- | | | | |
|---|---|---|---|---|---|
| Budget Function | FY 1995 Actual | FY 1996 Preliminary 1/ | FY 1997 Proposed | Percentage Change FY 1996-97 | |
| | | | | based on current dollars | based on constant dollars |
| Total……………………….. | 68,791 | 69,069 | 69,916 | 1.2 | -1.0 |
| National Defense…..……. | 37,204 | 37,791 | 37,477 | -0.8 | -3.0 |
| Health……………………… | 11,407 | 11,902 | 12,165 | 2.2 | 0.0 |
| Space Research and Technology……….. | 7,916 | 7,871 | 8,166 | 3.7 | 1.5 |
| General Science…………. | 2,794 | 2,862 | 2,984 | 4.3 | 2.0 |
| Energy…………………….. | 2,844 | 2,504 | 2,555 | 2.0 | -0.2 |
| Transportation……………. | 1,833 | 1,752 | 1,857 | 6.0 | 3.6 |
| Natural Resources and Environment………. | 1,988 | 1,877 | 1,959 | 4.4 | 2.1 |
| Agriculture………………… | 1,194 | 1,178 | 1,192 | 1.3 | -1.0 |
| Other Functions………….. | 1,611 | 1,332 | 1,561 | 17.2 | 14.7 |

1/ Fiscal year 1996 data reflect Omnibus appropriations (Public Law 104-134).

**Source:** Agencies' submissions to OMB Circular No. A-11, Max Schedule C; agency budget justification documents; supplemental data obtained from the agencies' budget offices; and conference report for FY 1996 Omnibus appropriations (Public Law 104-134).

Figure 9 on the next page will help describe this table and point out the overlaps in R&D funding and the network of research funding agencies and stakeholders in the United States Later, I will discuss which of these agencies has contributed to nanotechnology research and to what extent.

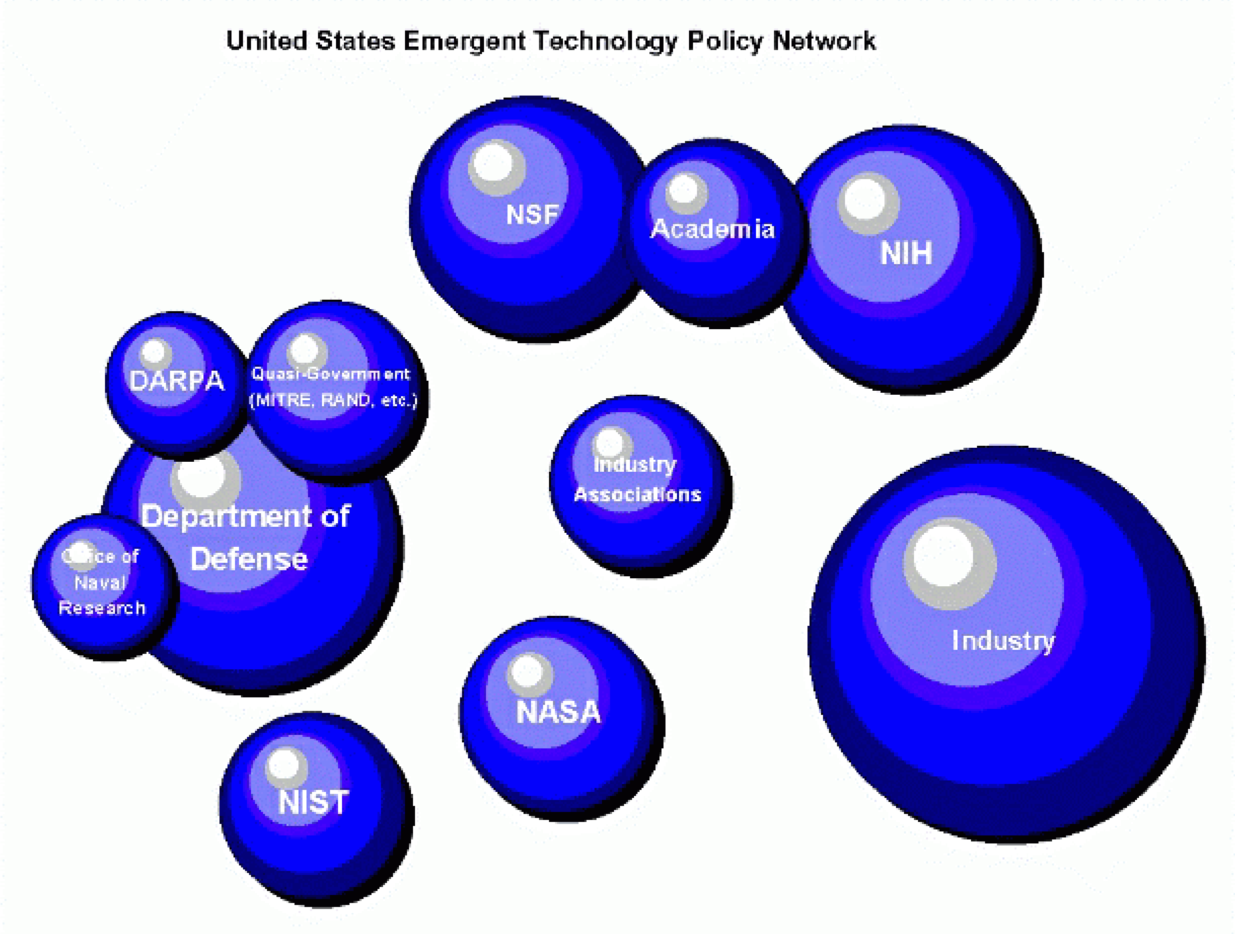

**Figure 9** U. S. Technology Policy Network

In Figure 9 above, there are two distinctive groupings and several stand-alone entities. The grouping to the left consists of the DoD and organizations subordinate to, or funded by, the DoD which, in the aggregate spend $37B per year on S&T research (see Table 1 on the previous page). These include the Office of Naval Research (ONR), several quasi-government organizations such as MITRE Corp. and the RAND Corp., and the Defense Advanced Research Projects Agency (DARPA.) The grouping at the top of the chart includes the National Science Foundation (NSF) which spends approximately $3B per year, the National Institutes of Health (NIH) which spends about $12B per year, and the academic institutions they support.

The stand-alone entities include the National Institute of Standards and Technology (NIST) which is a part of the Department of Commerce, the National Aeronautics and Space

Administration (NASA), industry associations such as trade groups and interest/lobbying groups, and industry. During the mid-1990's, research funds for all of the organizations listed above have been allocated, in the aggregate, such that 60% has gone towards development and infrastructure, and only 20% each for applied and basic research.

The President's FY1999 budget calls for substantial increases in federal R&D spending. But even if these increases are accepted by Congress, funding is shrinking as measured in constant dollars. This may not bode well for innovative projects such as nanotechnology that are removed from the course of "normal sciences" (Kuhn, 1962) as are typically pursued by these agencies. Programs that are considered scientifically conservative will likely fare better than those that are more speculative. Under such a regime, the programs that continue will tend to be those that make incremental additions at the edges of existing knowledge rather than those that attempt to break new ground. As the OTA correctly noted, "There is a connection between tight funding and peer review. As money gets tighter, peer reviewers become more conservative, less prone to take risks" (Congress, 1991a, p. 148). What policymakers must always do, at a minimum, is seek to ensure that the budget is adequate to support national security needs, promising scientific opportunities, and solving public health problems (Press, 1995, p.9).

While in its heyday in from 1950 through the 1970's, government support of R&D grew consistently. It has generally declined since 1988. Industry and other non-federal sources have picked-up some of the slack, but their support of basic research remains a very small percentage of the total investment. When budget submissions appear to increase funding for basic science, as is the case with the FY1999 budget, there is the risk of thinking (incorrectly) that basic research is maintaining its financial position (Payson & Jankowski, 1996). The following graph, taken from the 1996 NSF report *Trends in National R&D Support*, shows the annual changes in national R&D spending since 1980.

**Graph 1 U. S. R&D Patterns since 1980**

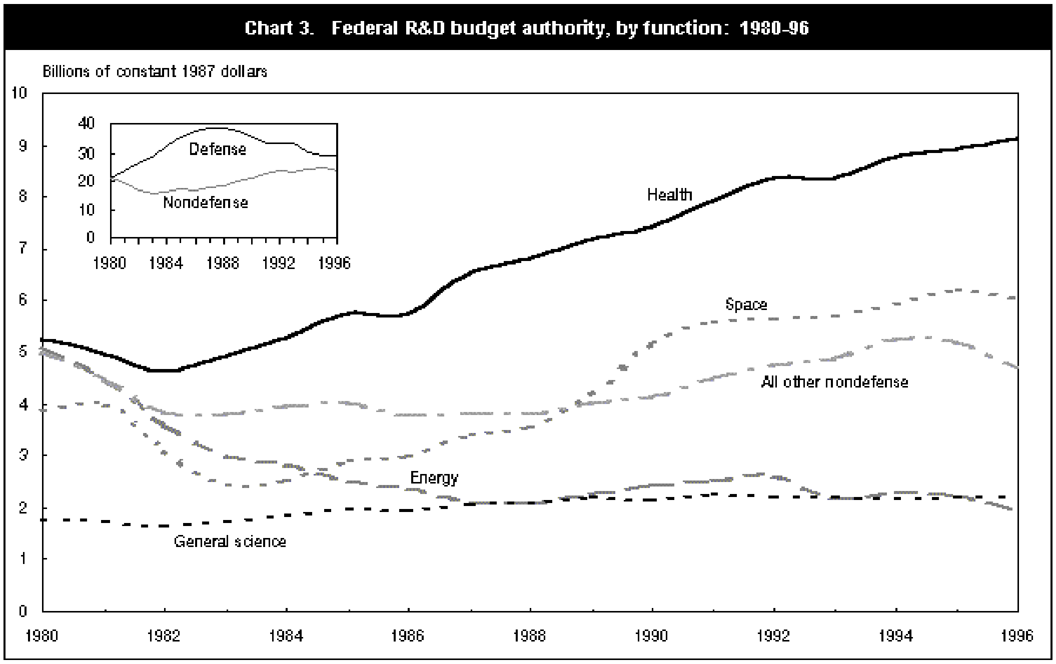

Chart 3. Federal R&D budget authority, by function: 1980-96

NOTE: Data are preliminary for 1995 and 1996.

SOURCE: National Science Foundation/SRS; table C-23

As one can see from Graph 1, there is an upward trend in health research spending, much of it attributable to spending on major programs such as cancer and AIDS research encouraged by public interest group and lobbyists. However, general science research has not increased since 1980 and “all other non-defense” has begun a downward trend not affected by the FY1999 budget.

Industry spending tends to be focused on short-term, profit-based projects. As has been the case in AIDS research, this can produce great social and economic benefits (Fried, 1997). Nevertheless, this approach usually does not lend itself to the support of S&T with long pay-back horizons. Nanotechnology, the success and character of which will be unknown for years—perhaps decades—is such a field. Federal budgets for basic S&T have not always increased and industry will only pick up the slack when there is an expectation of short-term payback. It is the government’s role to provide the funding flow for emerging fields that have proven to be deserving (Weinberg, 1967, p. 72-77).

### *U. S. S&T research infrastructure as it relates to nanotechnology*

We have seen that federal support for basic science is (relatively speaking) diminishing. Nevertheless, President Clinton has proposed that $31 billion be spent in FY1999 for non-defense research programs through his *Research Fund for America* (Clinton, 1998). Of this $31B, less than $150M will be spent on nanotechnology (Siegel et al., 1997).

Most of the nanotechnology research in the United States has been performed by academic institutions with funding from the National Science Foundation. In 1997, Dr. Mihail Roco, Program Director of NSF's Chemical and Transport Systems Division, said that the agency was spending "$65M per year on nanotechnology research" (Smith, 1997). The NSF report *Nanoparticles, Nanostructured Materials, and Nanodevices* estimated a total of $116M in U. S. government spending in FY1997 on nanotechnology research and estimated that current Japanese programs total over $220M per year (Siegel et al., 1997).

DoD spends, by far, the most R&D funds. Figure 10, below, shows the scale of S&T expenditures. Figure 11, on the next page, shows examples of current nanotechnology research sites with the network of research funding agencies and stakeholders in the United States. Figure 11, although illustrative, is not drawn to scale because to make it so would make the non-defense expenditures appear to be inconsequential by comparison.

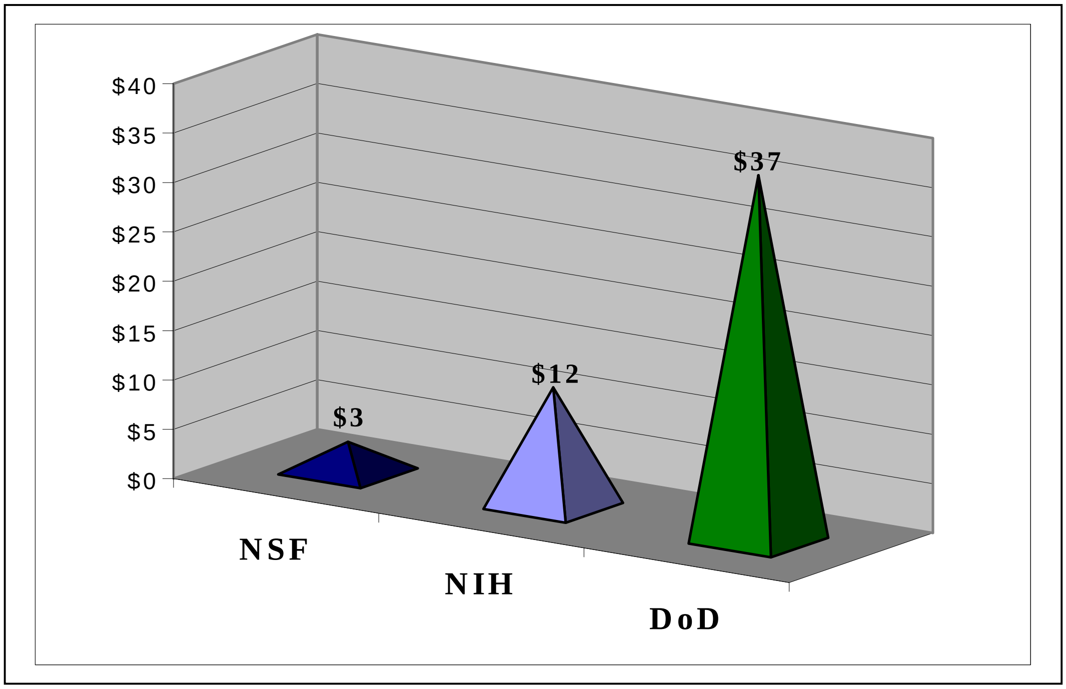

**Figure 10 Scale of Annual Investment in S&T Research in $Billions**

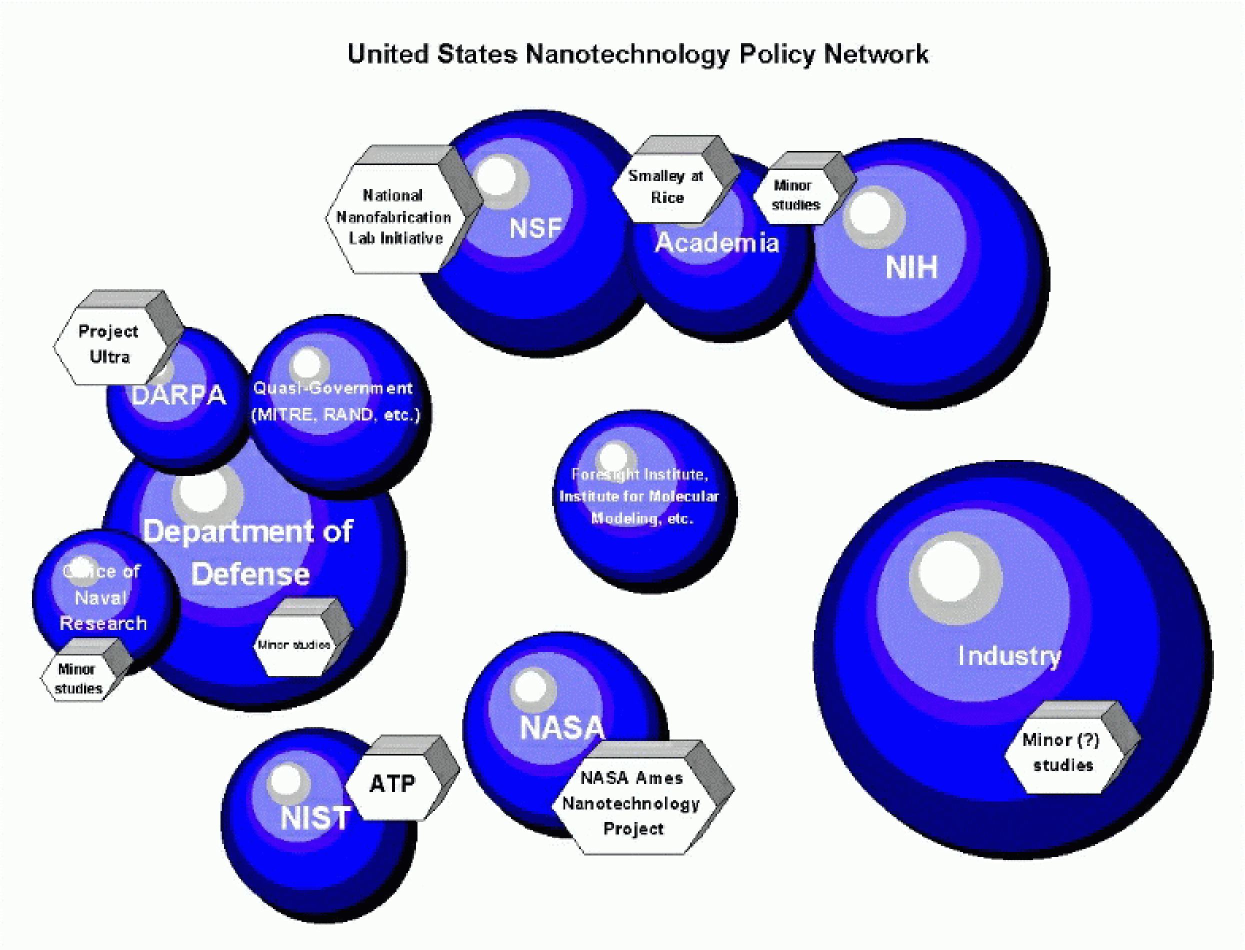

**Figure 11 U. S. Nanotechnology Policy Network**

Nanotechnology research in the United States is managed in several major unconnected groups of agencies and firms. According to the NSF report, twelve funding agencies and national laboratories participated in funding nanotechnology research, including the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), the Ballistic Missile Defense Office (BMDO), DARPA, the Department of Commerce (DOC) and NIST, the Department of Energy (DOE), NASA, NIH, NSF, the Office of Naval Research (ONR), and the Naval Research Labs (NRL) (Siegel et al., 1997, p. 1). There is a clustering of interested agencies in the Department of Defense, which includes DARPA, ONR, and several Federally Funded Research and Development Centers (FFRDC's) such as MITRE Corporation. There is another clustering around NIH and NSF and their sponsored institutions in academia. There are several major stand-alone efforts underway at NIST including synthesis and processing, characterization at nanometer sizes, and property measurement of materials phenomena at small scales. There are also several small nanotechnology-related research projects being funded by NIST’s Advanced Technology Program and several new ONR funded projects at Dr. Richard Smalley's Center for Nanoscale Research at Rice.

Perhaps the most extensive effort resides at the National Aeronautics and Space Administration (NASA.) Eleven NASA employees won the 1997 Feynman Prize for Theoretical Work for their extensive molecular modeling efforts. NASA has also committed to work in what it describes as Micro and Nano Technology (MNT) (Siegel et al., 1998, page 151) which its managers describe as being critical for human exploration and the development of space. NASA’s leaders estimate that nanotechnology research will provide benefits in the areas of mass reduction; increased robustness; miniature, autonomous vehicles; spacecraft early warning; maintenance and control; environmental monitoring; life sciences health monitoring; carbon-nanotube electronics; hydrogen and fuel storage; and the chemical storage of data (Siegel et al., 1998, page 152).

There is a major project at DARPA known as Project ULTRA (for Ultra Dense, Ultra Fast Computing Components/Nanoelectronics.) ULTRA is designed to investigate quantum devices, circuits, and architecture; materials and processing; silicon-based nanoelectronics; and high-density memory. DARPA also has programs for advanced microelectronics, advanced lithography, crystal growth, magnetic materials and devices, ultra-scale computing, ultra photonics, and virtual integrated prototyping (Siegel et al., 1998, page 148). DARPA categorizes all of these programs under the heading of nanotechnology although much of the work is arguably microminiaturization rather than nanotechnology. DARPA leaders do not discuss any research efforts in the areas of nanodefense and nanoweapons. The question of whether we already have a classified program is outside the purview of this paper.

Finally, there is much unpublicized work in the field being conducted by private industry. NSF estimates that industrial investments in nanotechnology research match those of the government (Siegel et al., 1998). Unfortunately, industrial programs are not easy to measure because firms tend to release much less information about their R&D than do their counterparts in academia and government.

Finding all of the nooks and crannies where nanotechnology research is situated is not particularly easy because there is no clearinghouse for nanotechnology research, although several recent studies have strongly recommended the creation of one. For example, Dr. Lorretta

Inglehart is Director of NSF's National Facilities and Instrumentation Program. Her primary interest is advancing new technologies such as the scanning tunneling microscope to observe and affect what happens at the molecular level. She reports that nanotechnology research is to be found in hundreds of labs and on dozens of campuses across the country. While most of the projects have grants in the $50,000 to $100,000 range, Dr. Inglehart has also directed projects with multi-million dollar awards. She said something in 1995 that is still true. “Each program, each division, has a piece of the puzzle. There isn’t really a central repository for nanotechnology research” (Inglehart, 1995). DARPA might be well-suited for this role, but the extent of its interest in civilian applications is problematic, and it already has the ULTRA project that would tend to claim precedence in any nanotechnology mission although ULTRA only covers a very small subset of the field.

The MITRE Corporation has also studied nanotechnology research in the United States and has published its findings of broadly dispersed military and civilian efforts on their web page (Ellenbogan, Montemerlo, & Mumzhiu, 1996) as synopsized in the following figure:

**Nanotechnology Research Sites**

- DoD and DOE Labs including the ARL nanofabrication facility;
- NRL centers for nanocomputing research, proximal probes, modeling of nanosystems, and novel approaches to nanofabrication;
- Los Alamos National Laboratory (LANL) Theory, Modeling, and High Performance Computing core competency work in nanoelectronics and nanofabrication;
- UCLA and University of Cincinnati Nanoelectronics Lab;
- Cornell University Nanofabrication Facility (CNF);
- MIT and University of Minnesota Nanostructures Laboratories;
- Notre Dame University’s Microelectronics Lab;
- Purdue University’s Nanoscale Physics Laboratory;
- Stanford University Nanofabrication Facility;
- Nanoelectronics Modeling (NEMO) Program;
- AFOSR’s next-generation electronics project;
- ARO’s R&D projects in nanoelectronics project;
- ONR’s nanoscale electronics and biomolecular nanocomputation programs;
- Aerospace Corporation’s nanoelectronics to reduce the size and weight of spacecraft.
- MITRE also noted the Mayo Clinic’s quantum-effect nanoelectronics research, and the work of Hughes Electronics, IBM’s Almaden and Zurich labs, Motorola, and Texas Instruments, as world leaders in nanoelectronics research.

**Figure 12 MITRE Corporation’s list of Nanotechnology research sites**

### *U. S. nanotechnology R&D — extensive but not coordinated*

It would seem that with all of this effort and resource being expended, there would be some national-level coordination of the work, at least to establish priorities and eliminate duplication and waste. Yet, in contrast to other countries, there is no coherent, coordinated policy in the United States. Technology policy tends generally to be more fragmented and less developed in the United States than in Japan (Branscomb, 1995) and this is particularly true for nanotechnology. As Neil Jacobstein writes, “The United States currently has no coherent molecular manufacturing research agenda. *Japan* has a molecular manufacturing research agenda” (Jacobstein, 1995, p. 207). Eric Drexler, who visited Japan to meet their nanotechnology researchers on a number of occasions said this about their efforts, “Where nanotechnology is concerned, Japanese research is impressive in its extent, organization, and direction. Japan may be somewhat weak in basic science, but it has growing strength in basic technology. What is more, Japanese leaders appear to regard molecular engineering as a very basic technology. This, together with long planning horizons, abundant capital, and a strong predisposition to interdisciplinary, technology-centered research, has had results much like those one would expect” (Drexler, 1990, p.1).

The RAND (Nelson & Shipbaugh, 1995), NSF (Siegel et al., 1997), and NAS (NRC, 1996) reports—as discussed in the next chapter—unanimously inform us that there is no coordinated effort in the field in the United States. As stated in the draft NSF report, “‘nano’ activities generally are fragmented in the United States. The current situation, RAND suggests, could be improved by promoting joint funding of projects and use of facilities in centers of excellence, collaborations among program managers in various agencies, and interdisciplinary activities (cross-disciplinary workshops, university-industry research groups, other mechanisms to facilitate knowledge and technology transfer)” (Siegel et al., 1997, p.2).

This chapter discussed organizations that have the task of making de facto policy and funding decisions. The next chapter will show how these government organizations influence the conduct of nanotechnology research by reviewing several recent analyses of the current state of nanotechnology research policy in the United States.

## *Chapter IV — Current State of Nanotechnology Research Policy*

The November 1997 NSF Request For Proposals (RFP) was perhaps the first large-scale nanotechnology research effort by the U. S. government. However, there have been several government-sponsored reports that reviewed the state of the field. These studies, beginning in 1991 with one by the OTA, have reported increasingly favorable outlooks for nanotechnology.

### *OTA, RAND, NAS, NSF-WTEC, and DoD reports on Nanotechnology*

There have been five major, government-sponsored reports that discussed nanotechnology research in the United States released in the last six years. They were conducted by the Office of Technology Assessment (Congress, 1991b), the RAND Corporation (Nelson & Shipbaugh, 1995), the National Academy of Sciences (NRC, 1996), the National Science Foundation (Siegel et al., 1997), and the Department of Defense (DoD) Task Force on Military Health Care (Olson et al., 1997). Let us briefly review each of these reports.

#### *The OTA Report*

In 1991, the Office of Technology Assessment issued the first “nanotechnology” report. Entitled *Miniaturization Technologies*, the report focused on silicon electronics miniaturization, lithographic capabilities, and semiconductors. It included a small section on molecular nanotechnology. The report covered such topics as the presumptive need for replacement of semiconductor technology, the possibilities for quantum effect devices, the potential for molecular and biological computing, the potential value of biosensors and chemical sensors, and micro-mechanical systems (now known as MEMS.)

The report included a two-page figure on “molecular machines” which could bring about remarkable benefits to society but which could also cause concern for policymakers should they become a reality. The presumption of the authors was that such capabilities were decades in the future. They said, “Basic scientific and engineering research in the fields of materials science, chemistry, molecular biology, advanced electronics, molecular modeling, and surface science are being funded by many Federal agencies and would be necessary precursors to the realization of molecular machines. It is impossible to estimate the level of funding, however, since there is no exact definition of precursor technologies” (Congress, 1991b, p. 21).

The OTA report suggested that, although there had been U. S. agency funding for precursor technologies, the Japanese had been much more active. It recommended the development of a policy framework to deal with this competitive threat as well as the potential risk from accident or abuse. The report stated that the completion of a “protoassembler” would signal a need to increase federal regulatory involvement. This report was far ahead of then-current capabilities. However, the pace of unexpected scientific events in associated fields has been rapid in the last seven years—especially accomplishments such as the unexpected (Kolata, 1998) successful small-laboratory cloning of adult sheep and transgenic cattle. This might prompt one to think that oversight is needed prior to the creation of a working assembler/disassembler.

### *The RAND Report*

In 1995, the RAND Corporation, a respected non-profit think tank, issued a self-funded report on molecular nanotechnology. Its research was undertaken to explore the potential for advanced manufacturing based on progress in the field. The report provides a framework for understanding the scope of this topic—its costs, the level of achievement of the current players in the field throughout the world, possible benefits, development risks, and policy options. The authors contended that “much basic and applied research needs to be undertaken to realistically assess the far-term viability of many of the most interesting emerging concepts, but a careful and objective feasibility assessment could help stimulate near-term achievements and prevent technological surprise by foreign players” (Nelson & Shipbaugh, 1995, p. iii). The report optimistically predicted that the first simple assembler might be constructed in the next several years.

The authors suggested that the most prudent course of action would be the creation of a cross-disciplinary working group. They concluded, “Although there has been much encouraging theoretical and conceptual study of the advanced manufacturing potential of molecular nanotechnology, a comprehensive, detailed technical assessment by a multidisciplinary, objective expert working group is lacking and should be conducted to determine engineering feasibility. A positive finding from such an assessment would indicate that cooperation at the basic and applied research level beyond the present situation should be organized” (Nelson & Shipbaugh, 1995, p. xiii).

The RAND report's authors, who understood nanotechnology to be merely an offshoot of biotechnology, suggested that molecular manufacturing could have much to offer for human health and performance. They recommended expanded research efforts on these grounds alone. They cited an exotic-sounding example that could be realizable in the near future—a "miniature 'submarine' that might detect problems and even perform operations within the circulatory system." This concept, reminiscent of the 1966 motion picture "Fantastic Voyage" might, "have a chance of being realized in the not-too-distant future with a vigorous research and development program combining various development of technology and nanotechnology" (Nelson & Shipbaugh, 1995, p. 7).

The RAND report suggested a number of steps needed to improve the ability of the R&D community to achieve the goal of producing an assembler. Between the options of maintaining a laissez-faire policy or conducting a detailed, comprehensive, objective assessment and feasibility analysis, they strongly recommended the latter. They recommended the formation of a working group comprised of biotechnology experts, chemists, computer scientists, electrical engineers, materials scientists, mechanical engineers, and physicists.  As they said, "The challenge is to bring together leading experts who can participate in unbiased but informed analysis of a multidisciplinary topic" (p. 35).

### *The NAS Report*

The National Academy of Sciences issued a report in 1996 entitled, *Biomolecular Self-Assembling Materials*.[4] This report stated,

> "Research on self-assembling biomolecular materials is an exciting new discipline lying at the intersection of molecular biology, the physical sciences, and materials engineering. Biomolecular materials are those whose molecular-level properties are abstracted from biology. They are structured or processed in a way that is characteristic of biological materials, but they are not necessarily of biological origin" (NRC, 1996, p. 1).

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[4] This project was supported by the Department of Energy under Contract No. DE-FG05-91ER45457, the Army Research Office under Contract No. DAAL03-91-G-0055, the National Science Foundation under Contract No. DNR-9103091, and the Office of Naval Research under Grant No. N00014-92-J-1867. Partial support for this project was provided by the Basic Science Fund of the National Academy of Sciences, whose contributors include AT&T Bell Laboratories, Atlantic Richfield Foundation, BP America, Inc., Dow Chemical Company, E.I. du Pont de Nemours and Company, IBM Corporation, Merck and Company, Inc., Monsanto Company, and Shell Oil Companies Foundation.

The authors described the process as follows, “a key feature of biomolecular materials is their ability to undergo self-assembly, a process in which a complex hierarchical structure is established without external intervention. Self-assembly is common in biological materials.”

The NAS panel identified many benefits which, they believed, justify continued and expanded work in the field and they identified four policy options that could help to stimulate progress: interdisciplinary collaborations, consortia in biomolecular materials, academic programs to encourage curriculum development and training in biomolecular materials, and the establishment of a national Biomolecular Materials Institute (BMI.) This last option was motivated by the panel’s consensus that interdisciplinary collaborations require special support and encouragement.

> “For example, in the study of many aspects of biomolecular materials, such as those described for molecular machines, close interaction between researchers is both difficult and very important. In addition, a national institute would broaden access to instruments and research facilities, facilitate contacts between the academic community and private industry, and enhance the visibility of the field in a way that would encourage the creation of university programs in biomolecular materials research and education” (NRC, 1996, p. 2).

The report never used the term nanotechnology. Unless one were familiar enough with the field, the connection might be missed. The report discussed the same fields of endeavor, the same technological underpinnings, the same needed developments, and the same comparable programs in other countries as I have outlined in this paper, but it used different terminology. Gilbert Devey, a long-time NSF official, suggested that the authors did not want to be associated with what some still consider a fringe science, but the answer was simpler than that. I wrote the two principal scientific and administrative officers on the panel and asked them why they had not used the term.

Dan Morgan, the NAS Program Officer replied, “I'm not completely sure of the right answer to your question. Part of it is the report’s focus on biologically inspired materials and self-assembly, topics that do not include such things as silicon nanomotors, for example, which are at the center of what is usually thought of (by me anyway) as “nanotechnology”. Also, the report is really about materials, not devices.” He continued, “I am a physicist, but this topic isn’t my own personal field of expertise, so my guesses above may be misconceived” (Morgan, 1997). Dr. Morgan, who has been the Program Officer or Senior Program Officer for at least nine NAS studies, underscored an important point—terms in one field do not always translate well for other fields. As a physicist, he did not know about the conjunction of multiple fields in what we have been describing as nanotechnology. At his suggestion, I wrote the panel Chair, Dr. Philip Pincus of the University of California at Berkeley.

Dr. Pincus replied, “I wouldn’t read much in the fact that our report didn’t use that specific word. We were focussing on how to harness biological self-assembly. Since biology doesn’t seem to use a lot of nanotech (in the semiconductor sense), we didn’t treat this as a central issue. Nevertheless, combining bio entities such as DNA, molecular motors, etc. with semiconducting patterned chips is a hot area of current research” (Pincus, 1997).

It is notable that the leader of a federally funded study was unfamiliar with much closely related work, but it is not surprising. The current environment is characterized by a lack of communication across disciplinary boundaries. To the extent that this is typical of other researchers, synergy is forfeited and science is the loser.

### *The Department of Defense MHSS 2020 Study*

In mid-December of 1996, I received an invitation to serve as a member of a tri-service DoD panel known as Military Health Service System (MHSS) 2020. This panel was designed to engage military and civilian health care experts to forecast clinical and non-clinical technologies and methodologies for health and health care from today into the year 2020. Under the leadership of the Deputy Assistant Secretary of Defense for Policy and Planning Coordination, the group's mission was to forecast changes in technology and allow military medicine to prepare for future health care possibilities in areas ranging from individual fitness to “warzone operations.”

Using Delphi study techniques and on-line discussion groups, MHSS 2020 participants worked throughout 1997 to study biotechnology and nanotechnology trends. At the direction of the Assistant Secretary of Defense for Health Affairs to “conduct a focused futures study to examine the future strategic impact of Biotechnology and Nanotechnology,” MHSS2020 issued its report in September of 1997.

The study group’s central conclusion was that advances in biotechnology and nanotechnology will “fundamentally and structurally transform military medicine over the decade ahead.” The report’s principal author, Robert Olson, stated that the participants “have discovered that our society is in the midst of a revolution along the same scale as the development of language, the printing press, the internal combustion engine, and the microprocessor.”

The report offered a number of forecasts for the next twenty years before proposing conclusions and recommendations. The Task Force projected that “genetic engineering, tissue engineering, and other areas of biotechnology will take health beyond the traditional treatment concepts of palliation (relieving symptoms), cure (stopping illness), and prevention (avoiding illness) and toward a new concept of enhancement (improving human performance)” (Olson et al., 1997). Figure 13 summarizes these forecasts and the complete list can be found in Appendix C.

### DoD Task Force Forecasts for 1998-2020

- Inexpensive hand-held biosensors based on nanoscale ion channel switches will eliminate the need for maintaining large laboratories, transporting samples within facilities, and sending samples out for analysis.
- Gene chips will allow the analysis of families of genetically defined subtypes of disease and allow individual genetic profiling and higher stages of customized care tailored to individual biochemistry.
- Drug discovery and developmental processes will be highly accelerated.
- New generations of antibiotics will counter the proliferation of antibiotic-resistant bacteria.
- There will be a new field of immunotherapy based the body’s own immune system rather than drugs.
- Scientists will create revolutionary gene therapies and DNA vaccines for both humoral and cellular immunity.
- Advanced sustainable agriculture will increase food production without causing unacceptable levels of environmental damage.
- New agricultural products will enhance health and treat disease.
- Genetically altered plants will greatly improve nutrition.
- A bio-industrial revolution will allow continued economic development with fewer adverse environmental and health impacts.
- New fields of “nanomedicine” and tissue engineering will arise.
- Biochemical-based nanocomputers and bioelectronic computers will be developed.
- We will see the advent of biological terrorism.

**Figure 13** **DoD Task Force forecasts for 1998-2020**
(Olson et al., 1997)

The Task Force's recommendations included the creation of systemic monitoring mechanisms for biotechnology and nanotechnology and policy initiatives to deal with the ethical, legal, and training implications of new technologies. The recommendations also included:

1. Systematic monitoring and participation in developments and applications of biosensors, naked DNA (plasmid) vaccines, phage therapies, and "nutraceuticals";
2. Development of a structure and process that will continue to monitor the biotechnology industry;
3. Monitoring research focused on memory enhancement, stress reduction and tolerance, and other biotechnology related applications for human performance enhancement;
4. Collaboration with other Federal agencies to initiate and co-sponsor a National Clearinghouse on Nanotechnology;
5. Creation of a formal process to address bioethical issues and conduct ethical analysis of decisions related to biotechnology;
6. Development of a multidisciplinary communications group to disseminate accurate and timely information to a wide spectrum of constituents concerning biotechnology; and
7. Organization of a future conference on technical and social implications for the 21st century military health care (Olson et al., 1997).

The report concluded that soon-to-be-realized advances in biotechnology and nanotechnology will fundamentally change military medicine, and by extension medicine in the greater society as a whole, within a very few decades. The authors do not pretend to be able to predict the future. We believe, however, that some trends can be discerned, and that planning for various futures is far more intelligent than waiting to see what happens.

Langdon Winner recently wrote that technology optimists are always predicting that a specific event will occur and that they are incorrect (Winner, 1998, p. 62). I disagree. Technology optimists do not—as charged by Winner—predict specific events. None among us can accurately guess what technologies will arrive, and thrive, in the next century. Optimists postulate that *some* events in technology will occur to change things for the better and they attempt to hasten the positive changes. No one would have predicted an electrically powered refrigerator at the turn of the last century but (s)he might well have predicted and tried to accomplish improved ways to store food. Mankind's technical capabilities today are demonstrably different from those in my grandfather's time. Life spans are longer, information flows more freely, knowledge is more extensive. As technological change accelerates, things will be even more different in the future.

### ***The NSF/WTEC Report***

The NSF, through the World Technology Evaluation Center (WTEC), is about to publish its own report on progress in nanotechnology research, the primary objective of which was to "highlight major achievements and research programs, and to work towards developing better interactions and eventually an interdisciplinarity community in the field of nanotechnology" (Siegel et al., 1997, p. 1). The draft report, entitled *Nanoparticles, Nanostructured Materials, and Nanodevices,* was sponsored by the NSF, the AFOSR, the ONR, NIST, the DOE, the NIH, and NASA. It estimates that "Nanotechnology is at a similar level of development as computer/information technology was in the 1950's". The report concludes that, "Scientific and technological discoveries in this area are growing at an unprecedented rate, and an attempt should be made to capitalize on emerging research opportunities" (p. 2).

"Tiny nanostructures can include materials like ceramics, optical materials, polymers, and metals, while nanodevices include microscopic sensors, switches, and reactors. Industrial applications are just as wide-ranging, from pharmaceuticals and electronics to biotechnology and space exploration (Siegel et al., 1997)." "There are practically no unaffected application fields," said Dr. Mihail Roco in the introduction to the proceedings. Another prospect the workshop explored was the bottom-up approach to molecular manufacturing

After the publication of the draft report, the sponsors held a symposium in Rosslyn, Virginia which I attended, to present and discuss the findings. During the day-long session, NSF officials and six sub-panel chairs (synthesis and assembly, biologically related aspects, dispersions and coatings, high-surface-area materials, functional nanostructures, and consolidated materials) gave reports (Siegel et al., 1998). There were also research reports by officials from each of the other government sponsoring agencies. The common thread was that there has been a great deal of success in nanomaterials research and development and that the pace of this success is accelerating. The dramatic progress reports lend an enormous amount of credibility to what used to be considered "fringe science."

Most of what was reported in the NSF symposium was close to manufacturability. According to the perspectives of Weinberg, Branscomb, and Rosenberg, this is the kind of work that should be done in the private sector. However, the effects of this near-to-fruition work could be so pervasive and so valuable to all sectors of the commonweal that government involvement is appropriate. It is what NIST's ATP Program calls "generic technology." In the final analysis, the NSF/WTEC study shows a great deal of promise for the near-term and commercializable, yet lends credibility to the long-range prospects for the manufacture of quantum computers, the merger of biology and electronics, and the creation of programmable nanobots.

In a telling exchange at the end of the day, panel Chair Dick Siegel of Rensselaer Polytechnic Institute (RPI) asked Co-chair Evelyn Hu of the University of California, Santa Barbara if she thought nanotechnology to be a brand new field and she responded immediately that she did. It is, she said, a nascent field in that even the most experienced practitioners in the underlying fields have so much to learn about the mixture of skills and knowledge. She suggested that the conjunction of technology and capabilities from so many branches of S&T (imaging, placement by STM's structural engineering theory, etc.) have created a paradigm shift in the making.

One step to facilitate the convergence of a new nanotechnology paradigm would be to establish a group to "compact the literature"—that is to correlate the "many seemingly disparate facts and the identification of regularity in a sea of diversity in Weinberg's terminology" (Weinberg, 1967, p. 50-53). As Weinberg says, "Scientists are adding a huge flood of new facts and observations to our existing store of data. A division of labor between those who create or discover the facts and those who sift, absorb, and correlate the facts seems to be inevitable" (Weinberg, 1967, p. 51). An effort by "symbolic analysts to help us negotiate an increasingly complex world" (Reich, 1992) might be beneficial.

We can—both politically and economically—afford a clearinghouse for nanotechnology research as recommended by the MHSS Study Group. A clearinghouse need not be large or expensive. It could be managed with a small cadre of analysts who among them have sufficient proficiency in the major contributing disciplines and an interest in multiple fields. Their purpose would be to scour peer reviewed journals and to identify and communicate with investigators in government, industry, and academia throughout the world. Their work would be conducted in person, by telephone, and—mostly—through the Internet. The NSF/WTEC study offers a good start, but it was narrowly focused on progress in materials research. There is far more to study.

The cost of such an office need not be high—perhaps no more than the cost of a few typical investigator-initiated grants. Out of the hundreds of millions of dollars spent each year on nanotechnology research, this would be a very small investment. The payback would come in the form of improved knowledge disseminated to knowledge workers who would otherwise never have the benefit of such synergy. Given its mission, its investment, and its familiarity with nanotechnology, NSF would be the most likely home for a clearinghouse function.

There are a few, including the authors of the RAND report, who suggest that NIH might be a viable candidate agency to monitor and support nanotechnology research. Given the close connection between nanotechnology and biotechnology and given that so many of the predicted benefits (e. g., cell repair) would fall under the NIH umbrella, this might make some sense. There have, however, been no substantive nanotechnology efforts at NIH. Its claims in the WTEC/NSF briefing notwithstanding, it is not yet a significant player in the field. Should it decide to invest in nanotechnology for medical applications, the Institute for General Medical Science would be a candidate locus.

Evelyn Hu suggested that nanotechnology might represent a paradigm shift in progress. If we are to use Kuhn’s framework for understanding scientific revolutions, it might be more appropriate to say that we are perhaps observing the emergence of a new paradigmatic technology. In the final chapter, we will discuss a number of policy issues that can be informed by this perspective.

## *Chapter V — Further Policy Dimensions to Consider*

There has been substantial work by scientists and technologists in molecular nanotechnology over the last two decades. However, since we have no national nanotechnology policy, this work has taken place in a completely ad hoc fashion. This allows for scientific pluralism but it could have the effect of jeopardizing individual investigators who are not working on megaprojects (Kleppner, 1994). Recent studies point out the advancements in nanotechnology but contend that the time has come for more structure.

Let us look, then, at some additional factors higher level policymakers might review in considering whether to continue our current ad hoc funding approach or somehow modify it to add more structure and strategic planning. If policymakers want to give serious consideration to the question, they will have to consider the issues we have discussed (risk, reward, cost, etc.) as well as other financial, management, political, and technical factors.

Molecular nanotechnology research is growing at a rapid and apparently accelerating pace, but the lack of a common set of terminology and experience has a dampening effect on research in the field. This chapter will therefore conclude with a discussion of scientific and technical disciplines and how our current, predominantly discipline-based practice detracts from nanotechnology research. This multi-disciplinarity may well be the essential area in which our current nanotechnology-related policies are most lacking.

### *Financial, management, political, and technical issues*

There are many financial issues to consider in making S&T policy, among them the cost of the investment. Different stakeholders (scientists, policymakers, managers, voters, etc.) view the cost issue in different ways. To lawmakers, cost is measured in impact on the budget (and by extension, impact on their reelection chances.) Sums that total in the hundreds of millions of dollars (in the aggregate or occasionally for individual projects) are not abnormal. Often, highly visible “big” projects (e.g. the Supersonic Transport) become politically impossible although they are no more costly than apparently less expensive projects with widely dispersed funding (e.g., cancer research). Nanotechnology research has only recently become a member of the class of expensive research and has not yet achieved political visibility.

Many politicians insist that industry should contribute more investments in basic research, but that can be problematic. Technology firms must relate the cost of an investment to its predicted return. Managers have fiduciary duties to their stockholders to protect the firm's assets. For this reason, only a small fraction of money spent on early-stage research is invested by companies outside their own laboratories (Sharp & Kleppner, 1994, p. 149).

There are some contrary examples, such as IBM and its Almaden and Zurich research facilities (see Appendix A), but firms investing in basic R&D are few and becoming fewer. "Companies have become increasingly reluctant to put resources into basic technological research that is long term, high-risk or both, even though this research might eventually pay handsome returns to the firm and to society as a whole" (Branscomb & Keller, 1997, p. 4). As firms "downsize their corporate research laboratories, the focus shifts to nearer time-horizons, perhaps increasing short-term profits, but at the expense of intellectual assets for future growth" (Branscomb & Keller, 1997, p. 4).

Policymakers and planners must also consider "schedule risk"—the risk of spending time and money only to fail (or *appear* to fail) which is embarrassing, wasteful, and limits future flexibility. This kind of failure is likely to result in overly cautious behavior resulting in opportunity costs that cannot be estimated. Managers can be influenced by pressure to provide a return of some kind, a proof that a policy was sound to begin with. This can be positive in that it forces them to be more discriminating. It can be negative in that it forces everyone involved to *appear* to be less prone towards risky research. Suffice it to say that when funding agents feel compelled to insist on short-term results, investigators feel compelled to offer to do what they have already done. They get grants, but the de facto policy can create a situation in which those who could benefit the most from research (the public) receive much less than an optimal return.

With government grants, the best way to ensure that one will not embarrass one's sponsor is to propose to do with next year's grant what one has already done with last year's money. Little new science or technology results, but all the stakeholders are protected from criticism. Robert Cook-Deegan, a leader in the creation of the Human Genome Project, articulated a similar point well in his paper "Does NIH Need a DARPA?" He states, "imposing a requirement that innovation prove itself early in small grants runs the risk of prematurely declaring failure and forcing investigators to write a follow-up grant at the same time that they have only a few months funding to do the pilot work" (Cook-Deegan, 1997, p. 28). As a research administrator at a major university medical school, I have often observed this strategy in action. That this happens with federal grants is unfortunate, but, all in all, in the private sector the demand for immediate results is far stronger.

Business firms tend to have planning horizons and payback requirements measured in a few years. Some large firms with extensive long-range R&D programs invest in prospective technologies (and even basic science) that they believe they will need to be competitive in the future. In the case of nanotechnology, there is little apparent likelihood of a short-term payback, although recent developments in the materials and biocomputing aspects may appeal to such industrial firms as IBM and Xerox.

So it has fallen, increasingly in recent years, on government to be the principal basic science and early-stage technology investor representing the public good. Private firms will under-invest out of rational self-interest, yet there is benefit to be derived by the public as a whole from long-term investments.

> “There is wide support for government research investments where (because they cannot capture the benefits) the returns to society as a whole might far exceed the public cost. This, after all, is the rationale for public support of basic research, where the benefits are widely diffused” (Branscomb, 1997b, p. 42).

The NAS report, *Allocating Federal Funds for Science and Technology*, likewise suggests that the government has a major role in fostering new and enabling technologies. The report singles-out nanotechnology and micro-manufacturing as offering “exciting commercial opportunities.” The report suggests that government should support research that helps establish *general* scientific and technical principles. “Such investments are appropriate for the federal government because they can generate large benefits that accrue to the nation but would not be captured by any one firm” (Press, 1995, p. 22). This expectation, in and of itself, may constitute sufficient reason for federal nanotechnology investment.

Cost/benefit analysis is not the only factor used to consider a policy or program. There are also non-financial returns expected by the stakeholders. Government stakeholders look for returns in such varied areas as scientific benefit for its own sake, political and electoral advantage, increases in tax revenues, and advantages in military and international market conditions. Companies seek improvements in markets and market share, profitability, public relations, and improvements in relationships with their stockholders. Scientists, of course, hope for new science, but also for future opportunities for funding, publications, and improved standing in the scientific community. The general public (which includes all of the above) care about the impact on their lifestyles, health benefits, and economic advantages for themselves and their families.

Another factor worthy of consideration regarding a proactive government role is that money spent in furthering early-stage technology can have society-wide, though indeterminate benefits. This is more than the "unpredictable but positive spin-offs" argument used for years to justify NASA spending. Research into emerging fields such as nanotechnology creates new knowledge and raises new questions and understandings. It often leads to better-informed choices among alternative technologies (Branscomb, 1997b, p. 43). Basic and early-stage research can also result in enabling capabilities for itself and for other fields, without which further advances would not be possible. Not to put too much emphasis on the benefits of "serendipitous discovery", many good things have come about though unintentional consequences. As the saying goes, chance favors the prepared mind. Gamma ray bursts, Bell's discovery that led to reed relays in the telegraph, and Fleming's discovery of penicillin, are all examples of positive unintended consequences that followed from exploratory research.

Who, then, should be the primary sponsor of emerging technology research? Perhaps, as Branscomb put it, "The rule is simple: let the intended beneficiary pay for the research" (Branscomb, 1997b). In the case of nanotechnology, it is not yet known who will benefit other than "all of society." It is not predictable whether nanotechnology will merely offer an improvement in materials and a follow-on to lithography, or whether it will revolutionize manufacturing and medicine. If nanotechnology bears any fruit, it is likely that there will be benefits to the public at large and not just to a single firm or industry. This is a significant argument for why the federal government should be the primary investor in this field. Other arguments that support this conclusion are that "long-range, broadly useful research that can produce benefits far in excess of what the private sector can capture for itself" should be sponsored by the government (Branscomb & Keller, 1997, p. 2) as should "opportunity-driven vs. need-driven research" (Branscomb, 1997a, p. 9).

S&T policy is about money and priorities—who gets them and who gets to make decisions about them (Averch, 1985, p. xii). The people in the organizations that fund S&T do not always share viewpoints with each other, much less with researchers or with the public at large. These financial sponsors include government, academia, philanthropic organizations, and industry. Although government policymakers try to represent the public's interests, most of them also have interests, agendas, histories, and preferences of their own. Based on these commitments, they filter the data they are given. When other factors are equal, they tend to support activities and programs that suit their interests or at least those with which they are familiar and comfortable.

No highly placed government policymakers currently sponsor nanotechnology research with the professional self-interest with which Admiral Rickover championed the nuclear navy. Under these conditions, there will likely be no pressure from the top to modify current policies. So far, in the relatively short time that nanotechnology could have impressed a political champion, none has arisen. If anyone had taken-on the mantle of nanotechnology sponsorship only a few years ago, he or she might have been laughed at. Today, the situation is quite different. It may be time for someone in political life to become a "champion."

Many scientists argue that the government should fund their research simply because it is "good science." Those in the nanotechnology community suggest that the anticipated benefits are sufficient to justify substantial investment. Weinberg said that science must seek its support from society on external grounds (Weinberg, 1967, p. 72). These external criteria—external, that is, to the scientist and the funding agency—can include the validity of the research as judged by the peers as well as budgetary considerations. And Branscomb adds that

> "Government should invest in research—both scientific and technological—where the expectations for long-term public benefit exceed expectations for private returns to the research performer. This is the correct answer to the question, 'When is it appropriate for the government to subsidize research?'" (Branscomb & Keller, 1997, p. 4)

### ***Risk***

One area that needs much more work by nanotechnology policy analysts is risk assessment. There are several theoretical technical risks to a successful nanotechnology. It is conceivable, though highly unlikely, according to leaders in the field, that runaway assemblers could roam free, converting all matter into copies of themselves. If this is even remotely possible, there must be oversight. Assemblers will, in theory at least, be designed (programmed) to make copies of themselves, make or take-apart other things, and then stop. The public must be assured that researchers know how to make assemblers stop replicating and not mutate. This is by itself a sufficient and compelling reason to have government regulate molecular nanotechnology research. There may well be industrial, academic, or individual laboratories capable of making the breakthroughs needed for an assembler. But we cannot rely on all of them being capable of—or motivated to—doing it safely and ethically.

Of course, there is also the possibility of nanoweapons. One has to assume that our Department of Defense is looking into this risk. If they are not, they need to do so now. Presumably, the sponsors of the 1998 "Nanotechnology for the Soldier System Conference"—the U.S. Army Soldier Systems Command (SSCOM), Army Research Office (ARO), Army Research Laboratory (ARL), and the National Science Foundation (NSF)—have plans to address this issue (SSCOM, 1998).

It was only months ago that experts told us that cloning was not expected for decades. Now we have the cloned sheep, Dolly and Polly, and the transgenic cows, Charlie and George. That something seems difficult and remote does not make it impossible. There has been far too much success and progress for anyone to dismiss nanotechnology as a dream.

Change is inherently risky and the changes that might come from something as powerful as control over matter at the molecular level are fraught with enormous risk. Much more exploration is needed before we can adequately assess the risks of nanotechnology research. It may be that the physical risks are manageable with moderate controls; it may also be that they require a program as strict as that which we now have for nuclear devices. This is not a question for casual review, nor is it a question to be addressed only as a subset of a broader policy issues; rather it is one that requires systematic study by experts in nanotechnology and in risk analysis, as well as consideration by those who could be affected by undesirable outcomes.

Aside from the physical risks, there is also the risk to economic and social systems if nanotechnology ever affords the capabilities suggested by its proponents. If scarcity of raw materials can be eliminated and if lifespans can be extended indefinitely, then today's economic and social rules would fall apart. To do justice to these issues is far beyond the scope of this paper. We are in need of biomedical and scientific ethics research that looks further out than a few years and that looks at possible changes from a broad range of ethical perspectives. If full-blown molecular nanotechnology becomes likely as suggested by the George Washington University study (Halal, Kull, & Leffmann, 1997), then we must begin to look at these questions very seriously. As the guardians of public safety, our government must not leave to private enterprise the responsibility for safeguards (Sarewitz, 1996).

The Office of Technology Assessment, in its 1991 report on *Miniaturization Technologies*, offered a way to measure when we might need to take such a hard look.

> "Development of a framework for government regulation and oversight of molecular machine technologies has been suggested by several analysts, driven by fears of abuse or accidents associated with the development of these technologies. The communities of researchers working on these precursor technologies are rather small and the concern over accidents or misuse of the technology is well known among them. Government regulation at this stage would be premature, might hamper emerging research efforts, and have uncertain advantages. The question of regulation and oversight should be revisited and analyzed in greater depth if developments in the field bring the technology closer to reality. The development of the first protoassembler might be an appropriate milestone to reconsider government regulatory involvement" (Congress, 1991b, p. 21).

I think the OTA was wrong—that waiting for an assembler is waiting too long. If and when someone demonstrates the *precursor capabilities* of an assembler, they will have demonstrated capabilities sufficient to necessitate government supervision or at least the kind of cooperative controls Drexler describes in *Unbounding the Future* (Drexler et al., 1991, p. 246-264). It is probably too early for this degree of control today because no one has yet proven that assemblers are feasible. It is also likely that the institution of strict controls at this time would stifle development.

There is, however, a way to determine when we have arrived at the prudent time to act. The Foresight Institute plans to award a Feynman Grand Prize, the requirement for which is proof of having designed and built two nanotechnology devices that would approach the capabilities of an assembler. The first is a robotic arm or other positional device that would fit into a 100 nanometer cube. The device must be able to perform actions as directed by specified input signals; be able to move to a directed sequence of positions anywhere within a 50 nanometer cube; perform directed actions with a positioning accuracy of 1/10th of a nanometer; and perform at least 1,000 accurate, nanometer-scale positioning motions per second for at least 60 consecutive seconds. This robotic arm specification would demonstrate the controlled motions needed to manipulate and assemble individual atoms or molecules into larger structures, with atomic precision.

The second required device would be a functional, nano-scale computing device that would fit into a 50 nanometer cube. The device would be capable of adding accurately any pair of 8-bit, binary numbers, discarding overflow; accepting specified input signals; and producing its output as a pattern of raised nanometer-scale bumps on an atomically precise and level surface. The device would be capable of performing the functions of a conventional 8-bit adder.

If someone could produce these two devices, (s)he would not have produced an assembler. However, they would have demonstrated the basic capabilities needed to do so within a relatively short time. This achievement should signal the government to look very closely at formal safeguards.

### ***Paradigms and normal science***

Philosopher of science, Thomas Kuhn, made his reputation by staking out a position that science does not grow along a continuous and predictable path, but instead plods along in a "normal" way until a crisis forces it to be revolutionized by a succeeding "set of commitments" through what he calls paradigm shifts. "The scientific enterprise as a whole does from time to time prove useful, open up new territory, display order, and test long-accepted belief. Nevertheless, *the individual* engaged on a normal research problem *is almost never doing any one of these things*" (Kuhn, 1962, p. 38). In Kuhn's terms, normal science is

> "a strenuous and devoted attempt to force nature into the conceptual boxes supplied by professional education" {that} "often suppresses fundamental novelties because they are necessarily subversive of its basic commitments … the very nature of normal research ensures that novelty shall not be suppressed for very long" (Kuhn, 1962, p. 5).

Some suggest that Kuhn's ideas were specifically about "hard" science, and therefore one could suppose that they do not apply to nano*technology*. But Constant (1980) has shown how Kuhn's ideas apply as well to aerospace technology. They could equally apply very well to discussions about nanotechnology. The difference between science and technology has been described as the difference between understanding nature and modifying nature (Bugliarello, 1997). The research processes are similar enough that applying Kuhn's ideas to a technology is a reasonable approach (Bijker et al., 1989, p. 168, 172).

In *The Structure of Scientific Revolutions*, Kuhn described the everyday job of researchers as performing, "mopping-up operations" that engage most scientists throughout their careers. This day-to-day activity constitutes what he called “normal science” and also characterizes what we could call “normal technology” (Bijker et al., 1989, p. 182). Scientists, said Kuhn, are often intolerant of the ideas of others who are possessed by the “drastically restricted vision” of the paradigm under which they work. (Kuhn, 1962, p. 24)

The question of whether we are heading towards an emerging nanotechnology paradigm arises from time to time. The answer is unclear. Vice President Al Gore, in his Commencement Address at MIT two years ago said “{Thomas Kuhn} showed how well-established theories collapse under the weight of new facts and observations which cannot be explained, and then accumulate to the point where the once useful theory is clearly obsolete. As new facts continue to accumulate, a new threshold is reached at which a new pattern is suddenly perceptible and a new theory explaining this pattern emerges” (Gore, 1996). He was talking about the concept of paradigm shifts and implying that information systems and communications, about which he cares a lot, will hasten the advance of new paradigms.

Some proponents (including the co-chair of the NSF study) have suggested that we may be beginning to change from a pre-nanotechnology society to a post-nanotechnology society. Kuhn’s guidance is very apropos to this discussion. What would be the signs of an emerging nanotechnology paradigm? “At the start”, Kuhn said, “a new candidate for paradigm may have few supporters, and on occasions the supporters’ motives may be suspect” (Kuhn, 1962, p. 159). This state is represented by scientific statements about nanotechnology prior to the 1995 *Scientific American* article.

> “Nevertheless, if they are competent, they will improve it, explore its possibilities, and show what it would be like to belong to the community guided by it. And as that goes on, if the paradigm is destined to win its fight, the number and strength of the persuasive arguments in its favor will increase. More scientists will then be converted, and the exploration of the new paradigm will go on. Gradually, the number of experiments, instruments, articles, and books based upon the paradigm will multiply. Still more {people}, convinced of the new view’s fruitfulness, will adopt the new mode of practicing normal science, until at last only a few elderly hold-outs remain” (Kuhn, 1962, p. 159).

While Kuhn was referring here to a shift from one paradigm to another, his reasoning also applies to the emergence of a new paradigm.

Nanotechnology is represented by many researchers in diverse fields consciously working on nanotechnology as well as many more researchers working on their own selfcontained projects, along what could be called the "pathway" to nanotechnology. As more dollars have been spent, more researchers have devoted time to the field and have gained recognition. As more conferences have been held, more good press has resulted and more investigators have decided to work in the field. One can see this kind of trend emerging in the chronology in Appendix A. It is too early to tell whether this trend will continue, but it seems to describe what has been occurring.

Even if the trend continues and we find new ways to advance S&T, the "tried and true" ways that have characterized the current approach have much to offer. Scientific research has flourished as it has because, in large measure, of the disciplinary way in which it works. "By ensuring that the paradigm will not be too easily surrendered, resistance guarantees that scientists will not be lightly distracted and that the anomalies that lead to paradigm change will penetrate existing knowledge to the core" (Kuhn, 1962, p. 65). Researchers are unlikely to abandon what has worked so well.

However, there is one notable price to be paid for the current disciplinary-based approach and that is incommensurability of the knowledge across disciplines. Kuhn described it this way, "Two men who perceive the same situation differently but nevertheless employ the same vocabulary in its discussion must be using words differently. They speak, that is, from what I have called incommensurable viewpoints" (Kuhn, 1962, p. 200). What is the problem from the perspective of a nanotechnologist? It is that not all scientists share common terminology or commensurable terminology even if they are working on similar problems. Kuhn (quoting Ludwig Wittgenstein) explains: "What need we know in order that we apply terms like 'chair', or 'leaf', or 'game' unequivocally and without provoking argument? …We must know, consciously or intuitively, what a chair, or leaf, or game *is*" (Kuhn, 1962, p. 44-45).

Part of the problem is that we see what we are used to seeing, and what we expect to see, based on our unconscious familiarity with and acceptance of current research paradigms. For example, today's computer architects tend not to see anything of professional interest in papers about DNA. However, as we saw in the chapter on nanotechnology and as emerges from the chronology in Appendix A, much theoretical work in future computing may involve just that. This kind of problem is not confined to nanotechnology, but the field certainly seems to provide many examples of interdisciplinary incommensurability.

Lack of a common terminology and today's disciplinary sets of distinct "normal science" practices (which follow from today's funding practices) unintentionally conspire to restrict the creation of novel science. Unless one is a determinist and believes that technology will follow a predestined path no matter what, one must look for some countervailing processes that will help overcome these obstacles.

### ***Multi-disciplinary, cross-disciplinary, and inter-disciplinary***

Nanotechnology is not now a discipline in and of itself. Perhaps one day there will be practicing "nanotechnologists." When and if a set of common nanotechnology paradigms are established (Bauer, 1990, p. 112) we will have a new, combined nanotechnology discipline. For the time being, nanotechnology is a holding category, staffed by practitioners from the fields of physics, chemistry, genetics, microbiology, materials science, electronics, computer science, and x-ray crystallography who bring with them a synthesis of skills, practices, knowledge, and tools from these disciplines.

While there is no à priori reason to insist that all sciences come from the cross-pollination of multiple disciplines, there is much reason to propose that *some* sciences be so constructed. Proponents of this idea usually call for "interdisciplinarity." The NSF's *Report of the Task Group on the Review of Interdisciplinary Proposals* underscores the difficulty even to define 'interdisciplinary' because the term has different meanings depending on who is doing the defining. "Many NSF Program Directors and Division Directors consider projects that are in different subdisciplines within a discipline to be interdisciplinary; thus all their programs and divisions are 'interdisciplinary'" (NSF et al., 1995, p. 2).

Practitioners of S&T who reside in the disciplines we have been discussing differ not only in the topics they cover, but also in the data they uncover. They are different culturally (Bauer, 1990, p. 105). They have different styles, different modes, different preferences, different expectations of perfection, different tolerance levels. And they use different terms to describe the same circumstances. Consider a hypothetical, but timely, example. A molecular biologist has an expiring NIH R01 grant and needs to find a new project to replace it. She is unlikely to look in a physics journal for ideas for the next project. Nor would she be likely to find comfort in a *Science* paper entitled something like "Self-Assembly of a Two-Dimensional

Superlattice of Molecularly Linked Metal Clusters." But that paper might be highly productive *and* extremely well-related to her work. It just is not framed in a way that is accessible to her.

Even though policymakers might decide that there would be some benefit to somehow forcing a team of investigators to think alike, they could not force them to adopt a paradigm. First, one cannot really force an investigator to do anything any more than one can herd cats. Second, they would not have the same opinions about what is important and what is valuable (Bauer, 1990, p. 106). Researchers may follow the same scientific method; they may use the same mathematics, and roughly the same chemistry and physics. However, they do not see them in the same way or internalize the significance of what they see—incommensurability, again. So, for policymakers to try to mandate truly "interdisciplinary" research is futile. What we can do is to look for and then to encourage investigators who know enough physics and chemistry and math and biology to see how a discovery in one could have positive impact on another.

### ***Peer Review***

Critical to any discussion of disciplinary science is peer review, because it is the "peers"—practitioners who are recognized as *the* subject matter experts—who have sufficient mastery of the knowledge, background, and language *in a given discipline* to judge whether a work is of sufficient merit to deserve funding and publication. Since they have the most experience, it is reasonable to expect that peers can help others in their field avoid pitfalls in their branch of science. Even though one might argue that experienced investigators are more likely to repeat the mistakes of the past, one cannot obtain a grant from NIH or NSF or most other funding agencies, except in remote circumstances, without being reviewed (and accepted) by one's peers.

The price we pay for this method of allocating resources is the timely acceptance of novel and innovative ideas that do not fall easily into a paradigmatic scientific discipline. Weinberg, in *Reflections on Big Science*, expressed one facet of the problem, "the scientific literature in a given field tends to form a closed universe; workers in a field, when they criticize each other, tend to adopt the same unstated assumptions… The editors and authors of a journal in a narrowly specialized field are, so to speak, all tainted with the same poison" (p. 70). He had a refreshingly skeptical way of questioning the process of peer review. "No one can say whether this means that we shall have relatively fewer revolutionary advances—breaking of paradigms, as Kuhn puts it—simply because our geniuses are surrounded by more blockheads than before" (p. 41).

Peer review is inherently a difficult process if anything other than "normal science" (or technology) is a goal. The toughest issue is that of disciplinarity—particularly the tendency of scientists to pay attention to events within their normal, paradigmatic, sphere of interest. This issue, which has captured the attention of many followers of S&T for years, is critical because nanotechnology research has not yet identified a paradigmatic structure and must rely almost exclusively on investigators looking at issues through the restrictions of a variety of disciplinary prisms. The OTA looked at this problem in its report, *Federally Funded Research - Decisions for a Decade*.

> "Recognizing the limits of specialization, agencies maximize expertise in subject-focused programs. Specialists are quite well suited to the task of making quality distinctions within disciplinary or problem-centered boundaries. But discriminations that must cross boundaries, no longer comparing like with like, are rarely ever accomplished by peer review, since reviewers in one field are very reluctant to judge the scientific or technical merits of information from other fields" (Congress, 1991a, p. 147).

Daryl Chubin and Edward Hackett wrote a text about the issue (Chubin & Hackett, 1990) and the National Science Foundation is well aware of the problem. It published a *Report of the Task Group on the Review of Interdisciplinary Proposals* in 1995, which said,

> "The additional time and effort needed to handle such (interdisciplinary) proposals is not properly recognized nor rewarded by NSF management. This is compounded by the fact that the external community tends to be hostile to such proposals, feeling that it is siphoning off scarce resources from core disciplinary research. Therefore, most program directors hesitate to initiate the process and take on the extra burden of co-reviewing and co-funding such proposals. Instead, the proposals are sent out for review within a single discipline where they tend to fare poorly" (NSF et al., 1995, p. 2).

In 1995, the NSF commissioned a Task Force to study the problem. Its *Report of the Task Group on the Review of Interdisciplinary Proposals* clarified one reason why a meaningful review of interdisciplinary proposals has been such a hard problem to solve.

> "One of the principal problems with such (interdisciplinary) proposals is that most reviewers do not feel qualified to judge all aspects of an interdisciplinary proposal. Although a reviewer may be impressed by the part of the proposal that falls in the reviewer's area of expertise, the reviewer's lack of familiarity with all

> of the aspects of the proposal leads, I think, to a reluctance to ‘stick one's neck out’ and give the proposal the highest rating” (NSF et al., 1995, p. 7).

> An August 1991 survey of nearly 9,000 reviewers concluded that respondents

> “... claimed that reviewers are not as well prepared to review interdisciplinary proposals, especially in emerging fields, and that program officers are reluctant to cross disciplinary lines to support such research. These reviewers urged NSF to adapt the review process to accommodate interdisciplinary research” (NSF et al., 1995, p. 1).

One of the survey’s findings was that many of the respondents claimed to be strong advocates of multidisciplinary proposals and they were critical of current review practices. A big problem, though, was that reviewers tend not to be prepared to review proposals in fields other than their own—especially in emerging fields. The report found that program officers are reluctant to cross disciplinary lines to support such research because of this unfamiliarity and lack of preparation (NSF et al., 1995, p. 6).

The impact of the peer review issue runs even deeper because of the conservative impact on junior research staff. In my experience, laboratory managers and Principal Investigators on grants insist that **their** issues be studied. They have authority, experience and expertise. Their junior investigators—post-doctoral researchers and graduate students—are forced by the weight of the system to support a form of scientific status quo. The peer review system will usually back the senior scientist in any controversy over what issues are studied. Recent changes in the NIH grant process eliminate the Young Investigator (R29) grant, further exacerbating this problem.

Because of the above issues, it might appear that the best approach for improvement would be to look to ways to improve or replace the peer review process. However, peer review works too well in too many other respects to throw it out in the interest of unquantifiable benefits to non-paradigmatic research—even if the result *might* be highly beneficial. Many articles and papers argue effectively that substantive change in the peer review process would be counterproductive.[5] The general conclusion is that we need to continue with the peer review process, as a rule. However, nanotechnology research is different enough to need something

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[5] *Peerless Science* (1990)—(Chubin & Hackett, 1990); *The Changing Relationship between Research Practice and Science Policy Making* (1997)—(Gibbons, 1997d); *Does NIH Need a DARPA?* (1997)—(Cook-Deegan, 1997); *Allocating Federal Funds for Science and Technology* (Press, 1995); *Reflections on Big Science* (1967)—(Weinberg, 1967), *Technology and Culture’s* (1986) Engineering in the 20th Century; and the OTA’s 1991 *Federally Funded Research - Decisions for a Decade* (Congress, 1991a).

different—a “nudge” of some kind. As Dick Siegel said in the NSF workshop, we lack, and must somehow find, “peers” with proficiency (or at least interest) in multiple, cross-disciplinary fields (Siegel, 1998). So let us look further at peer review from this multi-disciplinary perspective and see if there is any modest improvement that would allow us to improve the process without dismantling a system that has produced generally good results for decades.

### ***Multidisciplinarity***

Although the basic processes of research funding have not changed remarkably for years, there are some facets that are different from what they used to be. In the last decade, new fields and subfields have emerged. “The technology available for research and inquiry has become more powerful, permitting new and surprising connections between fields and disciplines” (Averch, 1985, p. 173). Although scientists can afford to, and in fact usually must, work within their disciplinary boundaries and comfort zones, society can benefit when more of them work in recombining fields.

As the NAS report, *Major Award Decisionmaking at the National Science Foundation*, says,

> “The research community is not homogeneous; it consists of many specialized, mostly discipline-based groups that have different needs and priorities. Depending on the project, it may be difficult to consult with, and gain the support of, every affected research community. Attempts to broaden the range of groups consulted also make consensus building more difficult. The panel nevertheless concluded that it is highly desirable to involve and seek the support of the research community as much and as early as possible in the process of deciding to support a major project” (NRC, 1994, p. 59).

Michael Gibbons, Director of the science policy research unit at the University of Sussex, adds that,

> “the number of inter-connections is accelerating, so far apparently unchanneled by existing institutional structures. The ebb and flow of connections follow the paths of problem interest, and the paths of problem interest are no longer determined by the disciplinary structure of science” (Gibbons, 1997d, p. 1).

Given this perspective on the structure of scientific problems, it is no surprise that the institutions charged with oversight and research funding allocation at the project level have made attempts (such as the NSF/WTEC study) to bridge the emerging gaps between the established disciplines and the new and combined disciplines.

One problem for the NSF and similar organizations is the fact that many activities are inappropriately called “interdisciplinary,” because the term has become popular. Use of the word makes the team leader or authors appear to be doing something that is highly valued. In fact, many activities that are called “cross-disciplinary” or “interdisciplinary” are really engineering centers, that typically involve science deriving from the same disciplines (NSF et al., 1995, p. 4). Occasionally, someone like Nobelist Rick Smalley at Rice can put together a more broadly multidisciplinary center. However, funding is usually awarded according to traditional disciplinary lines and the disciplines are based on adherence to tradition—not on the most current state of the art or practice (Constant, 1989, p. 224).

Science economist Nathan Rosenberg asked, “How can organizations and incentives be created that will be conducive to high quality interdisciplinary research? To what extent is it reasonable to expect such research to be conducted inside individual firms...? How can fruitful interactions between scientists and technologists, as well as among scientists from different disciplines, be most effectively encouraged? What measures can be taken to ensure that valuable findings or methodologies from any point on the science/technology interface will be transferred rapidly to other points” (Rosenberg, 1994, p. 157)? As Rosenberg suggests, it is imperative that we treat these questions in a systematic way.

None of this is meant to criticize peer reviewers for their lack of knowledge of disciplines in which they have not been trained and do not work. It is a systemic issue. The NSF report on *Major Award Decisionmaking at the National Science Foundation* said, “The panel concluded that merit review has generally served well to ensure fairness, effectiveness, and efficiency in decision-making on research projects over the years, but for major awards the system needs some changes to accommodate evolving conditions and special features of costly large-scale, long-term projects. Merit review is not perfect, but no clearly superior method of selecting research and research-related projects for support has been discovered after many years of experience here and abroad” (NRC, 1994, p. 3).

Proposal review is needed. However, when there are no peers, or when the peers are so few that they compete with each other, there is a problem. Cross-disciplinary peer review as currently, if rarely, practiced has some built-in structural deficits that make it difficult to improve on the process. The answer may be simply to let time take its course while new peers self-select. For normal science, which relies on incremental problem solving, this would be the best course. In today’s environment of rapid breakthroughs, which characterizes the nanotechnology field, this approach is somewhat less attractive.

While this critique can be generalized to most novel scientific research, it applies most pointedly to nanotechnology. In testimony before the subcommittee on Science, Technology, and Space of the Committee on Commerce, Science, and Transportation of the United States Senate, Eric Drexler of the Foresight Institute stated, “There are cultural problems in the scientific community, which is aimed at the study of nature, when the problem at hand is making pieces that fit together to form systems. Pieces fitting together does not happen spontaneously; it requires a degree of planning that is unfamiliar in the molecular sciences today” (Drexler, 1992b, p. 22).

Another way of putting this is that it matters who asks the questions in research. The nanotechnology research agenda is not currently set by study section leaders acting according to paradigmatic science, but through an unorganized, commonsense heuristic among a relatively small—albeit growing—cadre of researchers. One wonders if this might lead a new dominant model—a “presumptive anomaly” (Constant, 1980) or a “new paradigm” (Kuhn, 1962)—or whether research will remain dominated by current disciplinary perspectives. We will explore this further.

### ***Peer Review II (Synergy)***

Are there changes that would provide improvement without “throwing-out the baby with the bath water?” As Weinberg said, “…a scientist can get almost as much satisfaction working in a very narrow specialty appreciated by only a few of his colleagues as in working on a broader canvas. But if the prime purpose of science is to learn as efficiently as possible as much as possible about the world, then any breakdown in communication between the sciences or between neighboring branches within a science is, if not a calamity, certainly a cause for deep concern (because) …the sum total of a team's knowledge generally exceeds the knowledge of any member of the team” (Weinberg, 1967, p. 42-50).

There is a team-building drill called the *Desert Survival Exercise*. The point of the drill is the concept of synergy—shorthanded as "one plus one equals three." In it, the students—who typically have different backgrounds and do not share a common paradigm—are given a scenario of a desert plane crash and asked individually which items they still have in their possession might, in their opinion, offer the best hope of survival. They list them in order of likelihood of helping them stay alive. Then teams are formed and the team members discuss the list and arrive at a consensus on a team ranking. The team scores are almost always better than any of the single individuals' scores. In this case, one plus one invariably equals more than two. How can we create and improve synergy in scientific research?

The Santa Fe Institute was created, in part, to deal with the issues of interdisciplinarity and synergy. Its founders set it up to explore the most exciting problems in science that require insights from many disciplines. The Institute discourages the traditional disciplinary barriers that often keep scientists of different backgrounds from working together. "Here you can find physicists, biologists, psychologists, mathematicians, economists, immunologists and others nurturing various ideas and techniques" (Baake, 1997, p. 1). Examples of other organizations established for the express purpose of helping scientists overcome disciplinary boundaries include the Institute for Prospective Technological Studies, the Weizmann Institute of Science in Israel, and the International Consortium for Research in Energy and Environmental Management and Technology at the University of California - Irvine.

Probably the best way to improve synergy and cross-disciplinarity would be to encourage it within the funding agencies that drive research plans. Harvey Averch suggests in *A Strategic Analysis of Science & Technology Policy* that "For long-run effectiveness, government should provide some incentives for physicists, chemists, and economists who do not think within the confines of their professions, but who cross professional and disciplinary lines, who are able to link scientific and technical information from diverse sources" (Averch, 1985, p. 187). NSF is trying to implement this kind of change. The NSF/WTEC Workshop on Global Assessment of the R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices was a fine example and it shows great promise. But, as shown in NSF's own reports, demanding change is not always successful (NSF et al., 1995 and NRC, 1994). In NSF's *Report of the Task Group on the Review of Interdisciplinary Proposals,* the authors discussed a survey of internal NSF reports from 1987 and 1993. "Both reports found shortcomings in how interdisciplinary proposals are treated at the Foundation {and recommended actions most of which} have not been implemented" (NSF et al., 1995, p. 4,5). One of these unimplemented actions was the appointment of a Division-level Interdisciplinary Research Coordinator.

Another enhancement could come from improving communications among scientists. Editor Phillip F. Schewe of *Physics News Update* recently wrote a plaintive article entitled, *Driven to Abstraction*. In it he asks, "Don't scientists read journals, consult colleagues, serve on committees, attend meetings, teach genetics or quantum mechanics to the next generation, and deliver talks at Tuesday-afternoon colloquia? Don't they choose their own level of involvement with other scientists? As evidence of success, are we not blessed with a growing inventory of laborsaving (even life-saving) devices, procedures, and smart materials? Isn't this enough" (Schewe, 1997, p. 2)?

His answer is that it probably is not enough, that conditions are changing rapidly and that researchers only have enough time to do their own work and scan journal abstracts from within their own disciplines. "How can nuclear physicists who haven't the time to read about atomic physics be persuaded to read about the physics of the brain" (p. 3)? Schewe implores scientists to pay attention to the writing of their abstracts—to make them attract scientists other than the 30 or 40 experts who will read their papers anyway. This awareness of reaching out to researchers in complementary, though not identical fields, could be a valuable addition to traditional peer review.

There are other ways to encourage more cross- and multi-disciplinarity. For example, there is a new web-based journal published by the AAAS for the explicit purpose of helping scientists keep up-to-date on developments in other scientific disciplines. In a recent subscription advertisement, *ScienceNOW* quoted a letter from a subscriber, "I read the journals in my discipline, of course, so I can closely follow the latest findings affecting my work. I also read *Science* to get a broader perspective, to keep up with policy issues, and to look in depth at a few news items from other fields. But that requires a time commitment I can't always make. I need a better way to keep up with the latest findings across the sciences" (Nicholson, 1997, p. 1). It may not be much, but these approaches are a start and policymakers can encourage more, similar efforts.

In the final analysis, peer review and cross-disciplinary review are not mutually exclusive. Some funding organizations, publications, and individual scientists are working hard on improving the situation. However, more practitioners of S&T need to interact with and actually work with others from outside their disciplines. Since nanotechnology is highly cross-disciplinary and since it is consuming large sums of R&D dollars, policymakers should care greatly about inefficiencies inherent in today's implementation of cross-disciplinary peer review.

Although there is a price that is paid for fragmented multidisciplinary review and funding of nanotechnology, there is also a danger in prematurely creating a nanotechnology "discipline" by government decree. James Bennett is President of the Center for Constitutional Issues in Technology and a Director of the Foresight Institute. He calls a fully coordinated nanotechnology research effort "monocropping" (Bennett, 1995, p. 229). Bennett says that a big, unified government effort would, in essence, be placing all of our eggs in one basket. He suggests that a concerted effort by the government is not the right way to go about the business of nanotechnology research. "Just as a monoculture in forests or other agricultural areas is bad for the ecology in the long-term, so is what I would call monocropping in research, which I define as 'a tendency to concentrate all your research dollars on a common set of programs, a common set of directions.' When new technologies are emerging in many new areas, one must invest in multiple paths." Branscomb seems to agree with Bennett, calling for "numerous, smaller technology bets" because megaprojects rarely achieve their goals (Branscomb & Keller, 1997, p. 15).

Branscomb also says, "The federal government should follow the NSF/NIH model of relying primarily on relatively small grants spread out among many performers, awarded competitively but funded over multiple years. It should fund a variety of technology areas chosen with input from the technical experts from the private sector as well as from research institutions… It should achieve scale, where it is needed, by encouraging groups of institutions to collaborate in formulating plans for diversified research and the diffusion of the results" (Branscomb & Keller, 1997, p. 15).

As one looks at the chronology of nanotechnology research progress in Appendix A, it is apparent that there is no single approach, no single discipline that is at present provably more likely to be successful than any other. It would be highly speculative—and without current merit—to suggest a megascience solution.

There are a number of financial, management, political, regulatory, and technical issues policymakers might discuss in considering whether we should change our current policy towards nanotechnology research and development. Some seem clear, such as the need for placing a higher value on cross-disciplinarity (and improvement in the peer review process towards that end) and the need for improved communications in the field.

Scientists will not improve the cross-disciplinarity issue at the demand of policymakers. They do what they think they are supposed to be doing according to the paradigms and peer-reviewed directions of their fields. They will not generally change course because of someone else’s perception of a “higher public or national need.” Policymakers need to establish incentives via funding mechanisms—the best way to influence what scientists do—so that a higher premium is put on cross-disciplinary research. The NSF should implement its own suggestion to create a Director-level position to facilitate the handling of unsolicited cross-Directorate proposals and fund cross-Directorate awards (NSF et al., 1995, p. 2, 8).

## *Conclusions*

> *If our small minds, for some convenience, divide this... universe into parts—physics, biology, geology, astronomy, psychology, and so on—remember that nature does not know it!*
>
> (Feynman, 1963)

At the beginning of the 1990's, nanotechnology was considered by many scientists to be a novelty. As we approach the millenium, this is no longer the case. The outgoing Director of NSF, Neal Lane, recently testified in Congress,

> "If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering, often called simply 'nanotechnology.' The general idea of nanotechnology is not new—it has been studied since Nobel laureate Richard Feynman outlined the idea in a speech in 1959—but only recently have scientists been able to glimpse Feynman's vision by creating rudimentary nanostructures." (Lane, 1998)

I have attempted, in this thesis, to illustrate the potential societal importance of this emerging field of molecular nanotechnology and to bring into focus the interactions among researchers, funding agencies, and policymakers in advancing the field. I have endeavored to establish the importance of developing a framework for a national nanotechnology policy—where none currently exists—by demonstrating an extensive and growing financial investment and an accelerating investment of researchers' time and by reporting the results of government-sponsored studies that recommend some changes from the status quo. In this concluding chapter, I will recap some key points and then pose some questions in need of further reflection and study.

Molecular nanotechnology is a rapidly growing research site as measured by the number of investigators, the number of refereed journal citations, and federal government spending in the field. There are substantial potential benefits in materials, computing, medical and pharmaceutical science, space exploration, and manufacturing. But there are also considerable safety risks, economic issues, and ethical questions that need to be addressed in greater depth.

Researchers are making strides in all fields necessary to effect a working nanoscale technology: molecular design and modeling; software development and communications;

directed self-assembly; and the use of DNA and other biological materials as structural components. On the other hand, the research efforts, though dramatic, are hindered by disciplinary prejudices and the lack of cross-disciplinary terminology.

The strategic policymaking structure in the United States could have decisive impact on the timelines and safety of molecular nanotechnology but there remains some doubt as to how directed the federal effort will (or should) be. Most S&T for which a national policy exists is "big science," megaprojects with substantial budgets and substantial political support. The $153M in federal FY1999 nanotechnology investment does not qualify for "big science" attention or support. This may actually benefit researchers in the field by reducing the political micromanagement that often accompanies these megaprojects.

There is no current need for a highly structured nanotechnology program at the federal level nor is any single agency obviously appropriate to serve as the primary locus for such a program. But because current efforts are not coordinated (although many are successful as stand-alone projects) synergy is seriously lacking. Furthermore, federal R&D dollars are shrinking (in constant terms) as compared with other line items, restricting the funds available for future non-paradigmatic research.

Five significant federally-sponsored reports on the state of nanotechnology research agreed (with some variation in definitions) that nanotechnology is rapidly coming closer to fruition. They also agreed that nanotechnology could be characterized as interdisciplinary (or multidisciplinary). All recommended an effort of some kind to compact and combine efforts of researchers who currently work within the confines of disciplinary paradigms. They differed to some degree in recommendations as to what needs to happen next.

Whichever stakeholders believe they will benefit most from S&T are most likely to invest in it, with industry investing only if there is a reasonable expectation of a near-term payback. It is belief in benefit, not the realization of benefit, that tends to control the likelihood of investment. That there is no identifiable firm, industry, profession, or sector that will benefit more from nanotechnology than others, strongly suggests that current efforts should be federally sponsored. The issues of risk and foreign competition also suggest government, rather than commercial, leadership in the field.

A serious issue, one that particularly needs attention, is that nanotechnology research does not fit into discipline-based paradigms but crosses many disciplinary boundaries. The existing scientific disciplines have established successful networks of “peers” who safeguard resources as well as the scientific integrity of the paradigms in which they operate. The price the public pays for this form of social management is some stifling of emerging (non-paradigmatic) S&T.

Even if policymakers decide that nanotechnology deserves more extensive attention, investment, and freedom from disciplinary encumbrances, there is no need for them to make abrupt changes in the status quo. Paradigms cannot be forced into being. They occur over time in an evolutionary—sometimes revolutionary but nonetheless structured—process (Kuhn, 1962, p. 86). Nanotechnology as a concept is only 29 years old and it is clearly not characterized by a common set of paradigms. There is no need to push it along; it will either emerge as a new paradigmatic technology (Kuhn, 1962, p. 159) as researchers continue to cross disciplinary boundaries to work together in newly combining fields, or it will fail to produce the results its proponents desire. A plausible marker for the achievement of new nanotechnology paradigm would be the awarding of the Feynman Grand Prize by the Foresight Institute.

Until that time, and based upon what we have already established, three actions should be taken by the federal government as the initial steps in the formation of a national policy. First, as recommended in all five of the major reports on nanotechnology—and in order to alleviate the costs of incommensurable terminologies—there should be the establishment of a clearinghouse to gather information from all of the subsidiary fields and to coordinate nanotechnology research efforts among federal government agencies.

Second, there needs to be an assessment of whether it is strategically important for the United States to develop nanotechnology first or whether it will suffice for us to be cognizant of progress by others and able to defend against its aggressive use. The United States is alleged to be ahead of the rest of the world in some aspects of nanotechnology research but seriously behind in others (WTEC, 1998 p. 1121).

Finally, the severity of the risks of molecular nanotechnology (competition from other nations, dangerous misuse by terrorists or hostile powers, and the intrinsic risk of powerful new technologies) must be addressed. It is unclear as yet whether these risks should be addressed by one organization or by several coordinated groups. It may well be that in order to carefully avoid interest conflicts, the functions of information clearinghouse and technology promoter should be separated from that of risk analysis.

There is tension between a finding that the field does not need consolidation/oversight and a presumption about the severity of the risk. However, we are not yet sure whether assemblers/disassemblers are feasible, so it is not known how urgently we need to address the risk. It might be that this is an intelligence-gathering role that would best be assigned to an intelligence agency. A strategic federal research policy is required to address this current deficiency. Nevertheless, no later than coincident with the awarding of the Feynman Grand Prize, there needs to be an in-depth risk assessment.

Aside from actions the government should take, there are questions STS analysts need to ask. Frank Press said, “Prudent stewardship of science and technology, as much as any other area of federal policy, will dictate how our children and our grandchildren live” (Press, 1995, p. 30). Alvin Weinberg put it even more strongly, “The whole future of our society depends upon the continued success of our science and our scientific technology” (Weinberg, 1967, p. 2). If the trend of the last three decades continues, nanotechnology will have a substantial impact on society. Through nanotechnology, we could make marginal changes in our lot, invent improvements beyond our ability to imagine, or, if we are not careful, destroy much of what mankind has built over the last several thousand years. In this domain, the decisions we make truly matter.

Stephen Bailey, the Dean of the Maxwell School of Public Ethics at Syracuse University, reminded us of just how difficult it is to make decisions in such matters even when we think we have the facts. In his 1965 essay, *Ethics and the Public Service*, Bailey recounted what he called “the malignant effects of benign moral choices.”

> “An Egyptian once commented that the two most devastating things to have happened to modern Egypt were the Rockefeller Foundation and the Aswan Dam. By enhancing public health, the Rockefeller Foundation had upset the balance of nature with horrendous consequences for the relationship of population to food supplies; by slowing the Nile, the Aswan Dam had promoted the development of enervating parasites in the river. The consequence of the two factors was the more people lived longer in more misery” (Bailey, 1965).

In the case of nanotechnology, we cannot yet place plausible limits on the extent of the risks or the rewards and we do not yet know what the hard dollar and opportunity costs will be. It is, therefore, even more tricky to make the “right” decisions. Some critics of nanotechnology research suggest that those who would devote our limited time and resources to the question are overly optimistic. As Bailey said, “True optimism is the affirmation of the worth of the taking risks. It is not a belief in sure things; it is the capacity to see the possibilities for good in the uncertain, the ambiguous, and the inscrutable” (Bailey, 1965). Nanotechnology is decidedly not a “sure thing” but it does offer much promise and the required enabling technologies are moving forward at a rapid pace.

It has now been established that molecular nanotechnology research is a significant enterprise, both in the United States and in other nations. The National Science Foundation expects to spend $175M in FY1998—and other institutions around the world another $800M during the same period—on research in the field (Siegel, 1998). It therefore seems appropriate to pose some questions (such as “Where do we go from here?”) and identify several issues for further exploration. Historical questions about what has happened in the field of nanotechnology can be answered with relative ease as shown in Appendix A of this paper. Questions about the sociological workings of researchers have been addressed in this paper and in a myriad of books and essays in the field of Science and Technology Studies. There are several areas of inquiry that might logically follow. Among them are:

- philosophical questions specifically about nanotechnology per se and as a model of emerging technologies in general, and
- the ethical implications of nanotechnology research—issues of priority, who should make decisions and on what grounds, etc.

Nanotechnology research can be broadly defined to encompass dozens of projects within the established disciplines of physics, chemistry, biotechnology, etc. that deal with manipulating matter in the sub-micron domain. If nanotechnology were merely an extension of miniaturization, then the philosophical questions pertaining thereto would be no more challenging than those surrounding other new technologies. There is, however, a growing community of practitioners of nanotechnology research who claim progress (at least theoretical and computational progress) towards an ability to manipulate matter to allow the design, manufacture, and programming of molecule-sized, semiautonomous, communicating machines. These “nanomachines,” say the theorists, will be designed to perform such tasks as seeking and destroying cancer cells, identifying and correcting genetic damage (including aging factors), converting pollutants into directly-usable energy sources, and even making food out of dirt.

Outlandish? So some scientists with paradigmatic commitments would say. However, with research money pouring in and Nobel Prizes being awarded to researchers in the field[6], ignoring the potential seems imprudent. If philosophers of technology are to observe the field, what kinds of questions should we ask? Here are some examples that bear further exploration:

- What constitutes an appropriate field of inquiry? Should government funding agencies expend scarce resources (including opportunity costs) on something with enormous but conjectural benefits such as molecular nanotechnology or should they reserve them instead for marginal but more easily predictable improvements in "normal science" (Kuhn, 1962)? How will practitioners of S&T deal with the disruption and melding of existing disciplines?
- Is the work in this field, in which there is not yet a paradigm, really an example of Kuhnian pre-paradigmatic science? Peter Galison's Image And Logic (Galison, 1997) talks about how practitioners from different sub-fields interact to mediate conflicting views in a progression towards more complete resolution. He differs with Kuhn's formulation for paradigms, suggesting that alternative belief-sets that change over time are not incommensurable. As Clifford Geertz of the Institute for Advanced Study at Princeton suggests, one might look to Galison for assistance in a theory of how a community (in the present case consisting of experimentalists, chemists, biologists, physicists, etc.) who are normally "neither like-minded nor without a strong sense of professional identity" might work within Galison's concept of border-crossing 'trading zones.' (Geertz, 1998)
- How do we appropriately select from among possibilities like a here-and-now DNA Lab on a chip vs. a soon-to-be transgenic banana that can not only produce but also deliver a malarial vaccine that can work in real life where it's needed vs. molecular nanotechnology that can, in theory, produce artificial immune systems or nano-robotic cell/DNA repair systems but for which we need so many enabling steps?
- What is a theoretical technology? Can one "spray" (Hacking, 1983) nanomachines? How would one "falsify" (Popper, 1968) claims about that that do not exist yet (and does it make sense even to attempt to do so?) How much does computer modeling of

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[6] e.g., Hoffman, Rohrer, Smalley (and most recently, Kohn and Pople in 1998 for their work in computational quantum chemistry)

molecular machines count as evidence of progress? Is nanotechnology a prospective technology or is it science fiction?

- How should the S&T community deal with the immense potential risks inherent in a successful implementation of self-assembling nanodevices? When will we know whether it is time to form a RAC-like body? If scarcity becomes uncommon, what risk is there to micro- and macro-economic systems? What role should the military play in production of and defense from nanoweapons?
- Who should be asking the questions and on what grounds? Scientists (peers) only? Policymakers? Politicians? The citizens whose lives could be affected?
- What are the ethical implications of nanotechnology? Should we view this field and its potential consequences strictly through utilitarian lenses, or is there some other important source for guidance about the ethical obligations and benefits to be incurred in dealing with nanotechnology? Should religion play a role in our technical/ethical discussions? Will "progress" in the field further exacerbate the problem of technological haves and have-nots?
- What impact, if any, will a successful implementation of nanotechnology have on the way we think about the nature of knowledge? If knowledge is bound by technical capabilities, will the field's conceivable capabilities provide new ontological and epistemological lessons to learn and new ways of learning them?
- Will nano-assisted brains and bodies still be considered human? To what degree can we enhance ourselves genetically without creating a new species?
- Is a world populated by nanomachines that can (theoretically) solve today's problems of disease and aging, pollution and scarcity, overpopulation and starvation to be desired or avoided? Will these "solutions" enhance happiness or merely permit us to temporarily avoid inevitable sorrows.

Many of these issues need to be addressed whether or not nanotechnology work succeeds, for some of the changes could come about through other vectors, other new fields. Nevertheless, the current accelerating work in nanotechnology suggests that we think about the questions now, while we have the time to assess them carefully instead of later, when we may be forced to react too quickly to momentous change.

We began with the question of whether nanotechnology is of sufficient substance to merit a national policy. The answer to that question is yes. This paper provides a policy framework to employ in examinations of:

- Where we have been,
- Where we are now, and
- Where we need to go.

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## *Appendix A — Chronology of Significant Events in Nanotechnology Research*

### 1959 - 1980

- 1959 — Richard Feynman gives his “Plenty of Room at the Bottom” talk. (Feynman, 1959)
- 1959 — Feynman pays William McLellan $1,000 for building a one-millionth-horsepower motor using novel, but conventional techniques. (Gleick, 1992, p. 356) (Also see Noji, 1997)
- 1974 — The term “nanotechnology” is coined by Japanese researcher Nobuhiko Taniguchi. (Robinson, Helvajian, & Janson, 1997)
- 1977 — P. Lauger, writing in *Nature*, describes ion transport and rotation of a bacterial flagellar motor. (Lauger, 1977)
- 1979 — Carl Pabo publishes article on protein folding in *Nature*. (Pabo, 1979)

### 1981

- Gerd Binnig and Heinrich Rohrer announce the development of the Scanning Tunneling Microscope that is capable of displaying images of individual atoms. (Crandall, 1996, p. 21)
- Roald Hoffmann wins Nobel Prize in Chemistry for his work in the geometrical structure and reactivity of molecules — later (1994) becomes a member of the Technical Advisory Board of Molecular Manufacturing Enterprises, Inc. (Mills, 1995)
- Eric Drexler publishes paper on molecular engineering in the *Proceedings of the National Academy of Sciences*. (Drexler, 1981) and (Mills, 1989a)

### 1982

- Drexler publishes “When Molecules Will do the Work” in *Smithsonian Magazine*. (Drexler, 1982)

### 1983

- Feynman gives his “Tiny Machines” talk at Esalen. (Gleick, 1992, p. 407)
- Kevin M. Ulmer writes in *Science*, “The prospects for protein engineering, including the roles of x-ray crystallography, chemical synthesis of DNA, and computer modeling of protein structure and folding, are discussed. It is now possible to attempt to modify many different properties of proteins by combining information on crystal structure and protein

chemistry with artificial gene synthesis. Such techniques offer the potential for altering protein structure and function in ways not possible by any other method" (Ulmer, 1983).

**1984**

- R. Bruce Merrifield, Professor at Rockefeller University, is awarded the Nobel prize in chemistry for the development of a simple method for obtaining peptides and proteins, creating new possibilities in the field of peptide and protein chemistry (Sciences, 1984).
- A news article in *Science* announces that R. Lewin has found the first true RNA catalyst. (Lewin, 1984)

**1985**

- Richard Smalley and his team (Kroto, Curl, Heath, O'Brien, Liu, and Zhang) discover the soccer ball-shaped molecule $C_{60}$ (Buckminsterfullerene) — later to become known as "buckyballs." (Aldersly-Williams, 1995)
- Feynman pays Stanford student Thomas Newman $1,000 as the prize for shrinking the first page of "A Tale of Two Cities" onto a silicon wafer. (Gleick, 1992, p. 356)

**1986**

- Eric Drexler publishes Engines of Creation. (Drexler, 1986)
- Binnig and Rohrer win the Nobel Prize in Physics for the invention of the Scanning Tunneling Microscope. (Hellemans & Bunch, 1988, p. 599)
- Drake, Prater, Weisenhorn, Gould, Albrecht, Quate, Cannell, H. G. Hansma, and P. K. Hansma develop the Atomic Force Microscope that can display images of non-conducting surfaces including biological entities. (Crandall, 1996, p. 22) and (Drake et al., 1989)

**1987**

- Conrad Schneiker presents "NanoTechnology with Feynman Machines: Scanning Tunneling Engineering and Artificial Life" at a Santa Fe Institute workshop. (Crandall, 1996, 24)
- Poundstone describes universal constructors. (Poundstone, 1987)
- William DeGrado of Du Pont, citing Drexler, proposes to build an engineered protein consisting of four distinct helixes connected by a series of loops. (Regis, 1995, p. 202)

- The Foresight Institute is founded by Eric Drexler and Chris Peterson "to help prepare society for anticipated advanced technologies … with a primary focus on molecular nanotechnology: the coming ability to build materials and products with atomic precision (which) has broad implications for the future of our civilization."
- The Nobel Prize in chemistry is awarded to Charles Pederson, Donald Cram, and Jean-Marie Lehn for developing synthetic molecules with the protein-like capabilities of selective binding and molecular recognition. (Sciences, 1987)
- MIT holds its first Nanotechnology Symposium. (Mills, 1987)[7]
- Japan launches Human Frontier Science Program — expected to span 20 years and to cost some $6 billion. (Foresight, 1987)
- Julius Rebek of MIT discusses the world's first self-replicating molecule. (Regis, 1995, p. 241) and further described in *Acc. Chem. Res. 1994, 27, 198-203.*
- Drexler publishes paper on "Nanomachinery: Atomically Precise Gears and Bearings" in the proceedings of the 11/87 IEEE Micro Robots and Teleoperators Workshop. (Mills, 1987)
- Staley of Carnegie-Mellon, Milch of Eastman Kodak, and Deisenhofer of the Max-Planck Institute publish papers on molecular computing and electronics. (Mills, 1987)

**1988**

- O. Marti, H.O. Ribi, and others at Stanford describe improvements in Atomic Force Microscopy in *Science*. (Marti et al., 1988) and (Mills, 1988a)
- Foster describes molecular manipulation using a tunneling microscope in *Nature*. (Mills, 1987) and (Foster, Frommer, & Arnett, 1988)
- NIH computer scientist Richard Feldmann presents paper entitled, "Applying Engineering Principles to the Design of a Cellular Biology." (Crandall, 1996, p. 25)
- Hans Moravec, Director of Mobile Robot Lab at Carnegie Mellon discusses concept of nanocomputers in "Mind Children: The Future of Robot and Human Intelligence." (Crandall, 1996, p. 25)

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[7] References from Mills, Soreff, and others in the Foresight Institute's *Foresight Update Newsletter* are given as World Wide Web citations so the reader can more easily access the full text. All issues were published in hard copy (ISSN 1078-9731) and are available in libraries and from the Foresight Institute. References from web sites have been crosschecked with refereed journals where possible.

- The Office of Technology Assessment (OTA) of the U. S. Congress publishes its report on "Advanced Materials by Design." (Congress, 1988a)
- W. F. DeGrado builds an engineered protein. (DeGrado, 1988)
- Donald Cram of UCLA publishes a *Science* article on the problem of nano-effector design and the design of hundreds of molecules of varying shapes, hoping to learn how to make molecules with desired catalytic properties. (Cram, 1988) and (Mills, 1988b)
- *Science News* reports that Mark Wrighton, Tracy Jones, and Oliver Chyan at MIT have discovered a molecular-based transistor with signal-carrying abilities. (Mills, 1988a)
- Thomas Creighton, Charles DeLisi and Barbara Jasny, in separate *Science* papers, discuss possible solutions to the "protein folding" problem and the geometric conformance of nucleic acids. (Creighton, 1988), (DeLisi, 1988), (Jasny, 1988) and (Mills, 1988b)
- Researchers at Caltech, JPL, and the University of São Paulo, Brazil announce a molecular-sized shift register — a potential computer memory storage device — with one-thousandth the density and one ten-thousandth the energy consumption of its VLSI equivalent. (Hopfield, Onuchic, & Beratan, 1988) and (Mills, 1989a)
- Physicists at the National Bureau of Standards (now NIST) and Bell Labs announce in *Science* that they are able to confine groups of sodium atoms between a set of laser beams ("Optical Tweezers") and then slow down their motions to under 20 cm/sec. Refinements of this technique will later allow them to trap and manipulate microorganisms without damaging them. (Ashkin, Schutze, Dziedzic, Euteneuer, & Schliwa, 1990; Block, Goldstein, & Schnapp, 1990; Block, 1992; Mills, 1989a; Pool, 1988; Smith, Cui, & Bustamante, 1996)
- The Japanese government announces a 4-year effort called the Kunitake Molecular Architecture Project, part of Exploratory Research for Advanced Technology (ERATO.) (Mills, 1989b)
- B. W. Matthews of the University of Oregon publishes a paper in *Nature* in which he discusses redesigning traditional proteins to make them more stable — and incorporates a reversible molecular "on-off switch" into a T4 lysozyme. (Nicholson, Becktel, & Matthews, 1988) and (Mills, 1989b)
- Hansma, Elings, Marti, and Bracker write in *Science* about the application of scanning tunneling microscopy and atomic force microscopy to biology and technology (Hansma, Elings, Marti, & Bracker, 1988)

**1989**

- *Science* announces that the Program Advisory Committee on the Human Genome has adopted a general strategy for the effort, with NIH leading the project. (Roberts, 1989) and (Mills, 1989b)
- The *Wisconsin State Journal* reports that Iwao Fujimasa, MD, Ph.D. at Tokyo University's Research Center for Advanced Science and Technology, says his group is developing a robot small enough to travel inside the human body cutting and treating diseased parts in veins and organs. (Mills, 1989b)
- MIT holds “Nanotechnology: Prospects for Molecular Engineering” symposium. (Mills, 1989a)
- The 1st Foresight Conference, sponsored by the Foresight Institute, Global Business Network, and Stanford University, is held in Palo Alto, Ca.
- Kurt Mislow, a chemist at Princeton University publishes a paper entitled, “Molecular Machinery in Organic Chemistry” describing molecular gears similar to Drexler’s models. (Regis, 1995, p. 260)
- A group of researchers from the University of California at Berkeley announces in *Science* that they have used a scanning tunneling microscope (STM) for direct observation of native double-stranded DNA structures. (Beebe TP et al., 1989) and (Mills, 1989b)
- Roger Bone and his colleagues at the University of Chicago illustrate, in a *Nature* paper, the use of site-directed mutagenesis to broaden the specificity of an engineered protease. (Bone, Silen, & Agard, 1989) and (Mills, 1989c)
- Thomas Hynes and his colleagues at Yale and Stanford, according to a paper in *Nature*, make a hybrid between two unrelated proteins, yielding a fully functional protein. Essentially, they treat proteins as modular devices whose parts can be selectively interchanged. (Hynes, Kautz, Goodman, Gill, & Fox, 1989) and (Mills, 1989c)
- Jonathan Scholey reports in *Nature* on the mechanoenzyme kinesin, which consists of a pair of globular “heads” about 10 nm in diameter, a 45 nm stalk, and a fan-shaped “tail” about 20 nm long. Kinesin functions as what might be called a “cellular conveyor system.” (Scholey, Heuser, Yang, & Goldstein, 1989) and (Mills, 1989c)

- According to articles in *Biochemistry* and *Science News,* chemists J. H. Chen, Nadrian Seeman[8], and their colleagues at New York University say they intend to build three-dimensional structures out of DNA segments, then hook proteins to the resulting framework. (Mills, 1989c) (See 1991, 1995, and 1997 for more on Seeman.)
- A *IEEE Spectrum* paper by Anthony Arrott describes the use of molecular-beam epitaxy to lay down alternating layers of metals, each only a few atoms thick, exhibiting strong magnetic fields that can be switched from one direction to another by an electric current. (Mills, 1989c)
- In *J. Am. Chem. Soc.*, T. R. Kelly of Boston College reports that he and his colleagues have now constructed a rudimentary non-protein enzyme that binds two reactants, fosters the formation of an amide bond between them, then releases the product back into solution. (Mills, 1990a)
- In *Science*, C. J. Noren and his colleagues at the University of California at Berkeley report that they have developed a method for getting bacteria to make desired proteins that include nonstandard amino acids using the traditionally unused codon ‘TAG’. (Noren, Anthony-Cahill, Griffith, & Schultz, 1989) and (Mills, 1990a)
- In *Angewandte Chemie International (Edition in English),* Franz H. Kohnke of the University of Messina suggests that the next few years will see rapid development of “structure-directed synthesis, giving rise to molecules that look like ball bearings, beads and threads, belts, cages, chains, chimneys, clefts, coils, collars, knots, ladders, nets, springs, stacks, strips, washers, and wires — and concurrently and subsequently for molecules with function — that work like abacuses, capacitors, catalysts, circuits, clocks, conductors, dynamos, membranes, motors, nuts and bolts, resistors, screws, semiconductors, sensors, shuttles, superconductors, and switches” (Mills, 1990b).

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[8] Nadrian Seeman’s body of work is so significant, it bears being special attention. Peer-reviewed publications by Seeman include: Chen, Churchill, Tullius, Kallenbach, & Seeman (1988a); Chen & Seeman (1991b); Chen & Seeman (1991a); Chen, Seeman, & Kallenbach (1988b); Du & Seeman (1994); Du, Wang, Tse-Dinh, & Seeman (1995); Du, Zhang, & Seeman (1992); Fu, Kemper, & Seeman (1994a); Fu & Seeman (1993); Fu, Tse-Dinh, & Seeman (1994b); Kimball et al. (1990); Li, Wang, & Seeman (1997); Lu, Guo, Marky, Seeman, & Kallenbach (1992); Lu et al. (1990a); Lu et al. (1990b); Lu, Guo, Seeman, & Kallenbach (1989); Mao, Sun, & Seeman (1997); Mueller, Kemper, Cunningham, Kallenbach, & Seeman (1988); Mueller et al. (1990); Qiu, Dewan, & Seeman (1997); Seeman (1988); Seeman (1991); Seeman (1996); Seeman & Kallenbach (1994); Sekiguchi, Seeman, & Shuman (1996); Wang, Di Gate, & Seeman (1996); Wang, Du, & Seeman (1993); Wang & Seeman (1995); Wang, Mueller, Kemper, & Seeman (1991); Zhang, Fu, & Seeman (1993); and Zhang & Seeman (1994).

**1990**

- According to an article in *Science News*, Julius Rebek and coworkers at MIT have designed and built a primitive replicator: a 200 atom molecule that produces copies of itself, given appropriate raw materials. (Rebek J, 1991) and (Mills, 1990b)
- The 1st issue of *Nanotechnology* is published by the Institute of Physics.
- *Science* reports that Sylvia T. Ceyer (later a member of the National Academy of Sciences' Commission on Physical Sciences, Mathematics, and Applications) and her colleagues at MIT have been using molecular beams to study the adsorption of small molecules onto metal surfaces — perhaps confirming that atoms and molecules can be added to a workpiece by hammering them against it. (MIT, 1996) and (Mills, 1990c)
- Robert Pool writes in *Science* that there are now at least nine types of atomic or near-atomic resolution microscopes. (Mills, 1990b)
- The American Vacuum Society holds "NANO I", the 1st International Conference on Nanometer Scale Science and Technology.
- In *Nature*, J. A. Piccirilli of IBM's Zurich Laboratory for Organic Chemistry reports that his group has now added two new base-pair forming nucleotides (which they call kappa and pi) to the traditional set of nucleotides found in DNA (A, T, C, and G.) This 6-letter genetic code would increase the number of effectively usable amino acids from the present 20 to 68. (Piccirilli, Krauch, Moroney, & Benner, 1990) and (Mills, 1990a)
- Don Eigler spells 'IBM' in 35 Xenon atoms on a nickel crystal surface. (Regis, 1995, page 11) and (Eigler & Schweitzer, 1990)
- Shoichiro Yoshida and his research team with the Research Development Corporation of Japan complete a five-year ERATO project aimed at developing instruments and techniques for measuring and processing at nanometer scales. (Mills, 1990c)
- Ryoji Noyori of Nagoya University reports on his ERATO work with chiral metal complexes — catalysts could be thought of as rudimentary assemblers that are 'programmable' through changes in the reaction milieu. (Noyori, 1995) and (Mills, 1990c)
- In *Nature*, Eric Drexler of Stanford and John Foster of IBM suggest that Atomic Force Microscopes should be equipped with engineered molecular probe tips which would make them much more versatile and reliable. (Drexler & Foster, 1990), (Mills, 1990c), and (Drexler, 1992a, sec. 15.4)

- Block of Princeton University reports in *Nature* that his team of researchers attached kinesin motors to silica beads, then used optical tweezers to place the beads against a microtubule. (Block et al., 1990)
- Ashkin and his team use optical tweezers to model a system for the study of organelle transport in the giant amoeba Reticulomyxa. (Ashkin et al., 1990)
- David F. Blair, in *Seminars in Cell Biology*, surveys what is known about the structure, genetics and dynamics of the bacterial flagellar motor. (Blair, 1990; Blair & Berg, 1990)
- C. M. Dobson reports in *Nature* that the T4 lysozyme (an enzyme that dissolves bacterial membranes) molecule contains a bendable and foldable hinge. (Dobson, 1990)
- Separate *Science* papers by Hoshi, Zagatta, and Aldrich show that ion channels in nerve cells are opened and closed by a structure "resembling a ball and chain" and that these ion channels, made up of protein molecules arranged around a central cavity, serve as pores connecting the inside and outside of nerve cells. (Hoshi, Zagotta, & Aldrich, 1990) and (Zagotta, Hoshi, & Aldrich, 1990)
- According to the *Seattle Times*, MITI has announced that it would spend some $171 million over the next ten years to study "microtechnology" (seen by the Japanese as complementary to molecular manufacturing) and Germany is planning to devote some $255 million over four years to similar research. (Mills, 1991a)

**1991**

- Researchers from Affymax Research Institute note in *Science* that combining methods from the electronics industry with automated peptide and nucleic acid production techniques, they can carry out large numbers of simultaneous peptide syntheses in a small area reducing protein design time and improving techniques for the microfabrication of devices. (Fodor et al., 1991) and (Mills, 1991b)
- Nadrian Seeman and Junghuei Chen of New York University announce in *Nature* that they can build a cube-like object out of DNA and that "DNA might be used to make larger frameworks to which proteins or other molecules could be attached" (Chen & Seeman, 1991).

- A paper in *Nature* discusses the manipulation of ferritin molecules, “programming them” by changing a single amino acid to introduce a metal-binding site. (Lawson et al., 1991) and (Mills, 1991b)
- George Whitesides and his colleagues at Harvard write in *Science* about molecular self-assembly and nanochemistry which they describe as a chemical strategy for the synthesis of nanostructures. (Whitesides et al., 1991)
- Buckminsterfullerene is named “molecule of the year” by the American Association for the Advancement of Science (AAAS). (Crandall, 1996)
- IBM and MITI announce nanotechnology research initiatives (Crandall, 1996, p. 26)
- The Piccirilli team at the University of Chicago elaborates on its work on extending the DNA “alphabet.” (Piccirilli, Moroney, & Benner, 1991)
- Buckytubes are manufactured for the first time by Sumio Iijima and P. M. Ajayan of NEC in Japan. (Iijima, Ichihashi, & Ando, 1992) and (Crandall, 1996, p.32) They later patent their process. (Patents, 1993)
- AAAS publishes special issue of *Science* (*Science* 1991 Nov 29 254:5036) dedicated to nanotechnology. (Crandall, 1996, p. 26) Included are papers on reverse engineering biological systems (Freedman, 1991), molecular self-assembly (Whitesides et al., 1991), three-dimensional structures (Milburn et al., 1991), folding of transfer RNA’s (Pan, Gutell, & Uhlenbeck, 1991), microfabrication techniques for integrated sensors and microsystems (Wise & Najafi, 1991), and computer simulations of self-assembled membranes (Drouffe, Maggs, & Leibler, 1991).
- The 2nd Foresight Conference is held in Palo Alto.
- Biologist David Blair of the University of Utah discusses atomic-scale motors that exist in nature (e.g. MotA protein in *E. coli*) that are so tiny they are barely discernible by electron microscopes. (Blair & Berg, 1990) and (Regis, 1995, p. 247)
- Drexler completes his thesis entitled, “Molecular Machinery and Manufacturing with Application to Computation” and is awarded a Ph.D. from MIT. (Regis, 1995 p. 251)
- The Japanese Ministry of Trade and Industry (MITI) announces a $200M project to “promote research into nanotechnology.” (Regis, 1995, p.279)

- A group of scientists from the Panum and Ørsted Institutes in Copenhagen publishes results of computer modeling of the anti-sense compound PNA, hoping to develop a radically different backbone for DNA. (Nielsen, Egholm, Berg, & Buchardt, 1991) and (Mills, 1992)
- Vivian Cody of the Medical Foundation in Buffalo, New York, in *Genetic Engineering News*, discusses conducting drug binding studies by using virtual reality. (Mills, 1992) and (Wojtczak, Luft, & Cody, 1992)
- Two physicists at the U.S. Naval Research Laboratory, J.Q. Broughton and M.R. Pederson, hypothesize (and have performed computer simulations to confirm) that capillary action in fullerene tubules should draw some kinds of molecules into their interiors. (Mills, 1993b) (For an image of the nanotube, see: http://cst-www.nrl.navy.mil/gallery/jerm/tube/tube.html)

**1992**

- The Foresight Institute hosts the first General Conference on Nanotechnology.
- Drexler publishes Nanosystems - Molecular Machinery, Manufacturing, and Computation. (Drexler, 1992a)
- The Defense Advanced Projects Research Agency (DARPA) begins its ULTRA Project to "improve speed, density, power and functionality beyond that achieved by simply scaling transistors. These improvements should manifest themselves in systems operating at room temperature at speeds 10 to 100 times faster than current systems, denser by a factor of five to 100, and lower power by a factor of more than 50" (Pomrenke, 1997).
- *Nature* sponsors a nanotechnology conference in Japan with presentations by Smalley and Eigler. (Crandall, 1996, p. 28)
- Steve Block of Princeton University continues his work on 'optical tweezers' and pins molecular structures in place with beams of light. (Block, 1992)
- Ellman, Mendel, and Schultz develop a method for incorporating "unnatural" amino acids into proteins. (Ellman, Mendel, & Schultz, 1992)
- Richard Lerner and Sydney Brenner of the Scripps Institute discuss in the *Proceedings of the National Academy of Sciences* how their improvements in combinatorial chemistry will impact the creation of polymer libraries. They claim to be exploiting bacteriophages to study molecular interactions by fusing proteins to the structural components of viruses. (Brenner & Lerner, 1992)

- J. D. Bain and his colleagues at the University of California - Irvine describe in *Nature* their experiments in which an RNA message written with an expanded genetic code was correctly translated into a protein containing a 21st amino acid. (Bain, Switzer, Chamberlin, & Benner, 1992)
- Yun Kim and Charles Lieber of Harvard report that they have successfully demonstrated the ability of an atomic force microscope to perform elementary machining and cutting operations. (Kim & Lieber, 1991) and (Mills, 1993a)
- A team led by Michael R. Wasielewski of the University of Chicago and the Argonne National Labs designs a prototype molecular switch based on organic molecules for use in optical computing. (Wasielewski, 1997)
- There are nine patents issued in 1992 involving fullerene, including one for devices involving photo behavior of fullerenes, one for an atomic scale electronic switch, and one for materials with diamond-like properties and method and means for manufacturing them. (Pevzner, 1997)

**1993**

- The Association of American Publishers names Drexler's Nanosystems the outstanding book in computer science for 1992. (Regis, 1995, p. 263)
- Drexler receives the Kilby Young Innovator Award, named for Jack Kilby, the inventor of the integrated circuit “for advancement of the new field of molecular nanotechnology, leading to an expanding dimension of new engineering applications in the 21st century.” (Kilby, 1997) and (Regis, 1995, p. 263)
- Scientists at Texas Instruments demonstrate the world’s first quantum effect integrated circuit that operates at room temperature. (Seabaugh & Frazier, 1993)
- The American Vacuum Society holds “NANO II”, the 2nd International Conference on Nanometer Scale Science and Technology in Moscow.
- The National Science Foundation announces funding for a National Nanofabrication Users Network. (Crandall, 1996, p. 30)
- Japanese MITI invites Drexler to Japan to help launch its nanotechnology research program. It is Drexler’s 3rd trip to Japan and 2nd at MITI’s behest. (Mills, 1993b)

- Akira Harada of Osaka University publishes in *Nature* that he has assembled tubules 1.5nm in diameter from cyclodextrin, a glucose derivative, thus “making self-assembled polymer nanotubes not in an arc discharge — as is the case with carbon nanotubes — but in solution.” (Schewe, 1993)
- Reza Ghadiri and his team at Scripps build nanotubes from peptides. (Ghadiri et al., 1993);
- Joel Schnur and his team at the Naval Research Labs Center for Biomolecular Science and Engineering work with lipid nanotubes. (Crandall, 1996, p. 35)
- A. P. de Silva at Queen’s University in Belfast reports that he has fabricated a single molecule that behaves as an ‘AND’ gate in a logic circuit. (de Silva, Guaratne, & McCoy, 1993) and (Crandall, 1996, p. 38)
- Marvin Cohen of the University of California, Berkeley writes, “we have entered an era in which it is possible to use theory to design materials with predictable properties” (Crandall, 1996, p. 39)
- Debra Robertson and Gerald Joyce of Scripps Research Laboratory (according to *Science News*) use a ‘directed evolution’ version of polymerase chain reaction (PCR) to produce an RNA enzyme — a “tetrahymena ribozyme” — the first RNA enzyme that specifically cleaves single-stranded DNA. (Crandall, 1996, p. 39) and (Robertson & Joyce, 1993)
- Christopher Lutz, Michael Crommie, and Don Eigler of the IBM Almaden Research Center (who later share the AAAS Newcomb Cleveland Prize) position 48 iron atoms into a circular ring in order to “corral” surface state electrons and force them into “quantum” states of the circular structure. (Crommie, Lutz, & Eigler, 1993)
- Rice University announces a Nanotechnology Initiative, with Professor Smalley as its Director, to coordinate the ongoing research of about fifty researchers (25% of the Rice research faculty) in six departments — including chemistry, physics, biochemistry, and chemical engineering. (Regis, 1995, p. 275) and (Mills, 1994a)
- Researchers at the University of Bath publish a map, at atomic resolution, of the molecular motor responsible for muscle action. (Mills, 1994a) and (Rayment et al., 1993)
- The 3rd Foresight Research Conference on Molecular Nanotechnology: Computer-Aided Design of Molecular Systems is held in Palo Alto. (Mills, 1994a)

- In 1993 there were twenty-four patents issued involving fullerene including several for the preparation of diamonds and diamond-like films, one for electric propulsion using $C_{60}$ molecules, and one for directed evolution of novel binding proteins. (Pevzner, 1997)

**1994**

- Ernst-Ludwig Florin and V. T. Moy measure the adhesive force of avidin and biotin as functionalizers of an AFM tip. (Florin, Moy, & Gaub, 1994)
- Jack Gibbons, Director of the White House Office of Science and Technology Policy gives a speech advocating nanotechnology and molecular manufacturing at the National Conference on the Manufacturing Needs of U. S. Industry. (Mills, 1995)
- The Third International Conference on Nanometer-scale S&T (NANO 3) is sponsored by the American Vacuum Society. Sessions include Gopel (University of Tubingen) on “Nanostructural Sensors for Molecular Recognition”, Eigler (IBM Almaden Research Center) on “Quantum Corrals”, and Sugiyama (ERATO) on “Recent Progress on Magnetic Sensors with Nanostructures and Applications.” (Mills, 1994b)
- C. J. Hawker and J.M.J. Frechet of Cornell University develop a new approach to dendrimer synthesis in which the molecules are built from the outside inward. (Frechet, 1994) and (Mills, 1993b)
- Robert Birge of Syracuse University begins a series of publications in peer reviewed journals on the process of using light-harvesting bacteria to store and manipulate data. (Birge, 1994) and (Chen, Govender, Gross, & Birge, 1995)
- Rohrer and Binnig are inducted into the US National Inventors Hall of Fame for their invention of the scanning tunneling microscope. (Inventure, 1997)
- Masakazu Aono of the Aono Atomcraft Project in Japan (under the sponsorship of Japan's Science and Technology Agency) announces that his surface dynamics group can use a scanning tunneling microscope to extract a single silicon atom from the surface of a silicon crystal and can then re-bond it to the surface at a different location. (Mills, 1995)
- Sixty-one patents involving fullerene are issued in 1994, including several for conversion of fullerenes to diamond, one for a method for forming diamond and apparatus for forming the same, one for storage of nuclear materials by encapsulation in fullerenes, one for uncapped and thinned carbon nanotubes, one for a method of forming self-assembled, mono- and

multi-layer fullerene film and coated substrates, one for fullerene-grafted polymers, and one for the recovery of $C_{60}$ and $C_{70}$ Buckminsterfullerene from carbon soot. (Pevzner, 1997)

- Using x-ray crystallography, researchers at Los Alamos National Laboratory and at the University of Chicago capture the motions of the protein myoglobin as it seizes and releases small molecules such as oxygen. (Mills, 1995) and (Zhu, Sage, & Champion, 1994)
- C. O’Brien writes in *Science* about rotary engines in mitochondria — how ATP synthase goes about grabbing ADP and phosphate, bringing them together, and then releasing the energy transport molecule product, ATP. (Mills, 1995) and (O'Brien, 1994)
- Ghadiri, Granja, and Buehler of Scripps Research Institute show experimentally that their nanotubes are effective channels for ion flow across artificial membranes. (Ghadiri, Granja, & Buehler, 1994) and (Mills, 1995)
- Professor Aristides Requicha teaches a course in molecular robotics (“an emerging and highly interdisciplinary field that seeks to produce new materials and devices at a nanometer scale, by direct interaction with atomic structures”) at the University of Southern California using Nanosystems as a textbook. (Mills, 1995) and (Requicha, 1997)
- Robertson, Dunlap, Brenner, Mintmire, and White at the Naval Research Laboratories (NRL) describe simulations of atomically perfect fullerene gears in *Novel Forms of Carbon II*, the proceedings of the Materials Research Society 1994 meeting. (Soreff, 1995a) and (Renschler, Cox, Pouch, & Achiba, 1994)
- Steven Brenner and Alan Berry write a program to help systematically select amino acid sequences designed to fold in a pre-specified way. (Soreff, 1995a) and (Brenner & Berry, 1994)
- An editorial in *Science* high-lights the nanoscale efforts underway at the Beckman Institute, pointing out its “significant results from research using the scanning tunneling microscope (STM) in fabricating semiconductor nanostructures” (Abelson, 1994).
- Researchers from the Chemistry Division of the Naval Research Labs use an SPM to position molecular building blocks tagged with single-stranded DNA. The relative strength of attachments could be adjusted by changing the number of base pairs in the complementary region between two strands. (Lee, Chrisey, & Colton, 1994)

**1995**

- P.G. Wolynes, J.N. Onuchic, and D. Thirumalai survey recent work on the kinetics of protein folding. (Wolynes, Onuchic, & Thirumalai, 1995)
- The NSF Directorate for Biological Sciences issues a report ("The Impact of Emerging Technologies on the Biological Sciences") which states that "a highly sophisticated, biologically oriented nanotechnology will have a profound impact on biological research, medical practice, and perhaps the pharmaceutical industry. Clearly, the ability to perform incision-free surgery, replace diseased or defective tissues, and regulate endogenously systems that now require exogenous treatment (e.g., diabetes) could revolutionize medical practice" (NSF & Bloch, 1995).
- R. J. Lipton and E. B. Baum publish a paper on DNA-based computation. (Lipton, 1995) and (Baum, 1995)
- The Hughes Aircraft Company Studies and Analysis Group publishes a report on the impact of technology on military planning and points out the potential importance of the "increasingly fine control of matter" including biotechnology, molecular modeling, scanning probe microscopy, molecular computing, and digital material processing. (McKendree & Hagen, 1995)
- D. P. E. Smith, a frequent Binnig collaborator, describes an STM-based approach to nanometer-scale electronic circuits. (Soreff, 1995b)
- Former Chairman of the Joint Chiefs of Staff, Admiral David E. Jeremiah, USN (Ret) speaks on "Nanotechnology and Global Security." (Jeremiah, 1995)
- Nadrian Seeman wins the Foresight Institute's Feynman Prize for his work on DNA to make cube-like objects.
- There are thirty-four patents issued in 1995 involving fullerene including one for the conversion of fullerenes to diamonds, one for a single electron device including clusters of pure carbon atoms, and one for a method for constructing a carbon molecule and structures of carbon molecules. (Pevzner, 1997)
- Prospects in Nanotechnology: Toward Molecular Manufacturing by Markus Krummenacker and James Lewis is published. (Krummenacker & Lewis, 1995)

- Maureen Rouhi writes in *Chemical and Engineering News* that a new DNA technology that extends the range of metabolic products (allowing one to “cut and paste” DNA) is now available from the biotechnology start-up, ChromaXome. (Soreff, 1995b)
- Recent molecular modeling work on molecular ‘steam engines’, buckytubes as conveyors, molecular bearings, simulated motors, and simulated diamondoid bearings by Don Noid and Bobby Sumpter of Oak Ridge National Laboratory (ORNL) indicates “the path toward convergence of nanotechnology and computational chemistry.” Their work shows not only what designs could work but also which were unreliable. Noid and Sumpter use a program called MOLDESIGN that was developed at ORNL as part of a cooperative research and development agreement (CRADA) between Lockheed Martin Energy Systems, the U. S. Department of Energy, and Hoechst Celanese Corporation. (Vetter, 1995) and (Noid & Sumpter, 1995)
- M. R. Ghadiri's group has been successful in freezing self-assembled structures in place with covalent chemistry. (Soreff, 1996b) and (Ghadiri et al., 1994)
- J. R. Desjarlais and T. M. Handel, writing in *Protein Science*, describe a novel computational and experimental approach to redesigning the hydrophobic cores of proteins that will assist in future designs of protein structures. (Soreff, 1996b) and (Desjarlais & Handel, 1995)
- P. S. Stayton, T. Shimoboji, C. Long, A. Chilkoti, G. Chen, J. M. Harris, and A. S. Hoffmann, writing in *Nature*, discuss thermal control of affinity that could be used as a signaling mechanism for molecular-devices. (Soreff, 1996b) and (Stayton et al., 1995)
- Craig Venter, then of NIH and later of The Institute for Genomic Research (TIGR) and a team of researchers describe in *Science* how they have completely sequenced Haemophilus influenzae. They have used a unique computational technique that, if used by nanotechnologists, could “specify an existing system that can replicate itself using simple feedstocks.” (Soreff, 1996b) and (Smith, Tomb, Dougherty, Fleischmann, & Venter, 1995)
- J. W. Bryson, S. F. Betz, H. S. Lu, D. J. Suich, H. X. Zhou, K. T O'Neil, and W. F. DeGrado write in *Science*, “The de novo design of peptides and proteins has recently emerged as an approach for investigating protein structure and function. Designed, helical peptides provide model systems for dissecting and quantifying the multiple interactions that stabilize secondary structure formation. De novo design is also useful for exploring the features that specify the stoichiometry and stability of alpha-helical coiled coils and for defining the

requirements for folding into structures that resemble native, functional proteins. The design process often occurs in a series of discrete steps. Such steps reflect the hierarchy of forces required for stabilizing tertiary structures, beginning with hydrophobic forces and adding more specific interactions as required to achieve a unique, functional protein." (Bryson et al., 1995) and (Soreff, 1996a)

- A team consisting of researchers from the University of North Carolina and UCLA announce that they have built a "Nanomanipulator" that couples a scanning tunneling microscope (STM) to a virtual-reality interface to provide a "telepresence" (virtual reality-like) system that operates over a scale difference of about a million to one (Falvo et al., 1995), allowing them to "see, 'touch,' and 'feel' atoms" (Ellenbogan, Montemerlo, & Mumzhiu, 1997).
- Al Globus and Creon Levit of NASA Ames begin funded work in computational nanotechnology. "NASA is putting significant resources into nanotechnology research. Some forms of nanotechnology appear to have enormous potential to improve aerospace and computer systems. Computational nanotechnology — the design and simulation of programmable molecular machines — is crucial to progress." (Phelps, 1996b)
- Researchers at Rice University, led by chemistry and physics professor Richard E. Smalley, report advances in creation of "ropes" of single-wall nanotubes. (Phelps, 1996c) and (Thess et al., 1996)
- Calling it "only a first but major step toward massively parallel micro-instrumentation (MacDonald, 1996)," Noel MacDonald of Cornell University's National Nanofabrication Facility announces a micro-electromechanical scanning tunneling microscope (MEM STM) with a silicon tip and three actuators that provide the force to move the tip in three dimensions.
- The RAND Corporation, a (mostly) federally funded non-profit organization, publishes a report entitled,

> "The Potential of Nanotechnology for Molecular Manufacturing." It states in its conclusion, "Although there has been much encouraging theoretical and conceptual study of the advanced manufacturing potential of molecular nanotechnology (and panel reports and surveys of expert opinions), a comprehensive, detailed technical assessment by a multidisciplinary, objective expert working group is lacking and should be conducted to determine engineering feasibility. A positive finding from such an assessment would indicate that cooperation at the basic and applied research level beyond the present situation should be organized" (Nelson & Shipbaugh, 1995).

**1996**

- The American Vacuum Society holds its 4th International Conference on Nanometer-Scale S&T (NANO IV) in Beijing, China, on September 8-12, 1996. Topics include SPM and related techniques; nanostructural properties; nanofabrication; tribology, nanometrology, and applications of proximal probes; nanoelectronics; nanostructure materials and nanoclusters; and micro-instrumentation and sensors. (Owen, 1996)
- Scientists at IBM's Zurich Research Laboratory succeed in moving and precisely positioning individual molecules at room temperature. (Jung, Schlittler, Gimzewski, Tang, & Joachim, 1996)
- Gary Stix writes a generally negative article entitled, “Trends in Nanotechnology — Waiting for Breakthroughs” in *Scientific American* sparking a World Wide Web debate on nanotechnology and nanotechnology reporting. (Stix, 1995)
- Ralph Merkle leads a team of Foresight Institute responders to the Scientific American article who charge that Stix was biased and unscientific in his April, 1997 article. (Merkle, 1996)
- Cornell University researchers build a network of liquid crystal molecules that are linked together while aligned in an electric field that makes them orient themselves on-demand (“self-assemble”) lying parallel or perpendicular, depending on the frequency of the field. (Körner, Shiota, Bunning, & Ober, 1996)
- Dr. Tanya Sienko of Japan's National Institute of Science and Technology Policy reports that Japanese government-sponsored nanotechnology efforts are now in the hundreds of millions of dollars each year. (Sienko, 1996)
- Corey Powell writes a hypertext-linked web article entitled “Nanotechnology” for *Scientific American* (Powell, 1996) that is so much more balanced than the previous article that Foresight claims it “amounts to a correction of the previous story” (Merkle, 1996).
- Two groups have recently found that DNA can act as a constant-force spring. (Cluzel et al., 1996), (Smith et al., 1996), and (Soreff, 1996b)
- Twenty-one patents involving fullerene are issued in 1996, including one for carbon nanoencapsulates, one for carbon nanostructures encapsulating palladium, and one for the formation of diamond materials by rapid-heating and rapid-quenching of carbon-containing materials. (Pevzner, 1997)

- Robert F. Curl, Jr., Sir Harold W. Kroto, and Richard E. Smalley of Rice University are awarded the 1996 Nobel Prize in Chemistry for their discovery of $C_{60}$ (Buckminsterfullerene). (Sciences, 1996) and (Phelps, 1996a)
- P. E. Sheehan and C. M. Lieber describe in *Science* their fabrication of a working mechanical lock with a 58 nm wide crystal of Molybdenum Trioxide ($MoO_3$) as one of its moving parts. (Sheehan & Lieber, 1996) and (Soreff, 1996c)
- L. A. Bumm et. al., also writing in *Science*, describe experiments by James Tour of the University of South Carolina and David Allara and Paul Weiss of Penn State demonstrating that single conjugated molecules can act as molecular wires capable of conducting electricity. (Bumm et al., 1996), (Ellenbogan et al., 1997), and (Soreff, 1996c)
- K.F. Kelly et. al., writing in *J.Vac.Sci.Tech* describe fullerene covered STM tips. (Soreff, 1996c)
- M.D. Struthers, R. P. Cheng, and B. Imperiali describe the design of a 23-residue peptide that folds into a stable tertiary structure. (Struthers, Cheng, & Imperiali, 1996) and (Soreff, 1996c)
- R.F. Service describes recent work towards improving the understanding of beta sheet folding in proteins. (Service, 1996) and (Soreff, 1996c)
- Two groups writing in *Nature*, C.A. Mirkin et. al. (Mirkin, Letsinger, Mucic, & Storhoff, 1996), and A. P. Alivisatos et. al. (Alivisatos et al., 1996) describe controlled assembly of gold colloidal particles using DNA linkers. (Soreff, 1996c)
- A team of scientists from Purdue "demonstrate for the first time an extended, heterogeneous structure containing functioning molecular-scale circuit elements … based upon the principles of chemical self-assembly." (Ellenbogan et al., 1997) and (Andres et al., 1996)
- Tripos, Inc. of St. Louis introduces a software application called "ChemSpace", which allows real time searches of a database of over 100 billion ($10^{11}$) synthetically accessible small organic chemical structures. (Soreff, 1996c)
- Craig Lent and Wolfgang Porod of the University of Notre Dame, working with Zhi-an Shao, make a nanometer-scale 'two-state device' (a wireless electronic logic structure or switch) out of an arrangement of five quantum dots. (Ellenbogan et al., 1997) and (Shao, Porod, Lent, & Kirkner, 1996)

- Shuker, Hajduk, Meadows, and Fesik, describe a systematic method for designing high-affinity ligands using information from Nuclear Magnetic Resonance (NMR) — allowing them to “build up a composite ligand piece by piece, with excellent control of the detailed geometry of the protein/ligand interface.” (Shuker, Hajduk, Meadows, & Fesik, 1996) and (Soreff, 1997a)
- The Foresight Institute holds a meeting of Senior Associates in conjunction with its 10th anniversary. At the meeting, Jim Von Ehr announces that he is forming Zyvex, Inc. for the purpose of building the first assembler stating, “It's time to go beyond simulations and actually prove that nanotechnology is possible in the next 10 years” (Soreff, 1997b) and (Von Ehr, 1997).
- A multidisciplinary National Academy of Sciences (NAS) panel with expertise in the physical sciences, the life sciences, and engineering issues its report, *Biomolecular Self-Assembling Materials*. The report concludes,

  > “To have a significant impact specifically on the field of biomolecular materials there need to be directly targeted funding mechanisms that can create on a smaller scale the critical mass of activity that has been created over the last decade in materials science and engineering. Only then can we be sure that in the 21st century the United States will have the experience and knowledge needed to capture the scientific and technological opportunities that this report describes” (NRC, 1996).

**1997**

- S. S. Smith, et al, in the *Proceedings of the National Academy of Sciences*, describe a novel technology for covalently attaching functional proteins to a DNA backbone. (Smith et al., 1997) and (Soreff, 1997b)
- S. I. Stupp et al describe a nanostructure that they constructed out of miniature triblock polymers, calling it “a supramolecular nanostructure from a combination of atomically precise and deliberately disordered molecular substructures.” (Stupp et al., 1997) and (Soreff, 1997b)
- Eric Drexler and Ralph Merkle produce “an atomically detailed design for a far smaller molecular manipulator than previously had been considered — one intended not to do the whole job of molecular positioning, but to serve as a ‘hand’ for the final, precise step of applying a molecular tool” (Drexler, 1997).

- The U. S. Department of Defense Task Force on the future of military healthcare (MHSS2020) forms committee on Nanotechnology and Biotechnology.
- Hiroyuki Noji publishes paper in *Nature* (Noji, Yasuda, Yoshida, & Kinosita K, 1997) that describes a biological motor an order of magnitude smaller than a bacterial flagellum. This breakthrough technology would have satisfied what Richard Feynman intended as the prize criteria in 1959. (Soreff, 1997c)
- Bruce Cornell of the University of Sydney announces the first working nano-sized biosensor in *Nature*. The MHSS nanotechnology/biotechnology Task Force recommends that serious attention be paid to the near-term medical implications of this invention. (Cornell et al., 1997)
- Alan Hall begins a pro-nanotechnology *Scientific American* article entitled “A Turn of the Gear” with the words, “These incredibly tiny gears aren’t real — yet…” thus completing the turn-around of *Scientific American* on the scientific merit of nanotechnology. (Hall, 1997)
- Marc Bockrath and Richard Smalley describe conduction in a rope made of 60 single- walled nanotubes. (Bockrath et al., 1997) and (Soreff, 1997b)
- Heinrich Rohrer gives lecture on nanotechnology at the National Science Foundation. The abstract read, “The more conventional aspect of science and technology on the nanometer (nm) scale is seen in advancing observation and precision standards down to the atomic level and in continued miniaturization from today's microtechnology to tomorrow's nanotechnology. There is lots of room at the bottom of the scale, even now, thirty-five years after R. Feynman's famous lecture on reducing the size of computers until bits are of the size of atoms. A more adventurous approach to the nanoworld is the assembly-scenario where molecules and macromolecules serve as building blocks to form complex functional units. Miniaturization and assembly together should provide possibilities and new ways of solving problems, namely, the most elegant way nature solves them. Crucial will be our ability to handle nano-objects on an individual basis and to interface them to the macroscopic world for communication and control.” (Smith, 1997) and (Chong, 1997)
- Nadrian Seeman (who created cube-shaped DNA objects in 1991) and James Gimzewski of IBM (who designed the molecular abacus) are named *Discover* Magazine’s Emerging Technology Winners for 1997. (Discover, 1997)

- Newsweek Magazine names Drexler to its “Century Club” — 100 people to watch in the next century. (Newsweek, 1997)
- Donald Tomalia of the Michigan Molecular Institute describes synthetic metals — polymer molecules “with branches emanating from a central core (that) can be fabricated into magnets, light-emitting diodes, liquid crystals, lasers, and antennas.” (Wu, 1997)
- Using electron beam lithography, a group of students at Cornell University’s Nanofabrication Facility, which is funded by the NSF, create a working guitar (strummed by a atomic force microscope) that is only 10 microns long (about the size of a human blood cell) with strings 50 nanometers in diameter. (Levin, 1997) and (Bernard, 1997)
- Researchers at Stanford University, the University of Wisconsin, and Brown University collaborate to develop a technique combining test-tube chemical synthesis with the machinery of an enzyme to produce hundreds of compounds with potential antibiotic properties. (Jacobsen, Hutchinson, Cane, & Khosla, 1997)
- The U. S. Department of Defense Task Force on the future of military healthcare (MHSS2020) committee on Nanotechnology and Biotechnology issues its report to the Assistant Secretary of Defense for Health Affairs. It says,

  > “The MHSS senior leadership recognized the potential implications of biotechnology and nanotechnology when they directed the initiation of this study in late November 1996. There was a general consensus that of all the variables identified in MHSS 2020 that could have the greatest impact on the future of military health, advances in biotechnology and nanotechnology were the topics receiving the least formal and systematic attention from other groups within the MHSS. This report confirms that assessment and concludes there is a need to further develop systematic mechanisms to monitor developments in biotechnology and nanotechnology applications” (Olson et al., 1997).

- There are thirty-six patents issued in 1997 involving fullerene including one for superconductivity in carbonaceous compounds, one for fullerene hybrid materials for energy storage applications, one for the use of fullerenes in diagnostic and/or therapeutic agents, one for fullerene derivatives as free-radical scavengers, one for fullerene jet fuels, and several for using fullerenes to grow diamonds (IBM, 1998).
- Scientists at Northwestern University working with funding from NIH and ONR announce that they have created a new technique that allows the detection of infectious agents with a probe (coated with DNA and gold-particles) that changes color in the presence of the virus or

bacteria. With it, they can, “go after any type of DNA strand we like” (Elghanian, Storhoff, Mucic, Letsinger, & Mirkin, 1997).

- Hagan Bayley and his team of researchers at Texas A&M use recombinant DNA to create artificial pores that can serve as “molecular gatekeepers” — that is they can be switched to open or closed positions to allow or disallow the passage of predetermined molecules for “smart” drug delivery or chemotherapy. They can also serve as configurable biosensors. They claim in the peer-reviewed journals *Nature Biotechnology* and *Chemistry and Biology* that they can produce large quantities of the protein alpha-hemolysin via self-assembly. (Russo, Bayley, & Toner, 1997) and (Braha et al., 1997)
- In the August 29, 1997 issue of *Science*, an issue dedicated to “Frontiers in Materials Science”, Gero Decher of the Université Louis Pasteur publishes a paper entitled, “Fuzzy Nanoassemblies: Toward Layered Polymeric Multicomposites”. In his conclusion, Decher says, “Layer-by-layer assembly by adsorption from solution is a general approach for the fabrication of multicomponent films on solid supports. Materials can be selected from a pool of small organic molecules, polymers, natural proteins, inorganic clusters, clay particles, and colloids. Although we have only begun to explore useful combinations of materials, the organization of different elementary units in an ordered nanoscopic device may lead to a kind of nanomachinery like that envisioned by Feynman in the 1960’s” (Decher, 1997).
- On September 4-7, an international conference on Biomolecular Motors and nanomachines is held outside of Albany, New York. The aim of this meeting was “to stimulate a free exchange of information and ideas among researchers working on the design and fabrication of nanoscale devices and on the structural and functional characterization of biological motors. By bringing these two groups together, we hope to start a free flow of information and opinion about how nature has designed macromolecular and supermolecular machines and to explore how or whether these principles might apply to nano-engineering.” (See Appendix B for a list of participants and the papers they presented.)
- On September 16, the NSF announced the completion of a workshop entitled, “Nanoparticles, Nanostructured Materials, and Nanodevices.” The proceedings reported, “Tiny nanostructures can include materials like ceramics, optical materials, polymers, and metals, while nanodevices include microscopic sensors, switches, and reactors. Industrial applications are just as wide-ranging, from pharmaceuticals and electronics to biotechnology

and space exploration. 'There are practically no unaffected application fields,' said Dr. Mihail Roco in the introduction to the proceedings. The most radical prospect explored at the workshop is the so-called bottom-up approach to manufacturing, in which materials and devices are manufactured from the molecule level up" (Siegel et al., 1997).

- The November-December, 1997 issue of *The Futurist* includes an article about the George Washington University Forecast of Emerging Technologies (a Delphi study) in which nanotechnology and self-assembling materials were estimated with high probability to become realities early in the 21st century (Halal et al., 1997, p. 20-28).
- In November, The Foresight Institute held the 5th Foresight Conference on Molecular Nanotechnology with sessions on supramolecular chemistry and self-assembly, proximal probes (e.g. STM, AFM), biochemistry and protein engineering, computational chemistry and molecular modeling, computer science (e.g. computational models, system design issues), fullerene nanotechnology, natural molecular machines (e.g. flagellar motor), materials science, mechanical engineering (CAD) and robotics. Featured speakers included Nobel Laureate Richard Smalley, James Gimzewski of IBM, Al Globus of NASA, William A. Goddard III of CalTech, Ralph C. Merkle of Xerox, and Nadrian C. Seeman of New York University.
- Globus and his group from NASA win the 1997 Feynman Prize for theory and Gimzewski wins the 1997 Feynman Prize for experimentation.
- NASA's Ames Research Center and the National Science Foundation issue requests for proposals for molecular nanotechnology research projects.
- NSF issues an "Initiative Announcement" for research proposals into molecular nanotechnology. The announcement begins, "Four Directorates of the National Science Foundation (NSF) announce a collaborative initiative on research in nanotechnology, with a focus on functional nanostructures. The goal of the initiative is to catalyze synergistic, small-group, interdisciplinary, science and engineering research in emerging areas of nanotechnology, by combining resources from the participating programs to support coordinated research activities" (NSF, 1997). The announcement in its entirety can be found in Appendix D.
- Researchers discover that a protein called melanopsin enables light to set the biological clocks that tell frogs when to perform a host of basic functions. If controllable, this could be

used as a signaling/communications method with nanomachines (Provencio, Jiang, De Grip, Hayes, & Rollag, 1998).

- In March of 1998, twenty-nine years after Feynman’s “There’s Plenty of Room at the Bottom” talk, the American Physical Society featured sessions on nanotechnology at its annual meeting. In a press release, Dr. Michael Rourkes of Caltech said, “When we get there, nanotechnology will provide techniques for the mass production of tiny functional machines assembled, atom-by-atom, with perfect precision. This happens every day, in nature, within us, and in the truly miraculous living organisms around us. But right now, Mother Nature is really the only true nanotechnologist.” The press release continued that the overall goal of researchers in the field is to expand knowledge about nature’s functions and processes at the nanoscale, to allow the artificially engineering of those processes and create entirely new types of ultra-miniature machines (Enright, 1998).
- Along with NSF, the U.S. Army Soldier Systems Command (SSCOM), the Army Research Office (ARO), and the Army Research Laboratory (ARL) sponsored the “Nanotechnology for the Soldier System Conference” (SSCOM, 1998) for:
    1. Multi-agency presentations on the Army's current and near-term nanotechnology research programs;
    2. Insight to the direction of Army research programs;
    3. World-wide assessment overviews on current and near-term research programs;
    4. Active participation in defining Nanotechnology research programs and funding recommendations for near-term (1-5 years), mid-term (6-19 years), and long-term;
    5. (20+ years) Nanotechnology research initiatives that will benefit the Army's Soldier System and Army After Next concepts;
    6. Collaboration across Nanotechnology disciplines;
    7. Networking with key funding agencies and their decision makers;
    8. Exclusive invitations to follow-on Soldier System Research Initiative Workshops.

## *Appendix B — Papers presented at the 1997 Foresight Conference on Nanotechnology*

- Adami, M., M.K. Ram, P. Faraci and C. Nicolini “Transport Phenomena Investigation Towards Molecular Devices”
- Bishop, Forrest “Some Novel Space Propulsion Systems”
- Cagin, T., A. Jaramillo-Botero, G. Gao, and W. A. Goddard, III “Molecular Mechanics and Molecular Dynamics Analysis of Drexler-Merkle Gears and Neon Pump”
- Collins, Philip G., Hiroshi Bando, and A. Zettl “Nanoscale Electronic Devices on Carbon Nanotubes”
- Erokhin, Victor, Sandro Carrara, H. Amenitch, S. Bernstorff, and Claudio Nicolini “Semiconductor Nanoparticles for Quantum Devices”
- Frank, Michael P. and Thomas F. Knight, Jr. “Ultimate Theoretical Models of Nanocomputers”
- Gao, Guanghua, Tahir Cagin, and William A. Goddard III “Energetics, Structure, Mechanical and Vibrational Properties of Single Walled Carbon Nano Tubes (SWNT)”
- Frank, Michael P. and Thomas F. Knight, Jr. “Ultimate Theoretical Models of Nanocomputers”
- Garg, A., and S. B. Sinnott “Engineering of Nanostructures from Carbon Nanotubules”
- Globus, Al, Charles Bauschlicher, Jie Han, Richard Jaffe, Creon Levit, Deepak Srivastava “Machine Phase Fullerene Nanotechnology”
- Gubrud, Mark Avrum “Nanotechnology and International Security”
- Hall, J. Storrs, Louis Steinberg, and Brian D. Davison “Combining Agoric and Genetic Methods in Stochastic Design”
- Ito, Yoshihiro “Signal-Responsive Gating by Polyelectrolyte Brush on Nanoporous Membrane”
- Ito, Yoshihiro “Regulation of Cell Functions by Micropattern-Immobilized Biosignal Molecules”
- Kozlowski, W. “Possible Principle of Controlling the Self-Assembly of Biomolecular Materials”
- Leach, G. I., R. E. Tuzun, D. W. Noid, B. G. Sumpter “Positional stability of some diamondoid and graphitic nanomechanical structures: A molecular dynamics study”
- Matsushige, K., H. Yamada, H. Tanaka, T. Horiuchi, and X. Q. Chen “Nano-scale Control and Detection of Electric Dipoles in Organic Molecules”
- McKendree, Tom “The Logical Core Architecture”
- Michalewicz, Marek T. “Nano-cars: Feynman's dream fulfilled or the ultimate challenge to Automotive Industry”
- Merkle, Ralph C. “A proposed "metabolism" for a hydrocarbon assembler”
- Michelsen, John M., Mark J. Dyer, and Jim Von Ehr “Assembler Construction by Proximal Probe”
- Nicolini, Claudio, Victor Erokhin, Sergio Paddeu, and Marco Sartore “Towards a Light Addressable Transducer Bacteriorhodopsin-based”
- Paddeu, Sergio, Manoj Kumar Ram, Sandro Carrara, and Claudio Nicolini “Langmuir-Schaefer Films of Poly(o-anisidine) Conducting Polymer for Sensors and Displays”
- Ram, M.K., M. Adami, M. Sartore, M Salerno, S. Paddeu, and C. Nicolini “Rechargeable Battery Based on Substituted LS Polyanilines”

- Ruehlicke, Christiane, Dieter Schneider, Markus Schneider, Robert D. DuBois, Rod Balhorn “Protein Fragmentation Due to Slow Highly Charged Ion Impact”
- Seeman, Nadrian C., et al. “New Motifs In DNA Nanotechnology”
- Sienko, Tanya “Present Status of Japanese Nanotechnology Efforts”
- ten Wolde, Arthur “Nanotechnology Think Tank in The Netherlands”
- Walch, Stephen P., and Ralph C. Merkle “Theoretical studies of diamond mechanosynthesis reactions”
- Ware, Will “Distributed Molecular Modeling over Very-Low-Bandwidth Computer Networks”
- Wendel, John A., and Steven S. Smith “Uracil as an Alternative to 5-Fluorocytosine in Addressable Protein Targeting”

## *Appendix C — MHSS 2020 Task Force Forecasts*

The report of the Department of Defense Task Force on Biotechnology and Nanotechnology (MHSS2020) offered a number of forecasts for the future before proposing conclusions and recommendations. These forecasts included the following:

1. Within two to five years, inexpensive hand-held biosensors based on nanoscale ion channel switches will go into commercial production. They will allow simple detection of a wide range of diseases within minutes from a small sample of blood or saliva.

2. Within five to ten years, hand-held biosensors, along with the development of minimally invasive biosensors, will have a significant impact on the design and operation of hospitals and other health care facilities. Biosensors will eliminate the need for maintaining large laboratories, transporting samples within facilities, and sending samples out for analysis.

3. Gene chips for analyzing the distinctive pattern of genes active in different diseases will sweep aside traditional disease categories, replacing the old taxonomy with a far more powerful, complex one consisting of families of genetically defined subtypes of disease.

4. Gene chips will make individual genetic profiling, or genotyping, possible at reasonable costs.

5. Between now and 2020, health care will evolve to a higher stage of customized care in which therapeutic selection will be precisely tailored to individual biochemistry.

6. The drug discovery and developmental process will be accelerated and fundamentally redesigned over the decade ahead in response to progress in genomics.

7. Biotechnology and genomics will produce new generations of antibiotics over the next decade that will help stem a potential global health crisis caused by the proliferation of bacteria resistant to conventional antibiotics.

8. Biotechnology will open up a new field of immunotherapy based on novel methods for fighting diseases that enlist the cells of the body’s own immune system rather than drugs.

9. Gene therapy will emerge between now and 2020 as one of the truly revolutionary developments in the history of medicine, comparable in its impacts to past changes such as the introduction of microscopy, anesthesia, vaccination and antibiotics.

10. DNA vaccines will begin to be available over the next five to ten years, and are likely to be universally adopted before 2020. They will be far superior to traditional vaccines, safer, and more effective at conferring both humoral and cellular immunity.

11. Biotechnology will make it possible to develop an advanced sustainable agriculture capable of increasing food production to feed the world's burgeoning population without causing unacceptable levels of environmental damage.

12. Many new agricultural products will explicitly reflect a focus on enhancing health and treating disease. Plants will be genetically altered to improve nutrition.

13. Over the next 20 years, a bio-industrial revolution will help the U.S. and other nations achieve continuing economic development while sharply reducing the adverse environmental and health impacts of economic development.

14. If a breakthrough to a universal assembler occurs within ten to fifteen years, an entirely new field of "nanomedicine" will emerge by 2020. Initial applications will be focused outside the body in areas such as diagnostics and pharmaceutical manufacturing.

15. Progress in biotechnology will contribute to progress in nanotechnology.

16. Biochemical-based nanocomputers and bioelectronic computers will be developed over the next decade that will be superior to digital electronic computers for certain tasks such as solving complex combinatorial problems or recognizing patterns in complex images.

17. Biological terrorism will pose a growing threat to the U.S. civilian population over the next 20 years, and at least a few instances of biological attacks are likely during this period.

18. Within a decade, tissue engineering will grow from a research field to a major commercial sector.

19. Over the next 20 years, genetic engineering, tissue engineering, and other areas of biotechnology will take health beyond the traditional treatment concepts of palliation (relieving symptoms), cure (stopping illness), and prevention (avoiding illness) and toward a new concept of enhancement (improving human performance) (Olson et al., 1997).

## *Appendix D — NSF Nanotechnology Initiative Announcement*

NSF 98-20

NSF Announcement

# Partnership in Nanotechnology:
# Synthesis, Processing, and Utilization of
# Functional Nanostructures (FNS)

## INITIATIVE ANNOUNCEMENT FOR FY 1998

NATIONAL SCIENCE FOUNDATION
*Directorate for Biological Sciences (BIO)*
*Directorate for Computer & Information Science & Engineering (CISE)*
*Directorate for Engineering (ENG)*
*Directorate for Mathematical and Physical Sciences (MPS)*

*Deadline date: February 17, 1998*

Four Directorates of the National Science Foundation (NSF) announce a collaborative initiative on research in nanotechnology, with a focus on functional nanostructures. The goal of the initiative is to catalyze synergistic, small-group, interdisciplinary, science and engineering research in emerging areas of nanotechnology, by combining resources from the participating programs to support coordinated research activities.

### INITIATIVE DESCRIPTION

"Functional nanostructures" are structures that have at least one characteristic dimension in the range from molecular to 50 nm; they are conceived and constructed for a function (device or structural application or effect) that develops in that size range. Nanotechnology here means technology that arises from the exploitation of physical, chemical and biological properties of systems that are intermediate in size between isolated atoms/molecules and bulk materials, where phenomena length scales become comparable to the size of the structure. The discovery of novel phenomena and processes at the 'nano' scale (1-50 nm) and the development of new experimental and theoretical tools in the last few years for investigating these structures provides fresh opportunities for scientific and technology developments in nanoparticles, nanostructured materials and nanodevices.

This initiative encourages team approaches to functional nanostructures research in the belief that a synergistic blend of expertise is needed to make major headway. Theoretical modeling, synthesis, processing with a focus on building up from molecules and nanoprecursors, utilization, and characterization of structure and properties are components of this activity. Hence, this initiative has the aim of fostering interactions among physical, mathematical, chemical, biological and engineering disciplines by encouraging small groups of experts (up to 4 principal investigators) in these different fields. The initiative will support research on new concepts and methods for the generation of functional nanostructures, including synthesis and processing of nanoparticles and other precursor structures, self-assembly techniques, supramolecular chemistry, electronically and chemically functional structures, creation of bio-templates and sensors, “smart” materials and films, and fabrication of nanostructured materials, nanocomponents and nanodevices with unusual properties. The initiative does not include routine measurements research, conventional lithography, or purchase of large experimental facilities.

The NSF’s mission is to promote the progress of science, engineering and education in the United States. Its role in supporting research and education is particularly important in creating infrastructure in emerging areas such as nanotechnology. NSF also promotes partnerships, including collaboration with other agencies and national laboratories for projects of mutual interest. International collaborations with centers of excellence abroad are encouraged. Proposals should discuss effective ways in which education and training is integrated within the research program.

This initiative’s focus is on four high-risk/high-gain research areas, where special windows of opportunity exist for fundamental studies in synthesis, processing, and utilization of functional nanostructures:

- Synthesis/fabrication of nanostructures (1-50 nm) – clusters, particles, tubes, layers, biomaterials, self-assembled systems, with tailored properties to be used for building up functional nanostructures. Approaches may include gas-, liquid-, solid-, and vacuum-based processes, bio-self assembly, size-reduction, and development of techniques to generate these nanosystems at high rates.
- Processing/conversion of molecules and nano-precursors into functional nanostructures; nanostructured materials, nanocomponents and nanodevices, including sensors. This might involve sintering, sputtering, various forms of epitaxy, and chemically and bio-assisted assembling techniques. Examples include an optical waveguide, a multifunctional nanolayer, a nanostructured catalyst, and a nanofilter or a biochemical sensor deposited by using sol-gel or chemical vapor deposition methods.
- Physical, mathematical, chemical and biological modeling and simulation techniques in the mesoscale range (about 1-100 nm). This includes molecular dynamics, quantum mechanics, grain and continuum-based models, stochastic methods, and nano- and meso-mechanics.
- Fundamental physical (mechanical, thermal, optical, etc.), chemical and biological properties of nanostructures and nanostructure interfaces; unique size dependent phenomena and properties associated with nanostructures. Work may also include development of instrumentation based on new principles for probing properties and phenomena not well understood at the nanometer scale.

Funding for this initiative is derived from a coordination of existing resources from those programs within NSF that traditionally have supported research in nanoscience and nanotechnology. Total award size per project is anticipated to be between $300,000 and $700,000 with duration of up to three years, depending upon the nature of the research activity. Subject to the availability of funds, the participating programs have designated approximately $10 million for a total of about 20 awards in this competition in FY98.

## *Appendix E — Glossary of technical terms*

The following definitions are a combined subset of those found in <u>Engines of Creation</u> (Drexler, 1986) and the MHSS 2020 Focused Study on Biotechnology & Nanotechnology (Olson et al., 1997).

- Amino acids: Organic molecules that are the building blocks of proteins. There are some two hundred known amino acids, of which twenty are used extensively in living organisms.
- Antigen: A foreign substance that, when introduced into the body, stimulates an immune response.
- Assembler: A molecular scale device with a robotic arm under computer control. The assembler could grasp individual atoms and assemble objects from the "bottom up", atom by atom and molecule by molecule (Olson et al., 1997) or A molecular machine that can be programmed to build virtually any molecular structure or device from simpler chemical building blocks. Analogous to a computer-driven machine shop (Drexler, 1986). (See Replicator.)
- Atom: The smallest particle of a chemical element (about three ten-billionths of a meter in diameter). Atoms are the building blocks of molecules and solid objects; they consist of a cloud of electrons surrounding a dense nucleus a hundred thousand times smaller than the atom itself. Nanomachines will work with atoms, not nuclei.
- Automated engineering: The use of computers to perform engineering design, ultimately generating detailed designs from broad specifications with little or no human help. Automated engineering is a specialized form of artificial intelligence.
- B-lymphocytes: White blood cells that are thymus-independent, migrating to the tissues without passing through or being influenced by the thymus. They mature into plasma cells, which synthesize humoral antibodies.
- Bacteria: One-celled living organisms, typically about one micron in diameter. Bacteria are among the oldest, simplest, and smallest types of cells.
- Biochauvinism: The prejudice that biological systems have an intrinsic superiority that will always give them a monopoly on self-reproduction and intelligence.
- Biochips: An electronic device that uses organic molecules to form a semiconductor.
- Biomolecular materials: Materials designed to have molecular-level properties characteristic of biological materials, although they are not necessarily of biological origin.
- Bionic convergence: The convergence of the biological revolution with the information evolution, of biology with electronics.
- Bioremediation: The use of microorganisms in the management of hazardous waste. The process of using living organisms to degrade toxic wastes into harmless byproducts such as water and carbon dioxide.
- Biosensor: A device that senses and analyzes biological information. A simple example is a thermometer. They combine a biological recognition mechanism with a physical transduction technique.

- Biotechnology: The application of biological systems and organisms to technical and industrial processes. Production may be carried out by using intact organisms, such as yeasts and bacteria, by using natural substances (i.e. enzymes) from organisms, or by modifying the genetic structure of organisms.
- Bulk technology: Technology based on the manipulation of atoms and molecules in bulk, rather than individually; most present technology falls in this category.
- Capillaries: Microscopic blood vessels that carry oxygenated blond to tissues.
- Catalysis: Increase in the velocity of a chemical reaction or process produced by the presence of a substance that is not consumed in the net chemical reaction or process.
- Cell repair machine: A system including nanocomputers and molecular scale sensors and tools, programmed to repair damage to cells and tissues.
- Cell typing: A method of identifying a cell by comparing it to a typology of cell characteristics.
- Cell: A membrane-bound unit, typically microns in diameter. All plants and animals are made up of one or more cells (trillions, in the case of human beings). In general, each cell of a multicellular organism contains a nucleus holding all of the genetic information of the organism.
- Cellular immunity: Immunity resulting from activation of sensitized T-lymphocytes.
- Chip: See Integrated Circuit.
- Chromosome: A structure in the nucleus of a cell containing a linear thread of DNA that transmits genetic information and is associated with RNA. Genes are carried on chromosomes.
- Cross-linking: A process forming chemical bonds between two separate molecular chains.
- Cryobiology: The science of biology at low temperatures; research in cryobiology has made possible the freezing and storing of sperm and blood for later use.
- Crystal lattice: The regular three-dimensional pattern of atoms in a crystal.
- Design ahead: The use of known principles of science and engineering to design systems that can only be built with tools not yet available; this permits faster exploitation of the abilities of new tools.
- Design diversity: A form of redundancy in which components of different design serve the same purpose; this can enable systems to function properly despite design flaws.
- Disassembler: A system of nanomachines able to take an object apart a few atoms at a time, while recording its structure at the molecular level.
- Dissolution: Deterioration in an organism such that its original structure cannot be determined from its current state.
- Deoxyribonucleic acid (DNA): A complex protein of high molecular weight consisting of deoxyribose, phosphoric acid, and four bases. These are arranged as two long chains that twist around each other to form a double helix joined by bonds between the complementary components. Nucleic acid is present in chromosomes of the nuclei of cells and is the chemical basis of heredity and the carrier of genetic information for all organisms except the RNA virus (Olson et al., 1997) or DNA molecules are long chains consisting of four kinds of nucleotides; the order of these nucleotides encodes the information needed to construct protein molecules. These in turn make up much of the molecular machinery of the cell. DNA is the genetic material of cells (Drexler, 1986). (See also RNA.)
- Engineering: The use of scientific knowledge and trial-and-error to design systems.

- Enzyme: A protein catalyst that facilitates specific chemical or metabolic reactions necessary for cell growth and reproduction. A protein capable of accelerating or producing by catalytic action some change in a substrate for which it is often specific (Olson et al., 1997) or A protein that acts as a catalyst in a biochemical reaction (Drexler, 1986).
- Evolution: A process in which a population of self-replicating entities undergoes variation, with successful variants spreading and becoming the basis for further variation.
- Exponential growth: Growth that proceeds in a manner characterized by periodic doublings.
- Free radical: A molecule containing an unpaired electron, typically highly unstable and reactive. Free radicals can damage the molecular machinery of biological systems, leading to cross-linking and mutation.
- Fullerenes: Hollow cage-like all-carbon molecules that are generated when carbon burns.
- Gene: A segment of chromosome. Genes direct the synthesis of proteins.
- Gene Chip: Formally called “DNA arrays,” gene chips contain thousands of DNA probes, each with a different nucleotide sequence, which can detect active genes when diced genes from a human cell are poured over the chip. These chips are being used to determine what genetic malfunctions are associated with particular diseases. They are also being used as diagnostic devices.
- Genetic Algorithms: Mathematical Rules for solving a problem derived from putting the rules of genetics and natural selection into mathematical form.
- Genome: The total hereditary material of a cell, containing the entire chromosomal set found in each nucleus of a given species.
- Genomic: Concerning the genome, the study of genes and how they affect the human body.
- Genotype: The basic combination of genes of an organism.
- Gramicidin: An antibacterial substance produced by the growth of Bacillus brevis, one of two principle components of tyrothricin.
- Heisenberg Uncertainty Principle: A quantum-mechanical principle with the consequence that the position and momentum of an object cannot be precisely determined. The Heisenberg Principle helps determine the size of electron clouds, and hence the size of atoms.
- Heuristics: Rules of thumb used to guide one in the direction of probable solutions to a problem.
- Hypertext: A computer-based system for linking text and other information with cross-references, making access fast and criticisms easy to publish and find.
- Integrated Circuit (IC): An electronic circuit consisting of many interconnected devices on one piece of semiconductor, typically into 10 millimeters on a side. ICs are the major building blocks of today's computers.
- Ion: An atom with more or fewer electrons than those needed to cancel the electronic charge of the nucleus. An ion is an atom with a net electric charge.
- Ion channels: A large heterogeneous family of voltage-activated proteins that control the permeability of cells to specific ions by opening or closing in response to differences in potentials across the plasma membrane. Ion channels participate in the generation and transmission of electrical activity in the nervous system and in the hormonal regulation of cellular physiology.
- Liposomes: The sealed concentric shells formed when certain lipid substances are in an aqueous solution.
- Living machine: A device made up of living organisms of various types, usually housed within a casing or structure of semi-transparent material. Like a conventional machine, it is

comprised of interrelated parts with separate functions used in a performance of some type of work. Living machines can be designed to produce food or fuels, to purify water, treat wastes, or regulate climate.

- Lymphocytes: See B-lymphocytes and T-lymphocytes.
- Molecular Technology: See Nanotechnology.
- Molecule: The smallest particle of a chemical substance; typically a group of atoms held together in a particular patter, by chemical bonds.
- Mutation: An inheritable modification in a genetic molecule, such as DNA. Mutations may be good, bad, or neutral in their effects on an organism; competition weeds out the bad, leaving the good and the neutral.
- Naked DNA: DNA that is not surrounded by an outer protein envelope.
- Nano-: A prefix meaning ten to the minus ninth power, or one billionth.
- Nanocomputer: A computer made from components (mechanical, electronic, or otherwise) on a nanometer scale.
- Nanotechnology (Nanomachine): Functional machine systems on the scale of nanometers, or billionths of a meter. Some prefer to reserve the term for machine systems based on “assemblers”, nano-scale robot arms that can assemble things atom by atom. Others prefer a broader definition: any construction of molecular structures large and complex enough to function as machines or devices.
- Nanotechnology: Technology based on the manipulation of individual atoms and molecules to build structures to complex, atomic specifications.
- Nanotubes: Hollow carbon tubes (sometimes buckytubes) with diameters on the order of billionths of a meter.
- Nucleotide: The building blocks of nucleic acids. Each nucleotide is composed of sugar, phosphate, and one of four nitrogen bases. The sequence of the bases within the nucleic acid determines what proteins will be made.
- Nucleotide: A small molecule composed of three parts: a nitrogen base (a purine or pyrimidine), a sugar (ribose or deoxyribose), and phosphate. Nucleotides serve as the building blocks of nucleic acids (DNA and RNA).
- Nucleus: In biology, a structure in advanced cells that contains the chromosomes and apparatus to transcribe DNA into RNA. In physics, the small, dense core of an atom.
- Nutraceutical: Combines “nutrition” and “pharmaceutical” to describe food supplements from natural sources that are thought to deliver some specific health benefit.
- Organic molecule: A molecule containing carbon; the complex molecules in living systems are all organic molecules in this sense.
- Pathogen: A disease producing agent or microorganism.
- Phages: A virus with a specific affinity for inducing lysis of certain bacterial cells.
- Pharmacogenetics: The study of the influence of hereditary factors on the response of individual organisms to drugs.
- Pharming: The manufacturing of medical products from genetically modified animals or plants.
- Pheromone: A substance perceived by organisms that cause specific behavior (i.e. attraction) in the percipient.
- Plasmid: A diverse group of extrachromosonal genetic elements. They are circular double-stringed DNA molecules present intracellularly and symbiotically in most bacteria. They

reproduce inside the bacterial cell but are not essential to its viability. Plasmids can influence a great number of bacterial functions.

- Polymer: A long molecule of repeated subunits (Olson et al., 1997) or A molecule made up of smaller units bonded to form a chain (Drexler, 1986).
- Replicator: In discussions of evolution, a replicator is an entity (such as a gene, a meme, or the contents of a computer memory disk) which can get itself copied, including any changes it may have undergone. In a broader sense, a replicator is a system that can make a copy of itself, not necessarily copying any changes it may have undergone. A rabbit's genes are replicators in the first sense (a change in a gene can be inherited); the rabbit itself is a replicator only in the second sense (a notch made in its ear can’t be inherited).
- Restriction enzyme: An enzyme that cuts DNA at a specific site, allowing biologists to insert or delete genetic material.
- Reticuloendothelium: Tissue of the reticuloendothelial system (the system on mononuclear phagocytes located in the reticular connective tissue of the body - responsible for phagocytosis of damaged or old cells, cellular debris, foreign substances, and pathogens, removing them from the circulation).
- Ribonuclease: An enzyme that cuts RNA molecules into smaller pieces.
- Ribosome: An extremely small portion of the submicroscopic structure of a cell. It functions to receive genetic information and translates those instructions into protein (Olson et al., 1997) or A molecular machine, found in all cells, which builds protein molecules according to instructions read from RNA molecules. Ribosomes are complex structures built of protein and RNA molecules (Drexler, 1986).
- RNA: Ribonucleic acid; a molecule similar to DNA. In cells, the information in DNA is transcribed to RNA, which in turn is "read" to direct protein construction. Some viruses use RNA as their genetic material.
- Synapse: A structure that transmits signals from a neuron to an adjacent neuron (or other cell).
- T-lymphocytes: White blood cells that are produced in the bone marrow but mature in the thymus. They are important in the body’s defense against certain bacteria and fungi, help B-lymphocytes make antibodies and help in the recognition and rejection of foreign tissues.
- Transgenic organism: An organism modified by the insertion of foreign genetic material into its germ line cells. Recombinant DNA techniques are commonly used to produce transgenic organisms.
- Virus: A small replicator consisting of little but a package of DNA or RNA which, when injected into a host cell, can direct the cell's molecular machinery to make more viruses.

### *Appendix F — Glossary of government acronyms*

- ARPA — Advanced Research Projects Agency (DoD) (see DARPA)
- ATP — Advanced Technology Program (NIST, DOC)
- CEA — Council of Economic Advisors (EOP)
- CRADA — Cooperative Research and Development Agreement
- CTI — Critical Technologies Institute
- DARPA — Defense Advanced Research Projects Agency (DoD)
- DOC — Department of Commerce
- DoD — Department of Defense
- DOE — Department of Energy
- DOT — Department of Transportation
- EOP — Executive Office of the President
- GAO — General Accounting Office
- NASA — National Aeronautics and Space Administration
- NBS — National Bureau of Standards (now NIST)
- NEC — National Economic Council (EOP)
- NIH — National Institutes of Health
- NIST — National Institute of Standards and Technology (DOC) (formerly NBS)
- NSF — National Science Foundation
- NSTC — National Science and Technology Council (EOP)
- OMB — Office of Management and Budget
- OSTP — Office of Science and Technology Policy (EOP)
- PCAST — President's Committee of Advisors on Science and Technology (EOP)
- SBA — Small Business Administration
- SBIR — Small Business Innovation Research program (SBA and other agencies)

From "Towards a Research and Innovation Policy" (Branscomb & Keller, 1997)

## *Appendix G — Richard H. Smith's Curriculum Vitae*

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Science and Technology Studies
Virginia Tech
7054 Haycock Road
Falls Church, VA 22043

Education

Virginia Polytechnic Institute and State University
Ph.D. Science and Technology Studies, currently pursuing
M.S., Science and Technology Studies, 1998
Thomas Edison State College
B.S., Business Administration, 1995

Thesis

"A Policy Framework For Developing a National Nanotechnology Program"

Research Interests

Professional and biomedical ethics and the social impact of emerging technologies. How to distinguish what counts as science from non-scientific disciplines. Multi- and cross-disciplinary approaches to science and technology policy development. The politics of science.

Teaching Interests

Professional and biomedical ethics (business and research.) The politics of science. The history and philosophy of science and technology. Scenario development for long range strategic planning. Research funding strategies and grantmaking. Tactical business planning and situation management.

Publications

Smith, R., "Relating the Military's View of the Future of Medicine to Civilian Medical Group Practice". College Review. American College of Medical Practice Executives. Denver, CO. (in progress).

Smith, R., "The Philosophical Impact of Molecular Nanotechnology". Techné, the newsletter of the Society for Philosophy and Technology. Blacksburg, VA. (forthcoming).

Smith, R., "A Policy Framework for Developing a National Nanotechnology Program", NanoTechnology Magazine. (forthcoming).

Smith, R., "Molecular Nanotechnology: Research Funding Sources". NanoTechnology Magazine. Volume 2 No. 6. Honolulu, Hawaii. June 1, 1996.

Olson, R., Rowley, W., Bashford, J., Bruttig, S., Carroll, J., Christopher, G., Cramer, T., DaCorta, J., Gackstetter, G., Harahill, B., Kearns, C., Jones, S., Lilienthal, M., Lynch, J., Smith, R., Thompson, B., Zimnik, P. Focused Study on Biotechnology and Nanotechnology. Military Health Services System 2020 Task Force. Arlington, Virginia. July 29, 1997.

**Publications (continued)**

Smith, R., “Physics Nobel Laureate Briefs NSF on Nanotechnology”. Foresight Update No. 30. Foresight Institute. Palo Alto, California. September 1, 1997.

Smith, R., “The MHSS 2020 Report on Nanotechnology” NanoTechnology Magazine Volume 3 No. 6. Honolulu, Hawaii. August 1, 1997.

**Online Publications**

Smith, R., “A Policy Framework for Developing a National Nanotechnology Program” [Online]. Available: http://www.vt.edu:10021/arch/psk/papa6664/smith/thesis.pdf

Smith, R., “Nanotechnology - Will It Play in Peoria” [Online]. Available: http://nanothinc.com/NanoWorld/Introduction/RichardSmithIntro/smith_r1.html

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Smith, R., “Molecular Nanotechnology: Research Funding Sources” [Online]. Available: http://hoohana.aloha.net/nanozine/nanofund.htm

Smith, R., “Notes on the 1947 Shelter Island Conference and Its Participants” [Online]. Available: http://www.sherryart.com/nano/shelter.html

Smith, R., “Role of the Public in the Making of Science Policy” — AAAS Panel. [Online]. Available: http://www.vt.edu:10021/arch/psk/papa6664/smith/publrole.htm

**References**

Georgetown University
- Professor Sherman Cohn, JD, Professor of Law, (202) 662-9069
- Associate Professor John Cockerham, MD Professor of Medicine (202) 687-6871
- Professor Edmund Pellegrino, MD, John Carroll Professor-Medicine & Medical Ethics, (202) 687-8999

George Washington University
- Professor L. Gregory Pawlson, MD, MPH, Chairman, Department of Health Care Sciences and Director, Institute for Health Policy, Outcomes and Human Values (202) 994-7647
- Robert Bycer, Chief Operating Officer, Medical Faculty Associates, (202) 994-4022

National Science Foundation
- Daryl F. Chubin, Ph.D., Division Director for Research, Evaluation, and Communication Education and Human Resources Directorate, National Science Foundation, (703) 306-1655 x5801

Veteran’s Administration
- James F. Burris, MD, Deputy Chief Research and Development Officer, (202) 273-8284

Virginia Polytechnic Institute and State University
- Professor Richard Burian, Ph.D., Center for Interdisciplinary Studies, (540) 231-6760
- Associate Professor Gary Downey, Ph.D., Director, Center for Science and Technology Studies, (540) 231-4761

**Languages**

Reading ability in French

**Memberships**

Academic Practice Assembly
American Association for the Advancement of Science
American College of Medical Practice Executives
Center for Research in Ambulatory Health Care Administration
Foresight Institute
Medical Group Management Association
National Council of University Research Administrators
New York Academy of Sciences
Society of Research Administrators
World Future Society

**Related Activities**

Certified Medical Practice Executive, American College of Medical Practice Executives - 1998
Chairman, Medical Group Management Association’s Educational Poster Committee (proposed, organized and managed the 1st educational poster session ever at an MGMA national meeting—attended by 5,000 members)
Member - Center for Research in Ambulatory Health Care Administration Research Committee (1998 – present)
Co-chair, Colloquium on “STS—Beyond the Academy”, Center for the Study of Science in Society - 1998
Member, Biotechnology and nanotechnology study section of the tri-service DoD Military Healthcare Services Systems Year 2020 planning task force (1997 to present)
Member, Georgetown University task forces on research practices, research funding, general and sponsored-research financial systems acquisition
Member, Research Committee, Center for Research in Ambulatory Health Care Administration (1998 - present)
Member, Virginia Polytechnic Institute and State University’s Northern Virginia Center Advisory Board - 1997 to present
Section Chairman (Health and Safety), Center for the Study of Science in Society Science Policy Workshop - 1996
Member, Carlyle Towers Condominium Association Budget and Finance Committee (1997-1998) and Board of Directors (1998 - present).

**Teaching Experience**

AT&T

Developed and taught formal classroom courses in Business and Professional Ethics, Developing New Managers, Local Marketing Practices, Marketing Methods, Rate and Tariff Administration, Situation Management, Strategies of System Selling, and Transactional Analysis. This was a full-time position for two years.

Virginia Tech

Graduate teaching assistant in Philosophy of Science.

Georgetown University

Developed and conducted one-on-one and group instruction in research funding strategies and grantmaking.

## Professional Experience

**Georgetown University; Director of Planning and Research Administration — Center for Women's and Children's Services; Washington, DC; February, 1993 to October, 1998**

***Research Administration*** — Directed fiscal and administrative management of a multidisciplinary university medical research program with 200 researchers, 150 grants and contracts, and a $20M per year research revenue stream. Acted as liaison among funding agencies, researchers, and university administration for new and continuing research programs. Conducted university and department business with granting agencies (federal, state, and private) including contract negotiations and financial reporting. Managed Principal Investigators to insure the financial viability and ethical implementation of their research efforts. Managed the writing of grant proposals, patent disclosures, and technology transfer proposals in the areas of genetics, molecular biology, neonatal development, assisted reproductive technologies, immune system development, lung biology, cancer, and developmental neuroscience.

***Planning*** — Provided strategic and financial analysis for the Chairmen of the Departments of OB/GYN and Pediatrics. Designed management information and analysis tools for use by division managers in the Center’s $34M per year medical practice. Managed telemedicine efforts for both departments and serves in a decision-making capacity on the inter-departmental management team on all issues involving sponsored programs, information systems, human resources and personnel, salary administration, business operations, space planning, government policy compliance, the formation of new profit centers, and medical school faculty recruitments. Served as a member of Medical Center Fire Safety, Space Planning, and Grant Management System Committees and Task Force on Increased Research and Educational Funding.

**Consolidated Systems Group, Inc.; President; Alexandria, VA; October, 1990 to December, 1992**

Directed the start-up of a design, manufacturing, and marketing firm, which designed and Beta tested two artificial intelligence-based products, sold and shipped evaluation units, and was accepted from among sixty applicants into the Center for Innovative Technologies (CIT) Business Incubator Program. The firm was unable to attract sufficient venture capital in the early 1990's economy and ceased operations.

**SONY Corporation of America; Director of Systems Marketing; Washington, DC and Park Ridge, NJ; May, 1988 to October, 1990**

Served as the liaison and scientific translator between the U. S. Government marketplace and the managers in Tokyo. Worked with Japanese engineers and market planners to assess generic future product ideas and determine how they could become specific marketable products and applications for our government. Conducted frequent marketing strategy briefings to the SONY Corporation Executive Committee in the United States and Japan. Participated in the firm’s 100-year strategic planning process. Managed product lines including Telemedicine, Video Teleconferencing, and High Density Data Recording Systems. Managed a revenue stream with growth objective of $60M per year.

## Professional Experience (continued)

**UNISYS Corporation; Tactical Systems Division; Manager-Tactical Programs; Paoli, PA; January, 1986 to May, 1988**

Managed bid and proposal efforts and capture teams on procurements ranging in value from $40M to $1B. Directed subcontractor selection, make/buy analysis, competitive analysis, proposal development, and live test demonstration efforts. Managed the division's five-year strategic planning process and briefed these plans to senior company executives.

**A T & T Company; National Sales Manager (National Federal Marketing) and Director - Government Liaison in Corporate Headquarters; Staff Associate for Training; Richmond, VA, Washington, DC, and Morristown, NJ; January, 1978 to January, 1986**

Represented the government marketing organization in corporate headquarters with responsibilities for product development, pricing, compensation plans, competitive policy, and strategic planning. Managed sales to Department of Defense for Military Hospitals and later for Command, Control, Communications, & Intelligence. Created new products and found new applications for existing products including the first computers ever sold by an AT&T company to the U. S. Government. Highest revenue commitment was $120M per year. Served three terms on the Account Executive Certification Review Board, evaluating hundreds of strategic account plans and proposals and voting on the qualifications of the candidates for continued employment and advancement. Editor and publisher of Marketing Data Systems newsletter. Also served as Staff Associate for Training responsible for developing and teaching formal classroom courses in Business and Professional Ethics, Developing New Managers, Local Marketing Practices, Marketing Methods, Rate and Tariff Administration, Situation Management, Strategies of System Selling, and Transactional Analysis.

**Miners & Manufacturer's Insurance Agency, Inc.; President; Bristol, VA; January, 1975 to December, 1978**

Directed a seven-branch property and casualty insurance underwriting agency. The firm became the State's second largest underwriter of Coal Mine insurance. Presented a business case to the State Corporation Commission that substantially reduced premium costs and resulted in significant profit improvements to stockholders.