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A Critical Analysis of National Nanotechnology Research Funding

by

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ABOUT THE AUTHOR

Jon Horek is entering his senior year at the University of Illinois, Urbana-Champaign, where he is majoring in Mechanical Engineering. This paper is the result of his Summer participation in the Summer 2000 Washington Internships for Students of Engineering (WISE) program, which was sponsored by The Institute of Electrical and Electronics Engineers (IEEE).

THE WISE PROGRAM

The WISE program is a 10-week internship that bridges the intersection between engineering and public policy. Every year, the WISE sponsoring societies choose a total of 14-16 undergraduate engineering students to participate in the program. Each student chooses a complex technology policy issue that is both relevant to his or her own interests, as well as the interests of the sponsoring society. He or she then spends the Summer visiting various engineering-related policy organizations (i.e. – The Nuclear Regulatory Commission, The National Science Foundation), interviewing the key individuals involved in the issue, and performing relevant independent research. The final product of this work is a detailed policy analysis of the issue at hand. More information is available at http://www.wise-intern.org.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

In February 2000, as part of President Clinton's budget request, the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) released the National Nanotechnology Initiative (NNI). The NNI, the first large-scale government initiative in nanotechnology, proposes a framework for the next decade of Federal research funding. This study analyzes the three most-timely questions in the early stages of nanotechnology research:

- **Why** should the Federal government support nanotechnology research?
- **How** should all involved agencies coordinate research-funding priorities with one another?
- **Should** any Federal agency support the branch of nanotech known as "molecular manufacturing"?

Scientists often trace the birth of nanotechnology to December 29, 1959, when Nobel Prize-winning physicist Richard Feynman questioned whether or not it would be possible to manipulate matter at such a scale. In the 1980's, nanotech research accelerated, at which time a rift basically developed between those who advocate "molecular manufacturing," the creation of a self-replicating "assembler," and those who do not. This split in the nanotech community continues to this day.

In order for the U.S. to excel in nanotechnology, there must be a national effort to coordinate previously scattered pockets of research. The nation has taken the most intelligent route possible, pursuing an informal coalition of six funding agencies known as the IWGN (Interagency Working Group on Nanoscience, Engineering and Technology). However, in regards to the creation of an assembler, the nation has not yet taken any definitive action. This paper concludes that government groups, especially the IWGN, ought to hold dialogues with the

Molecular Manufacturing (assembler-advocating) community. Increased research into assembler-enabling fields may produce an assembler, but if it does not, it will nevertheless produce much research that is worthwhile in its own right. Either way, if the United States proceeds with funding as set forth in the NNI, the nation will be well-positioned in the 21st century nanotech economy.

I. Introduction

Since the 1980's, the United States has taken an interest in the science and engineering that occurs on the nanoscale, a field often colloquially deemed "nanotechnology." Funding for such research increased, slowly at first, and then more rapidly, but it was not until 1998 that the National Science and Technology Council took the necessary steps to coordinate the nation's research programs. The creation of the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) enabled the nation to examine broadly both the current state of United States research, as well as its relation to the international community.

In February 2000, as part of President Clinton's budget request, the IWGN released the National Nanotechnology Initiative (NNI). The NNI, the first large-scale government initiative in nanotechnology, proposes a framework for the next decade of research funding. This paper first analyzes the reasons to support nanotech research, and then questions whether or not the IWGN is the most intelligent way to coordinate such research. Finally, there is an examination of whether or not the Federal government ought to play a role in supporting the concept of the self-replicating "assembler," quite possibly the single most divisive issue in the nanotechnology community today.

II. Definition of Nanotechnology

It is first necessary to explore the boundaries of the term "nanotechnology," a word whose overuse has led to confusion about its intended meaning. A glance at only a few experts' descriptions of the term reveals slight discrepancies and vague generalizations in usage.

The National Nanotechnology Initiative describes the critical characteristics that distinguish the field:

> The essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization. Compared to the behavior of isolated molecules of about 1 nm (10^{-9}m) or of bulk materials, behavior of structural features in the range of about 10^{-9}m to 10^{-7}m (1 to 100 nm – a typical dimension of 10 nm is 1000 times smaller than the diameter of a human hair) exhibit important changes. Nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical, and biological properties, phenomena, and processes due to their nanoscale size.[1]

In his book Nanosystems: Molecular Machinery, Manufacturing, and Computation, Institute for Molecular Manufacturing (IMM) Research Fellow and Foresight Institute Chairman Dr. K. Eric Drexler distinguishes a specific branch of nanotechnology, which he terms ***molecular manufacturing (MM)***:

> The construction of objects to complex, atomic specifications using sequences of chemical reactions directed by nonbiological molecular machinery. Molecular nanotechnology comprises molecular manufacturing, together with its techniques, its products, and their design and analysis; it describes the field as a whole.[2]

Finally, Dr. Eugene Wong, former NSF Assistant Director of Engineering, expresses the fact that, contrary to a fairly widely-held belief,

> not all science and engineering that occurs at the nanoscale is new. Photography, for example, is a relatively old nanotechnology. Most of molecular biology also works at the nanoscale and some of it is clearly not new. What is new is the degree of understanding we are able to achieve with the new tools and precision and control that we are able to exert on the … molecules and devices at this scale.[3]

Taking these three explanations into account, the following is a concise and unifying definition used in the context of this paper:

[1] Interagency Working Group on Nanoscience, Engineering, and Technology, "National Nanotechnology Initiative." February 2000, pg. 15.
[2] Drexler, K. Eric. Nanosystems: Molecular Machinery, Manufacturing, and Computation. Pg. 1.
[3] Dr. Eugene Wong, House Subcommittee on Basic Research, "Nanotechnology: The State of Nanoscience

> Nanotechnology, synonymously called nanoscience and engineering, is an all-encompassing phrase given to the study, design, and synthesis of structures and devices with at least one dimension measured in nanometers (10^{-9} to approximately 10^{-7} meters). Due to the phenomena emergent at this length, these technologies exhibit novel properties. A specific subset of the field, molecular manufacturing, deals with the atomically-precise manufacture of objects as small as the nanoscale, and as large as mundane items.

This definition can be illustrated with specific examples from the promising areas of research identified by the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), a team comprised of representatives from all key nanotechnology funding agencies. Over the course of a year, the IWGN met and discussed a possible research agenda for the next decade.[4] In doing so, they identified the overriding themes that constitute nanotechnology:

- Biological, chemical, materials science, electronic, magnetic, optical, and structural properties of nanostructures;
- Synthesis and processing at the nanoscale;
- Characterization and manipulation at the nanoscale;
- Modeling and simulation of the nanoscale; and
- Device and system concepts (applied research)

This is a very general listing that can lead to a wide variety of possible scientific and engineering proposals. What should be clear, however, is the following: nanotech is the science and engineering that reaches the nanoscale from the "bottom-up," rather than the "top-down." This stands in contrast to top-down technologies such as MicroElectroMechanical Systems (MEMS) and microprocessors, which arrive at tiny lengths via a manufacturing process that begins with a large amount of material (i.e.- silicon) and creates a tinier structure. Since some scientists and engineers refer to such top-down technologies as nanotechnology, those who advocate the bottom-up approach typically refer to their field as molecular nanotechnology (MNT). Thus, the remainder of this paper will use the words nanotechnology and MNT

and Its Prospects for the Next Decade." June 22, 1999. Pg. 6.

interchangeably. It is MNT that this paper discusses, although this in no way implies that much fruitful work does not remain at the interface between bottom-up and top-down technologies.

Due to the fact that much bottom-up science has been underway for years, the boundaries of MNT possess a certain degree of arbitrariness. For example, certain aspects of biotechnology and molecular biology are sometimes described as "nanotechnology," and others are not. In short, the above definition can serve as a working explanation of the field. Over time, however, grant proposal reviewers, not a single standardized definition, will determine what qualifies as nanotech and what does not.

III. The Issue

A. Issue Definition

There seems to be widespread agreement about the benefits that the United States and indeed the entire planet will derive from research into the nanotech field. In 1998, the National Science and Technology Council's (NSTC) Committee on Technology created the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), which called the field the seat of the "Next Industrial Revolution."[5] Dr. Neal Lane, Assistant to the President for Science and Technology, and former director of the National Science Foundation (NSF), has been quoted as saying that "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."[6]

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[4] Iran Thomas, PhD. Department of Energy. Personal e-mail correspondence, July 18, 2000.

[5] Interagency Working Group on Nanoscience, Engineering, and Technology, "National Nanotechnology Initiative." February 2000. Pg. 3.

[6] IWGN, "Nanotechnology: Shaping the World Atom by Atom," September, 1999. Pg. 1.

After setting aside the vague hype, as in any emerging technological field, one must critically question whether or not the early trends in research funding constitute sound public policy. This study analyzes the three most-timely questions in the early stages of nanotechnology research:

- **Why** should the Federal government support nanotechnology research?
- **How** should all involved agencies coordinate research funding priorities with each other?
- **Should** any Federal agency support the branch of nanotech known as "molecular manufacturing"?

B. Interested Parties

Nobel Prize-winning chemist Dr. Richard Smalley, in a hearing before the House Subcommittee on Basic Research, stated that "the impact of nanotechnology on health, wealth, and lives of people will be at least the equivalent of the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in this century."[7] It is too early to tell whether or not Smalley's prediction is mere exaggeration, but nevertheless it is rather common to hear respectable scientists touting nanotech as one of the most all-encompassing and powerful technologies in the history of civilization. After all, the very term nanotechnology implies that science and engineering occur at the measurement of length relevant to the manipulation of individual atoms, the origin of many physical phenomena. As Dr. Eugene Wong says, "one nanometer is truly a magical point on the scale of length, for it is at this place where the smallest man-made things meet the natural atoms and molecules of the living world."[8] Thus, nanotechnology should lead humanity to achieve the ultimate level of

[7] Dr. Richard Smalley, House Subcommittee on Basic Research, "Nanotechnology: The State of Nanoscience and Its Prospects for the Next Decade." June 22, 1999. Pg. 11.

[8] Dr. Eugene Wong, House Subcommittee on Basic Research, "Nanotechnology: The State of Nanoscience

control over the physical properties of all our creations, a material feat that can benefit the entire planet. At the broadest level, one might say that the entire human race has a stake in nanotechnology.

In terms of those who deal firsthand with nanotech research itself, funding will affect projects in government laboratories such as Oak Ridge National Lab (ORNL), and Federal agency research arms such as the Office of Naval Research (ONR). It will affect infrastructure establishment, such as the funding of research centers specifically dedicated to nanotechnology, as well as support for the post-doc, graduate, and undergraduate fellowships for the students who will inhabit such labs. These students, in turn, will be the people who will power the coming nanotech economy – the top minds who will become the scientists, entrepreneurs, and policy experts. In short, it is not an exaggeration to state that today's funding decisions will touch every aspect of the present and future United States R+D infrastructure.

C. IEEE's Interest in Nanotechnology

IEEE represents the interests of electrical and electronics engineers, as well as all those who are in any way connected to the various applications of electrical and computing technologies. Historically, in order to increase processor speed/efficiency, and decrease cost, the semiconductor industry has sought a continual miniaturization of microchip components. Thus, the current paradigm is one in which engineers seek improved lithographic techniques in order to create increasingly smaller transistors. This continual shrinking has already begun to break the nanoscale size barrier. At this level, however, manufacturing begins to become both costly and physically impossible. In fact, Intel Fellow and National Academy of Engineering member Dr. Gene Meieran states that current trends predict a single fabrication facility will soon cost $20

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and Its Prospects for the Next Decade." June 22, 1999. Pg. 5.

billion to build.[9] This observation, that overall factory cost increases almost exponentially as complexity (defined by the number of active elements on a single semiconductor chip) increases, is known as Moore's Second Law.

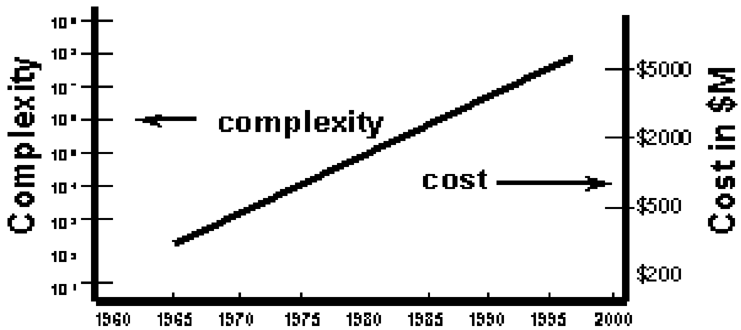

Figure 1 – Semi-log plot of Moore's Second Law, courtesy of Dr. Gene Meieran

In September, 1999, NSTC's Interagency Working Group on Nanoscience, Engineering, and Technology produced a report entitled <u>Nanotechnology Research Directions</u>. An entire chapter is devoted to the field of "nanoelectronics," whose impetus derives from one of the main forces governing progress in the semiconductor industry, Moore's First Law. As the report states,

> One of the primary justifications for investment in nanotechnology stems from the desire to continue 'Moore's Law,' which, in one form, states that the feature sizes of microelectronic devices shrink by half every four years. At this rate, feature sizes will be less than 10 nanometers by 2020 and atomic scale by 2035. In fact, Moore's Law will halt before then, about 2012, because of quantum mechanical effects that will prevent us from continuing to improve performance of logic devices simply by shrinking them. At that point, new information processing methodologies will be required if we are to continue to advance our ability to compute. Perhaps the most promising approach to getting beyond Moore's Law is that of quantum computing.[10]

Nanotechnology research indeed encompasses the development of more inexpensive means to compute at the nanoscale, as well as the methods to overcome the adversities associated with

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[9] Meieran, Gene, PhD. "21st Century Semiconductor Manufacturing Capabilities." <u>Intel Technology Journal</u> 4th quarter, 1998.
[10] IWGN, "Nanotechnology Research Directions: IWGN Workshop Report," Ch. 1.7.7.

quantum mechanical effects. Therefore, it is in the interest of IEEE members to support funding for research into nanotechnology.

IV. BACKGROUND

A. History of Nanotechnology

The history of nanotechnology is the story of science's attempt to manipulate the world at its most intimate levels. On December 29, 1959, Nobel Prize winning physicist Richard Feynman first posed the question of whether or not it would be possible to deal with matter at such a scale. In his speech delivered at Caltech, titled "There's Plenty of room at the Bottom: An Invitation to Enter a New Field of Physics," he stated that,

> the principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done, but in practice it has not been done because we are too big.[11]

Thus began the notion that scientists could deal with atoms and molecules directly at that level, the 1-100 nm range. It was not until the 1980's, however, that the invention of instruments such as the Scanning Tunneling Microscope (STM), Atomic Force Microscope (AFM), and Near-Field Microscope, gave scientists the most rudimentary ability to control and observe matter at the nanoscale. In 1989, IBM-Almaden scientists took the ultimate step when they used an STM tip to push 35 Xenon atoms into the formation of the word "IBM." (see figure 2)

[11] Feynman, Richard P. "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics." Pg. 10.

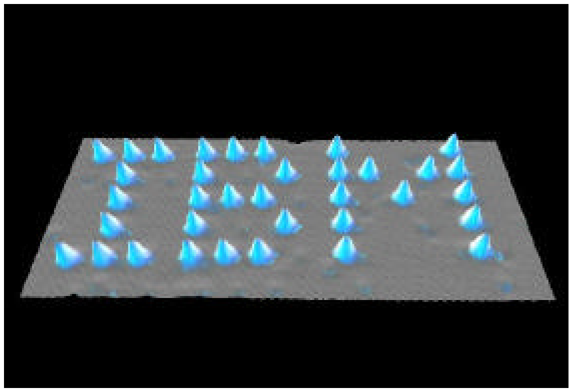

Figure 2 – 35 Xenon atoms arranged with an STM, courtesy of IBM Corporation

During the early years of the same decade, the basic ideas of Molecular Manufacturing (MM) surfaced in K. Eric Drexler's paper, "Protein Design as a Pathway to Molecular Manufacturing."[12] In this work, he described possible methods of fabricating devices and structures to complex atomic specifications. Drexler believed that the S&T community could best achieve "molecular manufacturing" via the creation of a self-replicating "assembler." In Unbounding the Future, Drexler defines this tool as "a general purpose device for molecular manufacturing, capable of guiding chemical reactions by positioning molecules."[13] In layman's terms, Drexler envisions a piece of technology that theoretically, can create most objects consistent with the laws of chemistry and physics, including other assemblers, via the bottom-up assembly of the relevant atoms.

The notion of the self-replicating assembler has become the defining characteristic of the split in an otherwise unified nanotechnology community. There are those who believe in the possibility of self-replicating nanosystems, and those who, at least for the moment, refuse even to consider discussing possible means of achieving such a goal. Advocates of molecular

[12] Drexler, K. Eric., PhD. Proceedings of the National Academy of Sciences of the USA. Vol. 78, No. 9, September 1981, pp. 5275-5278, Chemistry section.

manufacturing repeatedly state that the existence of pre-existing physical models validates their case. For instance, in the first chapter of Engines of Creation, Drexler argues that nature's ribosomes provide an example of a programmable molecular machine that assembles complex molecules from the bottom- up, rather than the top-down. On the other hand, opponents point to the fact that, although the sun provides a working model of fusion, scientists and engineers have had extraordinary difficulties creating their own controlled fusion reactors. In short, the nanotech community divides over this issue.

In the mid to late 1980's, Drexler had begun to move into what some might consider the fringe of the field. In 1986, he wrote Engines of Creation, which outlined the need to predict and prepare for emerging technologies before their arrival. With Chris Peterson and Gayle Pergamit, he then wrote Unbounding the Future, a book intended to educate the general public about the coming benefits of nanotech. In order to discuss MM consequences and educate the public about its possible uses, benefits, and harms, Drexler founded the Foresight Institute in 1989. In order to pursue theoretical work in MM, he founded the Institute for Molecular Manufacturing (IMM) in 1991. Finally, in 1992, he gave the first in-depth technical treatment of molecular manufacturing, Nanosystems: Molecular Manufacturing, Machinery, and Computation. In 1997, Jim Von Ehr, founder of Altsys Corporation, started and became CEO of Zyvex LLC, the first company created in order to pursue the building of an assembler.

Within the government-funded research community, Federal agencies began to pursue programs, independently of one another, into the various branches of nanotechnology – nanoelectronics, nanomaterials, etc. Despite steady increases in funding, the field lacked what one might call a coherent national focus, a definite effort to coordinate the growing research that

[13] Drexler, Eric, Christine Peterson, and Gayle Pergamit. Unbounding the Future: The Nanotechnology Revolution. New York: William Morrow and Company, Inc. 1991. Glossary.

agencies were supporting. Slowly, many began to see the need to view the field not as a fragmentation of various small-scale sciences, but as different aspects of the same science, nanotechnology. On September 23, 1998, in order to bring together representatives from all interested national agencies, the Clinton Administration called for the NSTC to form an Interagency Working Group on Nanoscience, Engineering, and Technology. They first produced a study, Nanotechnology Research Directions, and later the National Nanotechnology Initiative. (NNI)

The NNI is the most current and comprehensive document in U.S. nanotech policy. As a portion of Clinton's FY2001 budget request, the NNI is one of the main driving forces that has brought nanotech to the forefront of the national science and technology agenda. Nobel Prize-winning chemist Dr. Richard Smalley, testifying before the House Subcommittee on Basic Research, said nanotechnology "is a tremendously promising future that needs to have a flag. Somebody has to go out and put a flag in the ground and say: nanotechnology, this is here we are going to go, and we are going to have a serious national initiative in this area."[14] The NNI may very well have been that flag, and the IWGN, as led by the NSF's Dr. Mike Roco, was the group to place it there. The remainder of this paper will examine the NNI's goals, and how the United States plans to achieve them.

B. The Major Players

1. Congress: At the highest level, funding begins with Congress. Seeing as how the NNI is a multi-agency initiative, there must be continued support throughout the relevant appropriations subcommittees. The NNI requests money for the NSF, DOD, DOE, NASA, DOC/NIST, and the NIH, which receive their money from the appropriations subcommittees on

[14] Dr. Richard Smalley, House Subcommittee on Basic Research, "Nanotechnology: The State of

VA/HUD (NSF, NASA), Defense (DOD), Energy/Water (DOE), Commerce/Justice/State (DOC/NIST), and Labor/HHS/Education (NIH). Additionally, by holding hearings on the current state and future directions of research, both the House and Senate science committees play an important authorization role in promoting nanotechnology. Two of the most notable of such hearings were the June 26, 1992, hearing held by the Senate Subcommittee on Science, Technology and Space, chaired by former Senator Al Gore, and entitled "New Technologies for a Sustainable Future"; and the June 22, 1999, hearing held by the House Subcommittee on Basic Research, chaired by Representative Nick Smith, and entitled "Nanotechnology: the State of Nano-Science and its Prospects for the Next Decade." These are an integral part of the funding process, in that they keep Congress informed of the reasons to prioritize science and technology above other programs, and to prioritize nanotech above other forms of science and technology appropriations. In times of spending cutbacks, the fact that individual programs must compete for national priority becomes more pronounced, and thus sustained lobbying and educational efforts are necessary.

The current proposal, as set forth in the NNI, was to increase funding by double this year, and even more so over the next few years. Figure 3 shows the way in which the NNI proposes to divide funding for fiscal year 2001.

Agency	FY 1999 ($ M)	FY 2000 ($ M)	FY 2001 (+ from FY 2000) ($ M)	% Increase
DOC/NIST	16 (with ATP)	8	18 (+10)	125%
DOD	70	70	110 (+40)	57%
DOE	58	58	94 (+36)	62%
NASA	5	5	20 (+15)	300%
NIH	21	32	36 (+4)	13%
NSF	85	97	217 (+120)	124%
Total	255	270	495 (+225)	83%

Figure 3- National Nanotechnology Initiative funding proposal, FY2001

Whether or not this will occur for FY2001 is still a matter of debate. As the IWGN's coordinating party of national nanotech research, all interested players were watching the NSF, whose FY2001 appropriation came in far below the requested amount. Although the nanotech community has greatly hyped this appropriations setback, to the point that the online About.com

Nanoscience and Its Prospects for the Next Decade." June 22, 1999. Pg. 26.

nanotech newsletter gave a press release entitled “House Republicans Kill Nanotech Initiative,” what actually occurred was simply what many expected as an early portion of the budgeting process.[15] The initial appropriations bill of the House, not even the Senate as of yet, denied the NSF’s full budget request, and many interpreted this as a denial of the NSF’s nanotech request. The NSF had requested a total increase of $97 million to $217 million for nanotech alone, and this was only a portion of the unprecedented $675 million, or 17.3%, increase that they had requested for the entire agency.[16]

Nevertheless, one should note that the agency as a whole received an increase of $149 million. Even strongly pro-science Representative Joe Knollenberg (R-MI) voted against the NSF’s full budget increase. His staffer, AAAS Fellow and Nuclear Engineer Dr. Joseph Green, explains the situation as follows - “I do not think there are very many Congressmen who would speak against nanotechnology. It is simply the money that is the question.”[17] Thus, people are convinced of nanotech’s priority in the research agenda, but Congress cannot go over its 302(b) funding allocation. In addition, NSF appropriations must compete with Veterans Affairs (VA), as well as Housing and Urban Development (HUD), both of which are crucial to garnering votes as Vice President Al Gore seeks the presidency during this election year. In short, it is not the merit of nanotechnology that Congress questions. Rather, appropriators must constantly weigh the fact that the NNI is only one of a plethora of programs to which they can give money.

Such a rationale may help to explain why a steady increase may still be in the works. According to Kei Koizumi, Director of the AAAS R+D Budget and Policy Program, “In the end, the NSF will almost certainly end up with a far higher increase. It probably won’t get the full

[15] “House Republicans Kill the Nanotech Initiative,” http://nanotech.about.com/science/nanotech/library/blnews.

[16] American Association for the Advancement of Science (AAAS), “House Awards Increase to NSF, But Falls Far Short of Request.” http://www.aaas.org/spp/dspp/rd/nsf01h.htm

requested increase because a nearly 20 percent increase is a lot of money, and the request was probably jacked up that high as a strategy: ask for more than you need, wait for Congress to come in lower, and compromise at a more reasonable level."[18] In short, the future of nanotechnology begins with Congress. Most likely, this Federal body will eventually do what it can to catalyze the development of cutting-edge research.

2. Federal Agencies and the IWGN: The second level in the funding process consists of the agencies that receive their funding directly from Congress. The NSTC Committee on Technology's Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN), formed in 1998, is a loose confederation of the Federal agencies that fund and perform nanotechnology research – NSF, DOD, DOE, NASA, DOC/NIST, and NIH. Each of the IWGN's agencies has its own reasons for supporting nanotechnology. Appendix 1 shows the different research avenues that these agencies plan to pursue.

3. The Research Community: Finally, there is the community of researchers who receive their funding from either the Federal agencies themselves, or from individual companies. On the whole, except for a single very divisive issue, the nanotechnology community is fairly cohesive. Those who perform the research within the Federal agencies, Universities, companies, and non-profits, are essentially split over the need to pursue the vision that Drexler first proposed as molecular manufacturing. Though not all feel this way, there definitely exists the sentiment that Drexler's notion of the self-replicating assembler is worthless speculation. Stanford University Biophysicist Steven Block, opening speaker at June 2000 nanotech conference sponsored by the National Institutes of Health," writes "I am quite dubious about the Drexler

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[17] Dr. Joe Green, AAAS Fellow of the ANS. Personal e-mail correspondence, June 28, 2000.
[18] Kei Koizumi, AAAS, personal e-mail correspondence, June 28, 2000.

vision of nanotechnology (but NOT nanotechnology in general, and it is critical to draw the distinction) because the Drexler view calls for a number of fanciful prospects."[19]

On the other hand, Christine Peterson, President of The Foresight Institute, the primary MM-oriented educational nonprofit organization, attempts to explain this sentiment - "the first folks involved are often classed as too maverick to deal with, even after the original proposals or theories are accepted."[20] Nevertheless, such divisions are not cut and dry. Peterson believes that there is plenty of research throughout Chemistry, Physics and various branches of mathematics and engineering that will enable MM, but which the scientific community has not pinned with the negative label given to "the Drexler vision" of MM itself. For instance, the scientific community has praised the development of carbon nanotubes (CNTs) as an amazing feat that will bring widespread benefits to many branches of science and engineering. However, CNTs are the exact material that NASA Ames' Dr. Deepak Srivastava repeatedly utilizes in modeling various components of nanoscale machinery and computers, both of which might enable the eventual creation of an assembler.[21] Srivastava, like many others, believes that somehow, scientists and engineers will eventually create an assembler, but there are many others who support CNT research while simultaneously ridiculing assemblers.[22] The boundaries are not cut and dry, as many who support assembler-enabling work do not feel the need to consider possible means of creating assemblers themselves.

Thus, the most fundamental rift in the research community may be between those who believe there is value in currently discussing possible methods to create an assembler, and those

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[19] Dr. Steven M. Block, Stanford University. Personal e-mail correspondence. July 11, 2000.
[20] Christine Peterson, Foresight Institute. Personal e-mail correspondence, July 10, 2000.
[21] Dr. Deepak Srivastava, Nasa AMES. http://www.nas.nasa.gov/Groups/SciTech/nano/images.html
[22] Dr. Deepak Srivastava, Nasa AMES. Personal e-mail correspondence. July 25, 2000.

who do not. Since assemblers have become synonymous with molecular manufacturing, one can say that the following bodies support further research into MM:

The Foresight Institute: "Foresight is a nonprofit educational organization formed to help prepare society for anticipated advanced technologies. Our primary focus is on molecular nanotechnology: the coming ability to build materials and products with atomic precision. The development of this technology has broad implications for the future of our civilization."[23]

The Institute for Molecular Manufacturing: "The Institute for Molecular Manufacturing (IMM) is a nonprofit foundation formed in 1991 to carry out research aimed at developing molecular manufacturing (molecular nanotechnology)."[24]

Zyvex: "Zyvex is the first molecular nanotechnology development company. We are creating technology for atomically precise manufacturing."[25]

Various Professors and labs who accept the possibility of an assembler: much of current small-scale science entails research that could probably enable the creation of an assembler. (i.e. – carbon nanotubes, nanocomputers) However, there are scientists who believe in this basic nanotech research, yet feel that there is no foreseeable method to create such a device. In turn, they refuse to give it further consideration. On the other hand, there are others who think that, somehow, we will eventually create a programmable, self-replicating assembler. In turn, they advocate currently underfunded research areas, such as the modeling of molecular gears and machinery. Dr. William Goddard of Caltech University, Dr. Deepak Srivastava of NASA Ames, and others fall into this category.

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[23] Foresight Institute Homepage, http://www.foresight.org/FI/index.html
[24] Institute for Molecular Manufacturing Homepage, http://www.imm.org
[25] Zyvex Corporation Homepage, http://www.zyvex.com

V. Key Conflicts

A. Government's Role in Funding Emerging Technologies

Emerging Technologies are all those technologies that represent the cutting edge of engineering application. Due to the fact that much basic research must first occur, such technologies often will not come to market for a decade or longer. In fact, The NNI states that "the time from fundamental discovery to market is typically 10-15 years... historically, industry becomes a player only in the last 3-5 years."[26] Dr. Stan Williams, Hewlett-Packard principal laboratory scientist, states that "the current business models force companies to effectively discount everything more than three years out to zero."[27] Regardless of the exact number, it is clear that industry does not invest the necessary funding in emerging technologies. The point at which economic returns on research become feasible is simply too far into the future. The NNI highlights the fact that only a handful of companies, fewer than 100, are currently funding nanotechnology in any of its many branches.[28] Dr. Stan Williams estimates that this industrially-funded research amounts to less than $20 million per year.[29]

The question one must answer is then the following – in what types of research is industry investing, and are they significantly different than that which the government funds? In answering this question, one must realize that research funding is, in fact, not quite so binary – it is not the case that only government funds a certain branch of research such as molecular electronics, while industry never touches the field. Government and Industry funding

[26] IWGN, "National Nanotechnology Initiative." February 2000, pg. 17.
[27] Dr. Stan Williams, Hewlett-Packard. Personal e-mail correspondence, July 25, 2000.
[28] IWGN, "National Nanotechnology Initiative." February 2000, pg. 87.

tend to interweave, often with partnerships in Academia. Nanostructure Science and Technology states that some companies in the electronics industry, such as Hewlett-Packard, invest more private money into nanotechnology research than do most.[30] The investment of a few companies, however, is not an argument for the government to decrease funding either in general nanotechnology, or more specifically in nanoelectronics. In 1999, UCLA's Dr. James Heath and Hewlett-Packard's Dr. Stan Williams demonstrated a milestone in molecular electronics, an electronically addressable molecular switch that operates in a totally dry environment. This work was the joint effort of funding by HP, the NSF, and DARPA. Undoubtedly, the funding partnership between government and industry, as well as the research partnership between industry and academia, sped the research process.[31] In short, it is in the government interest not only to fund emerging technologies, but to do so in conjunction with industry. Such a funding infrastructure will not only speed the research process, but long-standing partnerships also aid in technology transfer from academia/government to industry.

B. The Federal Government's Impetus for Funding Nanotechnology

Support for nanotechnology consists not only of the Legislative branch's appropriations, but also the support of the various Executive departments and cabinet members. This section discusses various reasons that it is in the national interest for the entire Federal government to unite behind nanotechnology.

1. Economic Rationales: Nanotech has been repeatedly forecast as one of the leading fields of future economic development. Historical precedent shows that basic research into emerging technologies eventually translates into commercial opportunities for established

[29] Dr. Stan Williams, Hewlett-Packard. Personal e-mail correspondence, July 25, 2000.
[30] IWGN, "Nanostructure Science and Technology: A Worldwide Study,"

companies, as well as the startup of new companies. Of course, in a global Marketplace, this new science and technology (S+T) will not develop in a U.S.- dominated vacuum. The U.S. will only produce the world's leading nanotech companies if it indeed creates a proper infrastructure, one that is consistently able to fund and conduct the necessary research. Due to the fact that nearly every region of the world is pursuing nanotechnology in at least one of its many guises, such an international perspective gives the U.S. an even stronger impetus to follow suit.

Figure 4 - 1997 Government Expenditures in Nanotechnology Research (NTR)[32]

Geographical Area	Annual Budget, NTR ($ million)	Relative Annual Budget NTR/GDP* (ppm)	% of Total
Japan	120	27	27.8
United States	116	15	26.9
Western Europe	128	18	29.6
Other countries (FSU, China, Canada, Australia, Korea, Taiwan, Singapore)	70	-	16.2
Total	432	-	100

* NTR/GDP – (Nanotechnology Research divided by Gross Domestic Product) x 1million

Figure 4 illustrates that the United States currently has no significant lead in nanotech investment. In fact, the NNI repeatedly makes the point that this is the first area of R+D since World War II that the United States has not entered with a commanding lead. Despite the fact that the U.S. funds at overall levels that are comparable to Japan and Western Europe, the U.S. lags behind Japan when considering GDP. These statistics illustrate that since Japan is capable of funding at a higher percentage of their GDP, there is definite room for expansion in U.S. support as well. In addition, such an international perspective may serve not only as a warning to the

http://www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/iwgn/IWGN.Worldwide.Study/toc.htm

[31] IWGN, "National Nanotechnology Initiative." February 2000. Appendix B14.

[32] IWGN, "Nanostructure Science and Technology: A Worldwide Study," http://www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/iwgn/IWGN.Worldwide.Study/toc.htm

United States, but also as a possible source of infrastructure models and international collaboration.

Such an investment will hardly be in vain. According to the NNI, the various research areas in which the government proposes investment should affect industries based upon materials, manufacturing, nanoelectronics and computing technology, medicine, aerospace, environment, and energy, biotech and agriculture. In short, nearly every industry will feel the effects of a national nanotech investment initiative. Because nanotech should have such a widespread affect on the economy's many industries, it becomes difficult to estimate anything like the 'future revenue of a mature nanotech industry.' Dave Radzanowski, the White House Office of Management and Budget's representative to the IWGN, states that the IWGN discussed the future market payoffs, but made no attempt to quantify them. However, he states that many believe a mature nanotech industry will bring revenue levels similar to the Information Technology industry that we are currently witnessing.[33]

2. Quality of Life Rationales: Aside from the economic competitiveness argument that "many foreign countries, companies, and scientists believe that nanotech will be the leading technology of the 21st century"[34] and will therefore invest heavily, proponents also tout nanotech's potential to raise various aspects of the worldwide material living standard. The most optimistic reason for this claim lies in the Drexlerian notion of MM, which states that scientists and engineers will one day be capable of assembling nearly any object at all, using raw materials as simple as dirt. Hence, it is possible that the world may find a technological fix for material

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[33] Dave Radzanowski, White House OMB representative to the IWGN. Personal e-mail conversation. July 28, 2000.
[34] IWGN, "National Nanotechnology Initiative." February 2000, pg. 91.

poverty as it currently exists in many countries. In a more conservative forecast, nanotech experts foresee some of the following applications:[35]

- Cheap, efficient creation of a freshwater supply;
- Detection of cancer when a tumor is only a few cells in size; and
- The development of materials ten times stronger than steel, at a fraction of the weight.

These are only a few of the goals that the IWGN has decided the various Federal agencies will pursue. Please reference the NNI for a more in-depth treatment of these claims.

3. National Security Rationales: Both general nanotechnology and the MM vision of the self-replicating assembler raise issues involving powerful new weapons of war. On the one hand, military advances are nothing new, and it seems natural for nations to maintain cutting-edge technologies. Nanotech-based defense systems are the next step in this weaponry evolution. On the other hand, a secretive arms race may erupt, due to the fact that some new technologies often so radically alters the means by which wars are fought. One of the most blatant examples of such a scenario arms race was the Cold War stockpiling of nuclear weapons that occurred after their introduction to the world in the 1940's. Eric Drexler's vision of the assembler has led him to propose the idea that self-replicating armies of nanorobotic weaponry may one day arise. This has led some, such as Sun Microsystems' co-founder, Bill Joy, to propose that scientists and engineers should not pursue MM at all, for fear of the fact that some nation will create these weapons. As he puts it, "the only realistic alternative I see is relinquishment: to limit development of the technologies that are too dangerous, by limiting our pursuit of certain kinds of knowledge."[36]

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[35] IWGN, "National Nanotechnology Initiative." February 2000, pg. 12.
[36] Joy, Bill. "Why the Future Doesn't Need Us." Wired Magazine. April, 2000. Pg. 8.

There is often debate over whether or not Joy intended his words literally, or merely as an exaggeration intended to spark discourse. The very roots of his own industry, computing, lie in a military application, the calculation of missile trajectories. Today, computers, including Sun Microsystems, have found vast numbers of civilian applications. Nanotechnology does not require total relinquishment. Rather, as in any emerging technology, there must simply be ongoing, rational dialogue about possible consequences. Thus far, The Foresight Institute has the led the way in such dialogue about the ethical dimensions of nanotechnology.

In short, there is a definite military impetus for entering nanotech research, but there also exists the danger of beginning what one might call the Nano-Arms Race. In considering such a possibility, one should look to the example of the Cold War and those who attempted to prevent it. One of the most radical proposals at the time was the Baruch Plan, set forth in 1946 by the head of the U.S. delegation to the U.N. Atomic Energy Commission. Benjamin Baruch argued for the creation of an International Atomic Development Authority, which would be the only organization with the legal authority to conduct atomic weaponry research. In essence, this would have led all atomic weaponry secrets to become international knowledge. The intention of such an approach was to prevent weapons proliferation. If every country realized that building the bomb would most likely lead every other country to pursue a similar project, then possibly none of these nations would take that first step. However, few took him seriously. Historian Dr. Alonzo Hamby states,

> In the end, the Baruch Plan would serve as little more than a talking point for Truman and his diplomats, providing a vital part of the mythology of Cold War diplomacy--proof of the selflessness of the U.S. in offering to give up the bomb and share the secrets of peaceful development of atomic energy with the rest of the international community.[37]

[37] Hamby, Alonzo L. Man of the People: A Life of Harry S. Truman. New York: Oxford University

In the end, history showed that the Cold War did indeed erupt between superpowers.

If nano-scale weapons proliferation ever begins to arise as an issue, the Baruch Plan stands as an extreme example of a solution to the problem. Assuming that such an arms race will not occur, nanotechnology is nevertheless extremely useful in creating defense technologies against the nanoscale biological and chemical weapons of the future. The DOD has a large interest in the pursuit of nanotechnology for such defense mechanisms, as well as for the development of more advanced materials and military information technologies.

C. Funding of Molecular Manufacturing

Molecular Manufacturing, the branch of nanotechnology dealing with the atomically-precise assembly of objects, often makes claims that large portions of the scientific community view as ridiculous. Nevertheless, there are pockets of respectable researchers who believe assemblers are a worthwhile topic for discourse. This is a key point to make, since much of the scientific community tends to view assembler-advocacy as does Stanford's Steven Block, who states:

> The Drexler people seem to want to go from A to Z without passing through A,B,C... One has to walk before one can run, and bottom-up nanotechnology is a futurist's dream for the moment, not a serious forefront of scientific endeavor. But other types of nanotechnology represent the cutting edge of modern science. Certainly, we should be modeling and building small-scale structures, and studying their properties, and seeing what we can do with these.[38]

Interestingly enough, however, a glance at the Foresight Institute's set of conferences on Molecular Nanotechnology shows that "the Drexler people" are discussing the exact same research fields that the "serious forefront" of nanoscience discussed at the June, 2000 NIH

Press, 1995. pg. 351.

[38] Dr. Steven M. Block, Stanford University. Personal e-mail correspondence. July 11, 2000.

BECON Conference, “Nanoscience and Nanotechnology: Shaping Biomedical Research” - nanoelectronics, nanocomputing, nanomaterials, etc.[39] The only differences may very well be the fact that:

a) Assembler advocates hope to integrate these fields into a single very ambitious device; and

b) Eric Drexler chose to educate the public on the potential of his vision for the future of MM long before any other member of the scientific community believed in the feasibility of such an idea. More than anybody else, it is Drexler who popularized the idea of nanotechnology in the public mind.

What becomes apparent is that there exists a misunderstanding of the types of science that the two communities are actually performing. Both seem in favor of pursuing assembler-enabling research, the building blocks that the MM community believes are necessary for the eventual creation of assemblers. Stated another way, the MM community consists largely of members of the mainstream; the distinction is more imagined than not.

Nevertheless, it is critical to state that, even if a great deal of assembler-enabling research occurs, this does not guarantee that the government is pursuing all relevant avenues. Possibly, discussions between the Federal government and the MM head institutes, Foresight and IMM, are necessary in order to realize common ground. In the process, it may not even be necessary to spend very much more money at all. Drexler’s notion of the assembler may very well serve to do nothing more than integrate the various branches of nanotech currently under study. Thus, it may be the place of an interagency group such as the IWGN to discuss, with assembler advocates, the current state of nanotech research, the current feasibility of creating assemblers. This may occur via frequent meetings, either annually, bi-annually, or whatever the two communities feel

[39] www.foresight.org and http://www.masimax.com/becon/index.html

necessary. Such an event will in fact be taking place this fall, as the Eighth Foresight Conference on Molecular Nanotechnology will be the first MM conference that has been held in the Washington, DC area. A special panel of government officials will indeed be in attendance at this event, an excellent first step in the communications process.

Why has such a dialogue not already occurred? Christine Peterson believes that "the first folks involved are often classed as too maverick to deal with, even after the original proposals or theories are accepted."[40] However, the MM community has grown beyond its original "maverick" founder, Eric Drexler, to include quite a number of interested parties. The listing of participants in The Foresight Institute's eight conferences on molecular nanotechnology are a testament to this fact. All perform legitimate research that may enable MM, although some of this research occurs without government support. For instance, Cal Tech's Director of the Materials and Process Simulation Center (MSC), Professor Bill Goddard, used his own nongovernmental discretionary funds to model the molecular gear and neon pump proposed by Drexler and Merkle. As he puts the matter,

> Until recently, this has generally been perceived as crackpot thinking by the most respected scientists (likely reviewers). Thus, I would never put such ideas into a proposal, since it would likely lead to rejection. I personally believe that such research is worthy, although the vast majority will not end up being valuable.[41]

On the other hand, NASA Ames' Deepak Srivastava, chair of the Sixth Foresight Conference on Molecular Nanotechnology, does work similar to Goddard's within a government laboratory. There also exists a small group at Oak Ridge National Lab, including Dr. Don W. Noid, and Dr. Bobby G. Sumpter, which performs computational research into nanoscale machinery. Hence, the number of folks who both perform assembler-enabling research and support the assembler

[40] Christine Peterson, Foresight Institute. Personal e-mail correspondence. July 10, 2000.

concept has grown over time. This may very well be a sign that the government ought to take a more active role in funding this research. On the other hand, since the assembler is a single device on which corporations can capitalize, possibly this work should belong to private sector companies such as Zyvex LLC. The question of whether or not assembler research ought to belong to industry or government is indeed a matter of contention.

However the United States decides to pursue the assembler, or even **if** the United States decides to pursue the assembler, the shift to bottom-up rather than top-down manufacturing should lead to enormous savings, measured in terms of environmental friendliness, control over structure properties, and savings of wasted materials. If the assembler concept proves to be a failure, there may be no loss to any involved parties, due to the fact that much science and engineering that is worthy in its own right will have been performed. Such is the nature of assembler-enabling research – much of it, from CNTs to molecular computing, will find application regardless of whether or not engineers succeed in creating an assembler. In short, assembler-enabling research, the steps "A, B, and C" of which Dr. Steven Block speaks, is precisely what MM funding could entail. Molecular Manufacturing may seem to be a completely futuristic concept, but consistent funding of other enabling fields of nanotech, coupled with discussions of new research directions, may very well lead to the creation of the first assembler. Only one thing is certain – continually ignoring MM and saying it is impossible is the perfect way to create a self-fulfilling prophecy.

D. Coordination of Nanotechnology Research Funding

One of the main questions on the minds of Congress and the American taxpayers is how to coordinate research funding such that money is not wasted, and overlap does not occur.

[41] Dr. William H. Goddard III, CalTech. Personal e-mail correspondence, June 29, 2000.

Coordination, however, is a multi-sided issue, first of all because the need to prevent research funding overlap is not a simple matter. On the one hand, a favorable approach is to tightly coordinate funding priorities such that proposals do not overlap and waste taxpayer dollars. On the other hand, the very nature of scientific research requires that duplicate proposals receive funding. This is the way in which the community verifies ideas and theories. However, such overlap between agencies may often occur accidentally, in which case the government unintentionally spends money that could be spent on a different avenue of research. This, the accidental overlap of funding proposals, is the main problem that the government must avoid. However, one must also consider the fact that what appear to be duplicate funding priorities may only seem to lead to identical funding proposals. For instance, DOD states that they intend to pursue nanoelectronics research as a priority, while NASA plans to integrate robotics and nanoelectronics. At first, it may seem that such research will overlap. However, closer examination reveals that there exists enough distinction between the two priorities so that the DOD and NASA will both explore different niches of knowledge.[42]

Despite all of these arguments that both support and oppose research overlap, one should realize that there is an inherent contradiction in the funding of nanotechnology. This contradiction may override all previous arguments regarding funding priority overlap. The nation cannot proceed with this as they did with the space program or the Manhattan project, a coordinated national effort going for a single long-term goal. There exists the illusion that "nanotech" is a single goal, but in reality this is not the case. Nanotechnology requires the same enthusiasm as other streamlined programs, such as the Manhattan Project and the early space program, but not the same single-minded and streamlined approach. This is a critical distinction, and Federal agencies should keep such a funding philosophy in mind.

[42] IWGN, "National Nanotechnology Initiative." February 2000, pg. 28-29.

Currently, there exist long-term goals defined by the six key NNI funding agencies. Known as Grand Challenges, these are the application-driven goals by which the agencies, via the IWGN, currently coordinate themselves. Such diverse science will inevitably require collaboration, but not centralized planning and control. The IWGN can coordinate and discuss freely, as it did successfully for a year before publishing the NNI.

A glance at the NNI reveals that there is no significant interagency overlap of funding areas. Where similarities exist between certain research areas, they complement rather than override each other.[43] Various members of the IWGN, such as DOE's Dr. Iran Thomas,[44] and NSF's Dr. Thomas Weber,[45] feel that the group worked well in agreeing upon research priorities. Hence, the IWGN has succeeded in its first task. There is no foreseeable reason that the IWGN will degenerate as nanotech develops into a mature field, but only time will tell such a thing.

Despite positive arguments for the IWGN, there always exists the desire to centralize and streamline funding within a single agency. Some might feel that removing research from many agencies and consolidating it into a single agency would eliminate bureaucracy. However, this is most likely a superficial, incorrect judgment. Iran Thomas, DOE co-representative to the IWGN, extrapolates this sentiment:

> Consolidation does not make sense. It's very important for the Departments to do research important to their missions. Nobody is considering a new agency for every area of science. Just think what this would mean: a Department of Nanoscience, a Department of Semiconductivity, a Department of

[43] Interagency Working Group on Nanoscience, Engineering, and Technology, "National Nanotechnology Initiative." February 2000, pg. 27-31.

[44] Dr. Iran Thomas, Deputy Associate Director of Basic Energy Sciences, DOE. Personal e-mail correspondence, July 18 2000.

[45] Dr. Thomas Weber, NSF co-representative to the IWGN. Personal e-mail conversation. July 18, 2000.

> Superconductivity, a Department of Insulators, a Department of Polymer Chemistry, a Department of Catalysis, and so on.[46]

All of these are fairly specific fields. However, when considering the fact that nanotech encompasses such a wide variety of research areas whose common characteristic is only a measure of length, it becomes apparent that such an approach is not appropriate. There exist too many niche areas that are of interest to certain Federal agencies and not others. Centralization would most likely serve to eliminate many of these areas.

VI. Policy Alternatives and Recommendations

A. Regarding Agency Coordination

There seem to be three main options for Federal agency coordination, two that are fairly extreme and one that is more feasible.

1. No Coordination: The six agencies involved in the NNI can choose to revert to the days prior to the IWGN, when nanotech research was spread throughout isolated pockets of funding, and the agencies themselves communicated very little. However, given the fact that the NNI calls for coordination, such an option is definitely a thing of the past. If the United States is to move, rather than lurch, forward in nanotech research, funding coordination in one form or another must take place.

2. Centralized Coordination: The other extreme solution is to remove all nanotech funding from the jurisdiction of individual federal agencies and consolidate it within a single agency. This may already be an agency currently in existence, such as the current "lead agency," the National Science Foundation. On the other hand, the Federal government might create a new

[46] Dr. Iran Thomas, DOE co-representative to the IWGN. Personal e-mail correspondence, July 18 2000.

agency specifically dedicated to coordinating funding for the many branches of nanotechnology. Either way, the purpose of such an agency will be to prevent the overlap of proposal funding, and to promote efficient, directed research.

3. Informal Coordination: A final possibility is that the six key funding agencies can continue to pursue informal ties, via the IWGN. Since the IWGN has no jurisdiction to fund proposals, such a method of coordination will keep nanotech funding power spread throughout a variety of agencies. This has great benefits in terms of balancing research efficiency with research diversity. Dr. Clifford Lau, of the DOD's Office of Naval Research, adds that this method has traditionally worked - "the fact that the U.S. leads the world in scientific productivity is because of the diversity of research program opportunities," rather than the centralization of control."[47]

4. Recommendation: Currently, the Federal government has decided to coordinate work mainly based upon the long-term goals of each individual agency. Thus, on the surface, funding and research may appear to have a tendency to overlap. Since nanotechnology may sound like a single unified goal, this overlap might appear to be a waste of taxpayer dollars. However, the NNI bears little if any resemblance to truly streamlined Federal science programs, such as the Manhattan Project, which had a single endpoint in mind.

While there may exist **apparent** overlaps, such as the fact that both the DOD and NASA want to pursue research into "nanoelectronics," this does not mean that the DOD and NASA will be wasting taxpayer dollars by funding exactly the same research. Even slight differences in research proposals, highly likely due to the fact that agency application agendas differ, will constitute worthwhile funding. Finally, differences in review cultures may make formal funding coordination near impossible. **In the end, the smartest thing to do is to continue pursuing**

informal coalitions such as the IWGN, which spread funding power evenly amongst all interested agencies.

B. Regarding Molecular Manufacturing (MM)

1. Ignore MM: Currently, the Federal Government is essentially taking an approach that amounts to ignoring the MM community. Although there are indeed pockets of Federal researchers who believe in the assembler concept, as well as definite Federal funding of certain assembler-enabling fields, there is definitely no formal Federal acknowledgement of the need to pursue the creation of an assembler. One might say that there has simply been an oversight, as evidenced by the lack of even a single mention of assemblers within the NNI. On the other hand, one could also claim that an assembler is just another type of nanodevice, and the NNI does explicitly mention nanodevice research funding. Of course, assembler advocates might argue that this is an all-purpose device, and thus the most powerful form of nanotechnology that scientists and engineers can create. Hence, it may very well be inexcusable not to mention assemblers explicitly, at least in passing.

On a more extreme level, one might say that the Federal government has had an outright hostility toward assemblers, as evidenced by Dr. Steven Block's speech at a government-sponsored conference.

Thus, one option is that the Federal government can continue to ignore the voices of the MM community, simply because they may be too far ahead of their time. As Steven Block said later, "I see Drexlerian-type assemblers as a dream, just like the 'transporters' and 'replicators' in Star Trek episodes, or the tractor beams and warp drive for that matter. You don't launch a

[47] Dr. Clifford Lau, DOD's Office of Naval Research. Personal e-mail correspondence. July 20, 2000.

serious science program to build a warp drive when you have no idea whatsoever about how one might be constructed!"[48]

2. Discuss With the MM Community: A more productive option might very well be that those who constitute the "mainstream" nanotech community, including the IWGN and various scientists, begin to hold formal discussions with the Foresight Institute and others who believe in currently discussing the creation of an assembler. Until now, there has been an extremely low level of open discussion on the subject. There has been a good deal of name-calling, and a bit of discussion in magazines such as Scientific American, which engaged in a long-standing debate with the Foresight Institute.[49] However, there has been no open discussion within the Federal government, the main source of money that could move the nation forward in the creation of an assembler program.

3. Create an Interdisciplinary Assembler Program: Either a single Federal agency, or possibly the IWGN, can create a formal program dedicated to coordinating the research necessary to build the first assembler. Steven Block states that it is not intelligent to launch a large-scale government program when the scientific community has no understanding of how to pursue research into the relevant field. However, the creation of such a program may not actually cost anything more. It may simply bridge discussion over the fact that, aside from the mathematical and algorithmic properties involved in artificial self-replication, assemblers will most likely utilize much of the exact same research currently being touted by the scientific community – nanoelectronics, nanocomputing, nanodevices, etc. Even if such a program, for the moment, only lays down possibly strategies, this is better than nothing, especially because the future payoff seems to be so great.

[48] Dr. Steven M. Block, Stanford University. Personal e-mail correspondence. July 11, 2000.
[49] http://www.foresight.org/SciAmDebate/SciAmOverview.html

4. Leave to the Responsibility of Industry: Speaking about the creation of the first assembler, Dr. Thomas Weber, NSF co-representative to the IWGN, states that government is "not in the business of producing a single device. That is the domain of industry."[50] This raises a valid point – Eric Drexler's notion of the assembler, the all-purpose nanodevice, applies simultaneously to every agency's mission and no agency's mission. Hence, the pursuit of an assembler may be a grand project for a single company, but not for a government.

5. Recommendation: The Federal government and the MM community need to engage in more dialogue, in order to decide whether the government ought to fund any basic research directions that it currently is not supporting. The United States needs a productive first step to figure out the technical avenues that must be integrated in order for molecular manufacturing to work. If funding is weak in any of these areas, such as Dr. Ralph Merkle claims is the case for self-replicating systems research, then the appropriate agency, most likely the NSF, should increase such funding.

However, despite the fact that it is the Federal government's job to fund the basic research that industry utilizes, the responsibility for creating such a marketable device does belong to industry. If assemblers prove feasible, in the form that Eric Drexler proposes they may, their benefits will touch every aspect of the nanotech industry. Hence, it is in the United States' best interest to assure that an American company, not a Japanese or a European company, produces the world's first assembler.

In order to discover the areas of assembler-enabling research in which the United States needs to invest more money, the IWGN ought to first begin more dialogue with pro-assembler institutes such as Foresight and IMM. However, the actual creation of an assembler is applied

[50] Dr. Thomas Weber, NSF co-representative to the IWGN. Personal e-mail conversation. July 18, 2000.

research, and therefore it is industry's responsibility to capitalize upon the public availability of this Federally-funded knowledge.

VII. Conclusion

The creation of the IWGN, as well as the working group's proposal of the NNI into the President's FY2001 budget request, were two extremely intelligent moves for the United States. If Congress grants funding as the NNI has requested it, the United States will begin to amass the infrastructure, knowledge and workforce that will make this nation a key player in the 21st century global economy.

Nevertheless, there does exist a certain division within the nanotech community over the need to pursue "molecular manufacturing" (MM) as first proposed by Dr. Eric Drexler. His idea, to build an all-purpose nanomanufacturing device known as an "assembler," strikes much of the scientific community as pure speculation that belongs in the realm of a science-fiction film. However, if such a device is possible, the nation that creates it will surely play a lead role in the nanotech industry. Much of the research that assembler proponents deem necessary is currently accepted by the mainstream. Thus, it will be neither too drastic nor too costly a step for the IWGN and the heads of the MM community to hold more formal dialogues. In doing so, they may discuss whether or not any assembler-enabling research avenues deserve more funding. Once the government funds such research, it is the job of industry to capitalize. If assemblers prove true, the United States will benefit greatly. If assemblers prove to be a failure, the United States will have lost little if anything. The knowledge gained along the way, as supported by the NNI, will be enough to lead the nation to a competitive spot in the 21st century economy.

Appendix A – Agency Interests in Nanotechnology Research

Agency	**NSF**	**DOC/NIST**	**DOD**	**DOE**	**NASA**	**NIH**
Major Interests	Fundamental research: Novel nanoscale Phenomena, synthesis, Processing, and assembly Instrumentation and modeling Materials by design Biostructures and bio-inspired Systems Nanosystem architecture Infrastructure and education	Measurement Science and Standards Acceleration of commercial technology development	Information acquisition, processing, storage, And display. Materials performance and affordability Chemical and Biological warfare defense	Basic energy science and engineering: efficiency, defense, environment, and nuclear non proliferation	Lighter and smaller Spacecraft Biomedical Sensors And Medical Devices Smaller, more efficient Computers Radiation Tolerant Electronics Thin Films For Solar Sails	Biomaterials Devices Therapeutics Infrastructure and training

Appendix B – Listing of Abbreviations

AAAS – American Association for the Advancement of Science
AFM – Atomic Force Microscope
BECON – (NIH) Bioengineering Consortium
CNT – Carbon Nanotube
DARPA – Defense Advanced Research Projects Agency
DOC/NIST – Department of Commerce; National Institute of Standards and Technology
DOD – Department of Defense
FY – Fiscal Year
HHS – Health and Human Services
HUD – Housing and Urban Development
IEEE – Institute of Electrical and Electronics Engineers
IMM – Institute for Molecular Manufacturing
IWGN – Interagency Working Group on Nanoscience, Engineering, and Technology
MEMS – MicroElectroMechanical Systems
MM – Molecular Manufacturing
MNT – Molecular Nanotechnology
NASA – National Aeronautics and Space Administration
NIH – National Institutes of Health
NNI – National Nanotechnology Initiative
NSF – National Science Foundation
NSTC – National Science and Technology Council
ONR – Office of Naval Research
ORNL – Oak Ridge National Laboratory
R+D – Research and Development
S+T – Science and Technology
STM – Scanning Tunneling Microscope
VA – Veterans Affairs
WISE- Washington Internships for Students of Engineering

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