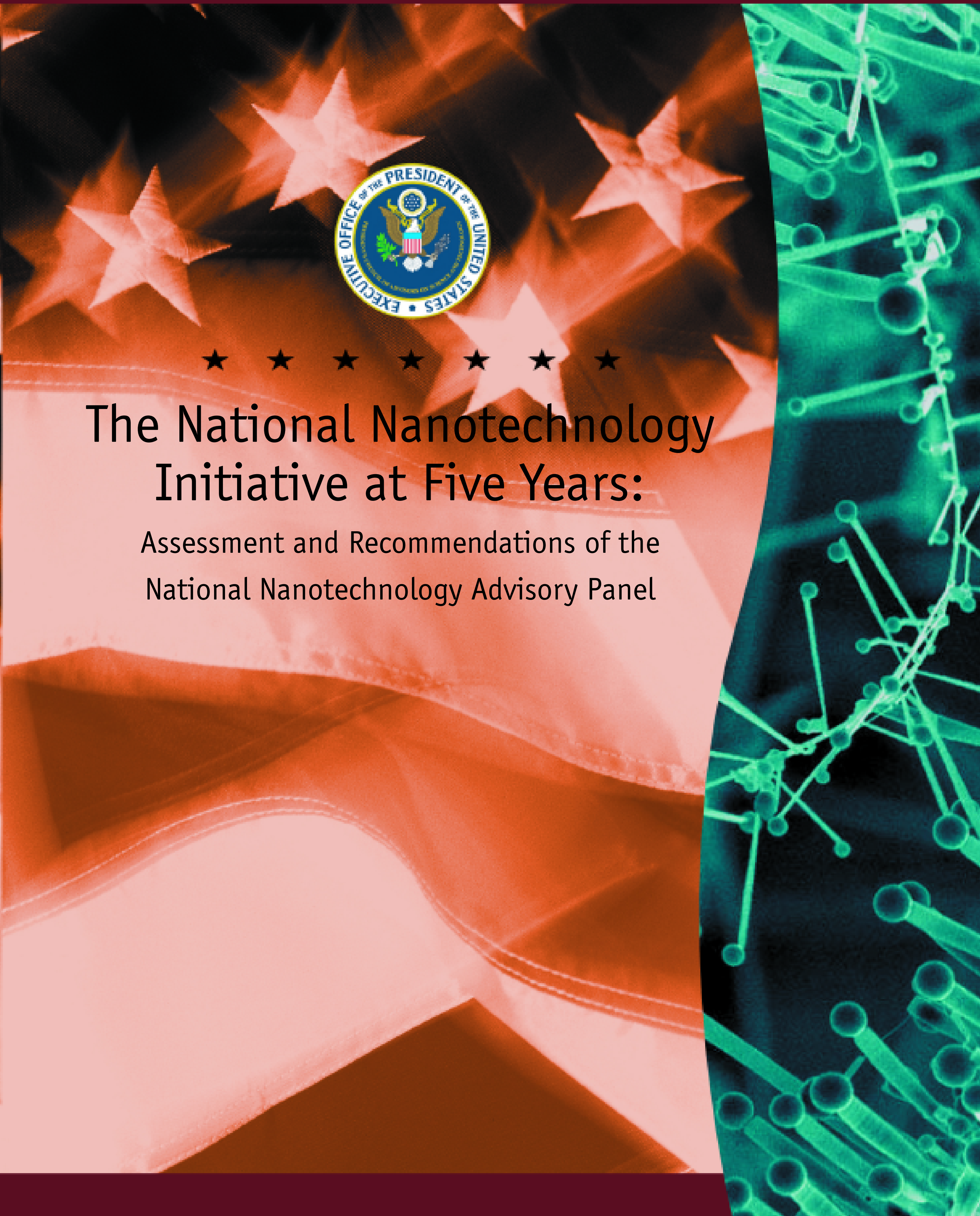
PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY • MAY 2005



The National Nanotechnology Initiative at Five Years:

Assessment and Recommendations of the National Nanotechnology Advisory Panel

About the President's Council of Advisors on Science and Technology

President Bush established the President's Council of Advisors on Science and Technology (PCAST) by Executive Order 13226 in September 2001. Under this Executive Order, PCAST "shall advise the President... on matters involving science and technology policy," and "shall assist the National Science and Technology Council (NSTC) in securing private sector involvement in its activities." The NSTC is a cabinet-level council that coordinates interagency research and development activities and science and technology policy making processes across Federal departments and agencies.

PCAST enables the President to receive advice from the private sector, including the academic community, on important issues relative to technology, scientific research, math and science education, and other topics of national concern. The PCAST-NSTC link provides a mechanism to enable the public-private exchange of ideas that inform the Federal science and technology policy making processes.

PCAST follows a tradition of Presidential advisory panels on science and technology dating back to Presidents Eisenhower and Truman. The Council's 23 members, appointed by the President, are drawn from industry, education, and research institutions, and other nongovernmental organizations. In addition, the Director of the Office of Science and Technology Policy serves as PCAST's Co-Chair.

About the National Nanotechnology Advisory Panel

The National Nanotechnology Advisory Panel (NNAP) was created by the United States Congress in the 21st Century Nanotechnology 21st Research and Development Act of 2003 (P.L. 108-153), signed by President Bush on December 3, 2003. The Act required the President to establish or designate a NNAP to review the Federal nanotechnology research and development program. On July 23, 2004, President Bush formally designated the PCAST to act as the NNAP.

About this Report

The Act that created the NNAP calls for this advisory body to conduct a review of the NNI and report its findings to the President. The Act calls upon the NNAP to assess the trends and developments in nanotechnology, and the strategic direction of the NNI, particularly as it relates to maintaining U.S. leadership in nanotechnology research. The Act also requires comment on NNI program activities, management, coordination, implementation, and whether the program is adequately addressing societal, ethical, legal, environmental, and workforce issues. The Act provides that the NNAP is to report on its assessments and to make recommendations for ways to improve the program at least every two years. The Director of the Office of Science and Technology Policy is to transmit a copy of the NNAP report to Congress. This is the first report of the NNAP under the Act.

Front cover: Zinc oxide nanorods with approximately 100-nm tin beads at tips. The properties of zinc oxide make these suitable for nanoscale, ultra-sensitive sensors. Courtesy of Prof. Zhong Lin Wang, Georgia Institute of Technology. Cover design by Nicolle Rager of Sayo-Art.

The National Nanotechnology Initiative at Five Years:

Assessment and Recommendations of the National Nanotechnology Advisory Panel

Submitted by the
President's Council of Advisors on Science and Technology
May 2005

EXECUTIVE OFFICE OF THE PRESIDENT
PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY
WASHINGTON, D.C. 20502

May 16, 2005

President George W. Bush
The White House
Washington, D.C. 20502

Dear Mr. President:

We are pleased to transmit to you a copy of the report, *The National Nanotechnology Initiative at Five Years: Assessment and Recommendations of the National Nanotechnology Advisory Panel*, prepared by your Council of Advisors on Science and Technology (PCAST).

In response to direction in your Fiscal Year 2004 Budget, PCAST initiated a review of the multi-agency National Nanotechnology Initiative (NNI). You subsequently signed Congressional legislation (P.L. 108-153) calling for an external National Nanotechnology Advisory Panel (NNAP), and in July 2004, by Executive Order, you formally designated PCAST as the NNAP.

The enclosed report represents PCAST's first assessment of the Federal Government's nanotechnology research efforts. PCAST undertook the legislatively required assessments in a manner that examined what we believe would be your four primary concerns:

1. **Where Do We Stand?**
2. **Is This Money Well Spent and the Program Well Managed?**
3. **Are We Addressing Societal Concerns and Potential Risks?**
4. **How Can We Do Better?**

We answer, in brief, that the United States holds a leadership position in nanotechnology, but it is being aggressively challenged by many nations. We find the Federal investment to date has been money very well spent, and the NNI program to be well managed—with social concerns and risks to human health and the environment being wisely acknowledged and addressed. We recommend several improvements to the program, including the need for the NNI to increase coordination with the States as avenues of economic development, and for the program management to remain flexible in this fast-developing field.

The full PCAST discussed and approved this report at its public meeting on March 22, 2005. We appreciate the confidence you placed in us by designating PCAST as the National Nanotechnology Advisory Panel, and we look forward to continuing to monitor the Federal programs engaged in this exciting field on your behalf. Please let us know if you have any questions concerning the enclosed report.

Sincerely,

John H. Marburger, III
Co-Chair

E. Floyd Kvamme
Co-Chair

Enclosure

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Executive Summary

The President's Fiscal Year (FY) 2004 Budget, released in February 2003, tasked the President's Council of Advisors on Science and Technology (PCAST) with reviewing the National Nanotechnology Initiative (NNI) and making recommendations for strengthening the program. Congress ratified the need for an outside advisory body with its passage of the 21st Century Nanotechnology Research and Development Act of 2003 (the Act), which called for the President to establish or designate a National Nanotechnology Advisory Panel (NNAP). By Executive Order, the President designated PCAST as the NNAP in July 2004. To augment its own expertise in managing large research and development (R&D) programs, PCAST identified a Technical Advisory Group (TAG) comprising about 45 nanotechnology experts representing diverse disciplines and sectors across academia and industry. The TAG is a knowledgeable resource, providing input and feedback with a more technical perspective.

The Act calls upon the NNAP to assess the NNI and to report on its assessments and make recommendations for ways to improve the program at least every two years. This is the first such periodic report provided by PCAST in its role as the NNAP.

The Administration has identified nanotechnology as one of its top R&D priorities. When FY 2005 concludes later this year, over 4 billion taxpayer dollars will have been spent since FY 2001 on nanotechnology R&D. In addition, the President's FY 2006 Budget includes over $1 billion for nanotechnology research across 11 Federal agencies. Such a substantial and sustained investment has been largely based on the expectation that advances in understanding and harnessing novel nanoscale properties will generate broad-ranging economic benefits for our Nation. As such, the NNAP members believe the President, the Congress, and the American people are seeking answers to four basic questions relative to the Federal investment in nanotechnology R&D:

1. ***Where Do We Stand?***
2. ***Is This Money Well Spent and the Program Well Managed?***
3. ***Are We Addressing Societal Concerns and Potential Risks?***
4. ***How Can We Do Better?***

Answers to these questions provide the assessments and recommendations called for by the Act. Our conclusions can be summarized as follows:

1. Where Do We Stand? Today, the United States is the acknowledged leader in nanotechnology R&D. The approximately $1 billion annual Federal Government funding for nanotechnology R&D is roughly one-quarter of the current global investment by all nations. Total annual U.S. R&D spending (Federal, State, and private) now stands at approximately $3 billion, one-third of the approximately $9 billion in total worldwide spending by the public and private sectors. In addition, the United States leads in the number of start-up companies based on nanotechnology, and in research output as measured by patents and publications. Our leadership position, however, is under increasing competitive pressure from other nations as they ramp up their own programs.

2. Is This Money Well Spent and the Program Well Managed? The NNAP members believe strongly that the money the United States is investing in nanotechnology is money very well spent, and that continued robust funding is important for the Nation's long-term economic well-being and national security. Nanotechnology holds tremendous potential for stimulating innovation and thereby enabling or maintaining U.S. leadership in industries that span all sectors. The focus of the NNI on expanding knowledge of nanoscale phenomena and on discovery of nanoscale and nanostructured materials, devices, and systems, along with building an infrastructure to support such studies, has been both appropriate and wise. The NNI has accomplished much already—advancing foundational knowledge, promoting technology transfer for commercial and public benefit, developing an infrastructure of user facilities and instrumentation, and taking steps to address societal concerns—and the economic payoffs over the long term are likely to be substantial.

The NNI appears well positioned to maintain United States leadership going forward, through both its coordinated interagency approach to planning and implementing the Federal R&D program and its efforts to interact with industry and the public. This approach is outlined clearly in the recently released NNI Strategic Plan, which spells out the goals and priorities for the initiative for the next 5 to 10 years. The NNAP members believe that this Plan provides an appropriate way to organize and manage the program.

3. Are We Addressing Societal Concerns and Potential Risks? The societal implications of nanotechnology—including environmental and health effects—must be taken into account simultaneously with the scientific advances being underwritten by the Federal Government. The NNI generally recognizes this, and is moving deliberately to identify, prioritize, and address such concerns.

Environmental, Health, and Safety. The NNAP convened a panel of experts from Government regulatory agencies, academia, and the private sector to discuss the environmental and health effects of nanotechnology. Based on these panel discussions, as well as on information received from the NSET Subcommittee and the TAG, the NNAP members believe that potential risks do exist and that the Government is directing appropriate attention and adequate resources to the research that will ensure the protection of the public and the environment. The NNAP members are particularly pleased that strong communication exists among the agencies that fund nanotechnology research and those responsible for regulatory decision-making.

Education. The future economic prosperity of the United States will depend on a workforce that both is large enough and has the necessary skills to meet the challenges posed by global competition. This will be especially important in enabling the United States to maintain its leadership role in nanotechnology and in the industries that will use it. The NNI has launched a range of education-related programs appropriate for classrooms at all levels and across the country, along with other programs that are aimed at the broader public. While the NNI cannot be expected to solve the Nation's science education problems single-handedly, the NNAP members believe that these NNI activities can help improve science education and attract more bright young minds into careers in science and engineering.

Other Societal Dimensions. Understanding the impact of a new technology on society is vital to ensuring that development takes place in a responsible manner. In addition to research into societal issues such as the environmental, health, and safety effects of nanotechnology, the NNI's diverse and growing R&D program is exploring other issues such as economic, workforce, and ethical impacts. In addition, communication among the various stakeholders and with the public on these topics is an important element of the program, as indicated by the establishment of an interagency subgroup to address this topic.

4. How Can We Do Better? The NNAP will monitor progress on the program elements discussed above; in the meantime, the NNAP offers the following recommendations aimed at further strengthening the NNI.

Technology Transfer. The level of interest and investment across many industrial sectors is growing and will likely outpace Government investment in the United States soon, if it hasn't already. The NNI needs to take further steps to communicate and establish links to U.S. industry to further facilitate technology transfer from the lab to the marketplace. The NNAP calls attention to two areas that would augment the existing suite of activities and enhance commercialization of research results.

- **The NNI's outreach to, and coordination with, the States should be increased.** Such efforts would complement those NNI activities already underway with various industrial sectors. The States perform a vital role in fostering economic development through business assistance programs, tax incentives, and other means. In addition, collectively the States are spending substantial amounts in support of nanotechnology R&D and commercialization. The NNAP members believe that practical application of NNI-funded research results, workforce development, and other national benefits will increase with improved Federal-State coordination.

- **The NNI should examine how to improve knowledge management of NNI assets.** This would include assets such as user facilities and instrumentation available to outside researchers, research results, and derivative intellectual property. Through mechanisms such as publicly available and searchable databases, the NNI can—and should—improve infrastructure utilization and the transfer of technology to the private sector.

The NNAP notes that, although ultimate commercialization of nanotechnology is desirable and to be supported, the NNI must remain mindful that its primary focus is on developing an understanding of the novel properties that occur at the nanoscale and the ability to control matter at the atomic and molecular level. While we all want the United States to benefit economically from nanotechnology as quickly as possible, it is critically important that the basic intellectual property surrounding nanotechnology be generated and reside within this country. Those who hold this knowledge will "own" commercialization in the future.

Environmental and Health Implications. The NNI should continue its efforts to understand the possible toxicological effects of nanotechnology and, where harmful human or environmental effects are proven, appropriate regulatory mechanisms should be utilized by the pertinent Federal agencies. Nanotechnology products should not be immune from regulation, but such regulation must be rational and based on science, not perceived fears. Although it appears that the public and the environment are adequately protected through existing regulatory authorities, the NNAP encourages the Government regulatory agencies to work together to ensure that any regulatory policies that are developed are based on the best available science and are consistent among the agencies.

The NNAP notes that research on the environmental and health implications of nanomaterials and associated products should be coordinated not only within the Federal Government, but with other nations and groups around the world to ensure that efforts are not duplicated unnecessarily and information is shared widely.

Education/Workforce Preparation. A key to realizing the economic benefits of nanotechnology will be the establishment of an infrastructure capable of educating and training an adequate number of researchers, teachers, and technical workers. To maximize the value of its investment in developing materials and programs for education and worker training, the NNI should establish relationships with the Departments of Education and Labor. While the science agencies such as the National Science Foundation (NSF) can conduct education research and design excellent programs and materials, ultimately the mission agencies, Education and Labor, must be engaged to disseminate these programs and materials as widely as possible throughout the Nation's education and training systems.

The NNI's education focus should be on promoting science fundamentals at K-16 levels, while encouraging the development and incorporation of nanotechnology-related material into science and engineering education. To promote mid-career training for professionals, the NNI should partner with and support professional societies and trade associations that have continuing education as a mission.

Societal Implications. The NNI must support research aimed at understanding the societal (including ethical, economic, and legal) implications and must actively work to inform the public about nanotechnology. Now more than ever, those who are developing new scientific knowledge and technologies must be aware of the impact their efforts may have on society.

In summary, the NNAP supports the NNI's high-level vision and goals, and the investment strategy by which those are to be achieved. Panel members feel that the program can be strengthened by extending its interaction with industry, State and regional economic developers, the Departments of Education and Labor, and internationally, where appropriate. The NNI should also continue to confront the various societal issues in an open, straightforward, and science-based manner.

Introduction and Background

"Nanotechnology" touches upon a broad array of disciplines, including chemistry, biology, physics, computational science, and engineering. Like information technology, nanotechnology has the potential to impact virtually every industry, from aerospace and energy to healthcare and agriculture. Based on the ability to see, measure, and manipulate matter at the scale of atoms and molecules, nanotechnology was born, in many ways, with the advent of atomic force microscopy in the mid-1980s. Today many industries such as semiconductors and chemicals already are creating products with enhanced performance based on components and materials with nanosized features.

The breathtaking possibilities for useful and powerful nanotechnology applications led to the formal establishment of a National Nanotechnology Initiative (NNI) in Fiscal Year (FY) 2001. Due to its potential to promote innovation and economic benefits, as well as to strengthen the position of the United States as a leader in science and technology, the Administration has identified nanotechnology as a top research and development (R&D) priority for the past several years. Since its inception in FY 2001, the NNI budget has more than doubled and the number of participating agencies has grown from 6 to over 20.

Such a broadly distributed program demands strong interagency coordination, which is provided by a subgroup of the National Science and Technology Council (NSTC), the Cabinet-level body by which the President coordinates science and technology policies across the Federal Government. Within the NSTC Committee on Technology, the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee is responsible for coordinating, planning, implementing, and reviewing the NNI.

The history of the President's Council of Advisors on Science and Technology (PCAST) involvement with the NNI extends back to 1999 when the analogous body under the previous Administration supported the proposal for establishing such an initiative. In a letter to the President, that body included a recommendation that "the progress toward NNI goals be monitored annually by an appropriate external body of experts, such as the National Research Council." In part based on this recommendation, the National Research Council was commissioned to do a study of the NNI, which was released in 2002 (NRC 2002). The first of that study's ten recommendations was that the Office of Science and Technology Policy establish an independent standing nanoscience and nanotechnology advisory board to provide advice to the NSET Subcommittee on policy, strategy, goals, and management.

The President's FY 2004 Budget, released in February 2003, acknowledged the National Research Council's recommendation for external review, and directed PCAST to conduct an assessment and provide advice regarding the strategic direction of the NNI program. PCAST began this task shortly thereafter.
The requirement for an ongoing outside advisory panel was ratified by Congress in the 21st Century Nanotechnology Research and Development Act of 2003, Public Law 108-153 (the Act), which called for the President to establish or designate a National Nanotechnology Advisory Panel (NNAP). PCAST's role was reaffirmed when, in July 2004 by Executive Order, the President formally designated PCAST to fulfill the duties of the NNAP (Bush 2004). The order amended the original Executive Order (Bush 2001) that commissioned PCAST, thus establishing that nanotechnology should be included in the formal PCAST charter.

The Act calls upon the NNAP to assess the NNI in the following areas:

- Trends and developments in nanotechnology
- Progress in implementing the program
- The need to revise the program
- Balance among the component areas of the program, including funding levels
- Whether program component areas, priorities, and technical goals developed by the NSET Subcommittee are helping to maintain U.S. leadership
- Management, coordination, implementation, and activities of the program
- Whether social, ethical, legal, environmental, and workforce concerns are adequately addressed by the program

The Act requires the NNAP to report on its assessments and to make recommendations for ways to improve the program at least every two years. This is the first such report provided by PCAST in its role as the NNAP. (Hereafter, "NNAP" is used to refer to PCAST in its capacity as the panel called for by the Act.)

To augment its own expertise in managing large R&D programs, the NNAP identified a Technical Advisory Group (TAG) comprising approximately 45 nanotechnology experts who represent diverse disciplines and sectors across academia and industry. The TAG is a knowledgeable resource, providing input and feedback with a more nanotechnology-specific technical perspective.

In the course of performing its assessment, the NNAP convened panels of experts to discuss advancements and opportunities in science and technology as well as the potential environmental, health, and safety implications of nanotechnology. The NNAP also met with members of the NSET Subcommittee throughout the review process to discuss the NNI R&D programs and thereby understand how the initiative is organized and managed. In addition to these sources, the NNAP called upon its TAG on several occasions for broader expert opinions on various topics. Members of the NNAP attended a number of the workshops organized by the NNI over the past two years, including the Research Directions II Workshop held in September 2004, to gain a better understanding of the broad research and application opportunities. These activities, along with numerous informal interactions by NNAP members with a range of nanotechnology stakeholders around the country and worldwide, have provided the basis for this report.

Including the more than $1 billion that the Federal Government estimates it will spend in FY 2005, over 4 billion taxpayer dollars have been spent since FY 2001 on nanotechnology R&D. In addition, the President's 2006 Budget includes over $1 billion for research across 11 Federal agencies (including both NIH and the National Institute for Occupational Safety and Health, or NIOSH, within the Department of Health and Human Services). With such a large and sustained investment, the NNAP members believe the President, the Congress and the American people are seeking answers to four basic questions relative to the Federal investment in nanotechnology R&D:

1. ***Where Do We Stand?***
2. ***Is This Money Well Spent and the Program Well Managed?***
3. ***Are We Addressing Societal Concerns and Potential Risks?***
4. ***How Can We Do Better?***

These questions provide the underlying structure for this report, and the answers provide the assessments and recommendations called for by the Act.

As the first of what will be periodic assessments, this report focuses especially on the question of U.S. competitiveness. The Nation cannot afford to cede leadership in this emerging area of science and technology. Remaining at the forefront in nanotechnology requires not only sustained investment and public-private cooperation, but also an understanding of where the opportunities lie, and of the level and direction of activity in other nations.

Definition of Nanotechnology

Since its inception, the NNI has defined "nanotechnology" as encompassing the science, engineering, and technology related to the understanding and control of matter at the length scale of approximately 1 to 100 nanometers. However, nanotechnology is not merely working with matter at the nanoscale, but also research and development of materials, devices, and systems that have novel properties and functions due to their nanoscale dimensions or components.

Wisely in our view, the NNI has distinguished nanotechnology R&D from other types of ongoing scientific research that have achieved a certain level of miniaturization or that operate at a nanometer-length scale. One area in which this distinction is especially challenging is at the intersection of nanotechnology and biology. Many biological structures and processes are on the nanoscale. The National Institutes of Health (NIH) have the following corollary:

> *While much of biology is grounded in nanoscale phenomena, NIH has not re-classified most of its basic research portfolio as nanotechnology. Only those studies that use nanotechnology tools and concepts to study biology; that propose to engineer biological molecules toward functions very different from those they have in nature; or that manipulate biological systems by methods more precise than can be done by using molecular biological, synthetic chemical, or biochemical approaches that have been used for years in the biology research community are classified as nanotechnology projects.*

The NNAP endorses this definitional focus upon the novel properties that occur at the nanoscale and the distinction made between nanotechnology and biology, and the associated goal of understanding and gaining control over them.

CHAPTER 1: Where Do We Stand?

Following the establishment of the NNI in FY 2001, worldwide interest and investment in nanotechnology R&D have grown steadily. Today, virtually every country that supports scientific and technology R&D has a nanotechnology initiative; by many estimates, the total investment by governments outside the United States surpasses $3 billion annually, with comparable investment by the private sector.

While technical and business experts continue to debate the future advancements and economic impacts of nanotechnology, public interest and media coverage have grown dramatically. Scientific advances and technical progress continue, spurred on by vast investments by governments and the private sector, yet most agree that nanotechnology is, by and large, still in a nascent stage and that its ultimate impact on the world economy remains to be seen. What all agree upon is that significant potential clearly exists.

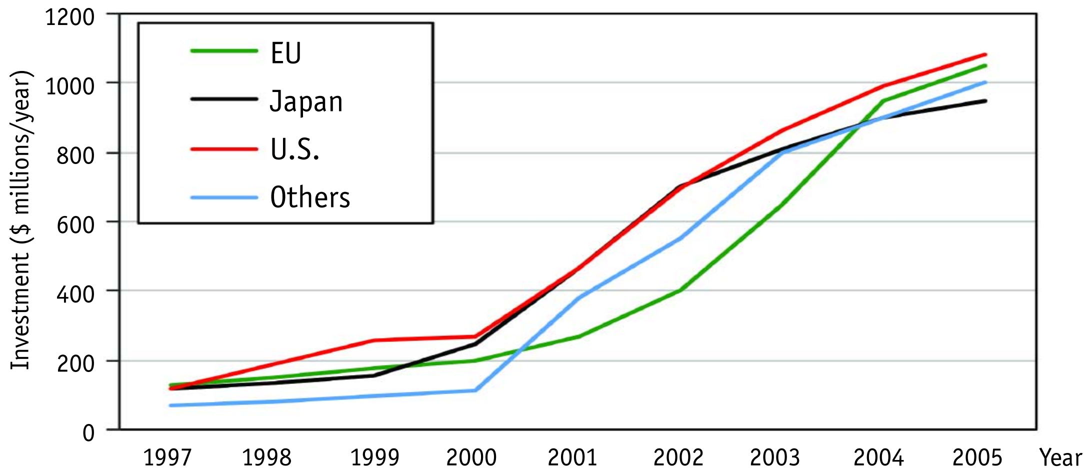
The question, “Where Do We Stand?” refers to the basic competitive position of the United States relative to other countries in the nanotechnology arena. Because nanotechnology is still at an early stage and is dominated by both publicly and privately supported R&D activities, a determination of the Nation’s competitive position depends on benchmarking research rather than on economic indicators such as market share. The measurement of research outputs is notoriously challenging (Committee on Science, Engineering, and Public Policy 2000); frequently used metrics include the numbers of and citations to scientific and technical publications and patents. Because some of the knowledge created through research is not captured by these measures of output, the amount going into the pipeline in the form of financial support often is used as an indicator of research activity level, and presumably correlates to some degree with the generation of new knowledge. The NNAP therefore has chosen to compare nanotechnology R&D investment, as well as publication and patent output, as a means of assessing the position of the United States in this emerging area.

Table 1.
Estimated Government Nanotechnology R&D Investments in 1997-2004 ($ Millions)

Region	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
EU	126	151	179	200	~ 225	~ 400	~ 650	~ 950	~ 1,050
Japan	120	135	157	245	~ 465	~ 720	~ 800	~ 900	~ 950
U.S.	116	190	255	270	465	697	862	989	1,081
Others	70	83	96	110	~ 380	~ 550	~ 800	~ 900	~ 1,000
Total (% of 1997)	**432** (100%)	**559** (129%)	**687** (159%)	**825** (191%)	**~ 1,535** (355%)	**~ 2,350** (547%)	**~ 3,100** (720%)	**~ 3,700** (866%)	**~ 4,100** (945%)

Source: M. Roco, National Science Foundation

Figure 1.
Government Nanotechnology R&D Investments in 1997-2004



Source: M. Roco, National Science Foundation

1. Nanotechnology R&D Investment

Nanotechnology R&D spending is distributed among governments (including national, regional, State, and local), universities, corporations, and venture capital investors. The availability and consistency of accurate figures varies for the different categories. When comparing the data available for various countries, difficulties may arise due to differences in the definition of nanotechnology, the inclusion of private contributions or other variations in the calculation of government funding, difficulty in getting some private—especially venture capital—investment data, mismatch in investment periods, and the various exchange rates employed. Rather than attempt to normalize disparate data sets, the NNAP has chosen to review a sampling of available data and to identify common trends.

1A. International Government Spending

While sources vary regarding international levels of nanotechnology R&D investment, one thing that all the data sets agree upon is that nanotechnology spending has been steadily increasing, reaching record levels in 2005. For the purpose of illustration, Table 1 and Figure 1 show one set of estimates indicating that national investments in nanotechnology worldwide increased over eightfold during the period from 1997 to 2005. Investment estimates shown in Table 1 are made using the nanotechnology definition of the NNI (this definition does not include microelectromechanical systems [MEMS], microelectronics, or general research on materials).

Other estimates vary from the amounts shown in Table 1. A report by the European Commission (EC) (2004) estimates that total worldwide government spending in 2003 was just over $3.5 billion, including funding by U.S. States (in addition to Federal programs) and by original European Union (EU) members and associated and acceding European countries.

In a more recent report, Lux Research (2004) estimated that worldwide government spending on nanotechnology research reached $4.6 billion in 2004: approximately 35% ($1.6 billion) was by governments in North America; another 35% ($1.6 billion) was by Asian governments; 28% ($1.3 billion) was by European governments, including the EC; and 3% ($133 million) was by all other governments. The Lux Research data include U.S. State funding in the total for North America and incorporate figures from associated and acceding EU countries in the European estimate.

As previously stated, available figures do not always allow for an "apples to apples" comparison, even among Federal Government expenditures. For instance, some countries invest in research through a combination of Government and corporate contributions. There is often inconsistency in the definition of nanotechnology for purposes of counting R&D expenditures. For example, some countries may include MEMS or biotechnology funding that is not counted under the strict U.S. definition of nanotechnology. Another variable between countries is the treatment of salaries for researchers. Whereas, U.S. figures include a salary component (e.g., as a portion of research grants and for Federal laboratory employees), many other countries fund salaries out of separate accounts from those reported as "nanotechnology R&D."

Although direct comparisons are difficult, the data collectively show that many countries are making significant public investments in nanotechnology R&D, and that these investments have increased sharply since 2000. The similar levels in the investments by the United States, Europe, and Japan, as shown in Figure 1, suggest an element of competition among these leaders. Because the NNAP members believe it is important for the United States to understand how its Federal investments stack up against public investment by other countries, the Panel has commissioned the Science and Technology Policy Institute (STPI), a Federally Funded Research and Development Center (FFRDC) that provides technical research and analysis to the Federal Government, to do a more detailed study to assess U.S. funding as it compares to other governments, including developing a means for normalizing and comparing international government investments.

1B. Regional, State and Local Spending

One difficulty in comparing U.S. Government spending to foreign government spending is that the contributions of U.S. State and local governments (and their foreign counterparts, where they exist) are often overlooked. A fair assessment of the overall U.S. competitive position must therefore include the significant contributions of U.S. State and local governments.

Regional, State, and local initiatives provide a vehicle for additional R&D funding, and a vital avenue for commercialization and economic development activity. In fact, State and local governments typically develop initiatives and commit funding precisely for the expected local economic development benefits this investment will yield. Lux Research reports that in 2004 U.S. State and local governments invested more than $400 million into nanotechnology research, facilities, and business incubation programs (Lux Research, Inc. 2005). Funding provided by State governments is often augmented, or leveraged, by additional resources provided through partnership with local private sector interests, universities, Federal Government agencies, and/or other interested regional organizations. These partnerships typically seek to build on existing regional competencies (e.g., a local research institution, a Government laboratory, and/or a strong local high-technology business community). A partial list of State investments in R&D infrastructure, typically at universities, is shown in Table 2.

In addition to supporting university-based infrastructure, many regional, State, and local initiatives support the development of a technically skilled workforce through the creation or promotion of education and training opportunities. Some have done this by leveraging existing Federal programs (e.g., NSF's Nanotechnology Undergraduate Education and Research Experience for Undergraduates programs) or through the establishment of new programs, such as providing nanotechnology-relevant curriculum assistance to community colleges. Another function of many regional initiatives is to facilitate partner access to NNI user facilities as well as to other nanotechnology resources and business expertise.

Table 2.

Nanotechnology R&D Infrastructure Investments at State Level

State	Recipient	Description	Partnership Model
AZ	Nano-bio research center	Research Infrastructure	University-State
CA	California Nanosystems Institute	Building Infrastructure	Metropolitan-State
FL	Center at University of South Florida	Faculty Recruitment & Infrastructure	University-State
GA	Center at Georgia Tech.	Building & Research Infrastructure	
IL	Nanoscience Centers (Northeastern Univ., U. of IL, Argonne National Laboratory)	Building & Research Infrastructure	Non-profit-Metropolitan-Regional
IN	Nanotechnology Center at Purdue	Building Infrastructure	
NJ	Support at NJ Institute of Tech. and photonics consortium	Building Infrastructure	State-Industry
NY	Nanoelectronics Center, Albany	Building & Research Infrastructure	University-State
OK	NanoNet	EPSCoR	University-Region
OR	ONAMI – Oregon Nano-Micro Interface Institute	Research Infrastructure	University-Industry
PA	Nanotechnology Center		Non-profit-University-State
SC	NanoCenter	Building Infrastructure	
SD	Center for Accelerated Applications at the Nanoscale	Research Infrastructure	UniMversity-State
VA	Various institutions and Luna Innovations	Research Matching & Infrastructure	University-State
WA	University of Washington, Washington Tech. Center	Clean Room Maintenance	University-State Partnership

Source: NSTC Report of the NNI Workshop on Regional, State and Local Initiatives in Nanotechnology, September 30-October 1, 2003 (2005). Note: The examples offered here provide a sampling of infrastructure investments by various U.S. States. This list is not comprehensive and does not include non-infrastructure investments.

Defining the Nanotechnology "Industry"

Attempts to define the nanotechnology "industry" inevitably result in definitions that are either too narrow or too broad.

If the definition were limited to that part of industry in which the nanotechnology aspect is dominant—that is, to companies that deliver pure nanotechnology—then it would only capture highly specialized activities such as the manufacture and sale of carbon nanotubes. Under this narrow definition the industry appears extremely small, and is likely to remain so for some time. The definition could be broadened somewhat by including the manufacture and sale of instruments that are necessary for measuring and manipulating matter at the nanoscale, because these sales are nanotechnology dependent. Even this expanded definition, however, continues to suggest a very small industry.

Taking a broader economic view, it is noteworthy that a wide variety of industries—including electronics, cosmetics, textiles, and pharmaceuticals—already use nanotechnology to make existing products better. Nanotechnology is used to produce stain-free khakis, transparent zinc-oxide-based sunblock, scratch-resistant automobile paint, more powerful semiconductors, and many other products. Under this further expanded 'count-any-contribution' definition, the nanotechnology industry is already quite large, and likely to grow to an enormous scale. Because nanotechnology does not dominate these products, however, this definition arguably over-counts the actual contribution of nanotechnology to the economy. Nonetheless, nanotechnology does contribute to the performance of these products and, in many cases, makes the performance possible in the first place.

Ultimately, nanotechnology is expected to be embedded throughout our economy, its contributions ranging from barely detectable to wholly dominant. Any credible attempt to define a nanotechnology "industry," therefore, will have to establish a threshold contribution level and explain why that level was chosen. This report does not attempt to choose or defend such a threshold.

While much activity is taking place to organize and secure support for regional nanotechnology initiatives from State and local governments and the private sector, the ultimate economic development success of most of these ventures remains to be seen. To the extent that nanotechnology parallels the biotechnology industry, regional "cluster" development may prove an excellent model for equipping local communities with competitive advantages. Technology-based cluster development builds upon a foundation of critical components for economic success—research expertise and infrastructure, technical and management talent, risk capital, commercial infrastructure, and an entrepreneurial culture. Certainly, this type of activity should be encouraged and its progress monitored to determine which of the arrangements ultimately yield long-term economic development and growth.

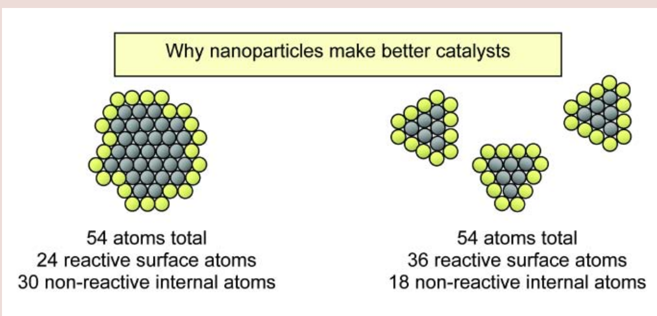
A workshop held in the Fall of 2003 brought together representatives from regional, State, and local nanotechnology initiatives across the country to share information and experiences. The resulting report (NSTC 2005), to be released soon, will serve as a useful primer for those who are at the early stages of launching similar activities. The NNAP strongly encourages the NNI to continue to interact with those regional, State, and local initiatives to assist their progress and to seek additional channels by which technology transfer may take place.

Nanomaterials for Clean Energy

Nanotechnology is helping to clean our air through better-performing and cheaper catalysts. By controlling the size and composition of platinum-based catalytic materials, the number of active sites can be dramatically increased, leading to improved catalytic converters that reduce auto emissions and help control pollution from power plants or stationary industrial sources. In today's converters, much of the platinum, which makes up roughly two-thirds of the total cost of the converter, is buried inside relatively coarse metal particles where it is unable to react with pollutants.

Researchers at Stanford University (supported by NSF and DOE) and NASA Ames Research Center developed new concepts for computationally modeling nanomaterials. In 2003, Nanostellar, Inc. was formed to develop the concepts into technologies for designing and fabricating controlled nanomaterials with optimized properties for catalytic reactions. Nanostellar has dramatically reduced the amount of platinum required for automotive emission control by designing and producing nanoparticles that combine the precious metal with other less costly metals. In addition to lowering cost, converters based on nanocomposite catalysts outperform traditional products, particularly at "cold start" where most gasoline and diesel engine pollution is generated.

Nanotechnology's contributions to pollution control may just be beginning. In a separate study, researchers at Brookhaven National Laboratory have shown that platinum mixed with iridium in single atomic layers is more than 20 times more active on a per atom basis than commercial catalysts.



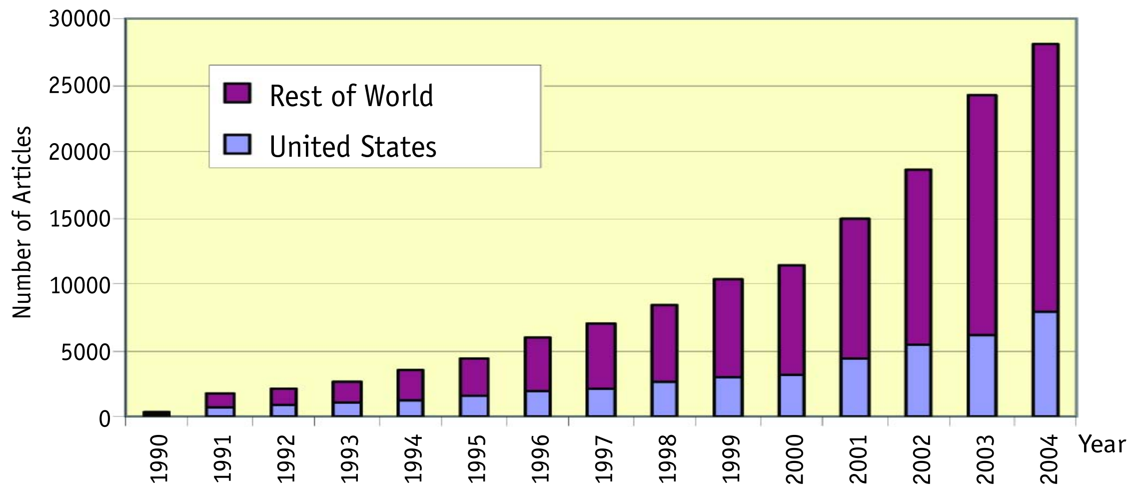
In addition to finding use in pollution control devices, nanostructured catalysts can improve the efficiency and reduce the cost of conventional and next-generation technologies for energy production and storage (e.g., in fuel cells, coal gasification, and improved photovoltaic cells).

1C. Private Investment

Measures of private investment include both corporate internal investment and venture capital activity. Obtaining firm data in this area is difficult, because private corporations and investors often consider such information to be proprietary. However, in 2003 the European Commission estimated worldwide private R&D funding to be close to 2 billion Euros (Commission of the European Communities 2004).

Of the $8.6 billion that Lux Research estimates was spent on nanotechnology R&D worldwide in 2004, $3.8 billion was by corporations: 46% ($1.7 billion) was by North American companies, predominantly in the United States; 36% (1.4 billion) was by Asian companies; 17% ($650 million) by European firms; and less than 1% ($40 million) was by businesses in other regions. Additional private sector investments were made by venture capital firms investing in nanotechnology start-up companies. These investments totaled roughly $400 million in 2004 (Lux Research Inc. 2004).

Figure 2.
Number of Articles in ISI Web of Science Database Found by Searching "nano*"



Source: J. Murday, U.S. Naval Research Laboratory

Because nanotechnology is a relatively new area, the "industry" is evolving rapidly. A study by EmTech Research (2005) identified approximately 600 companies based in the United States or with significant U.S. operations that are engaged in nanotechnology R&D, manufacture, sale, and use. Of these nearly three-quarters (72.9%) were founded in the past 10 years. A significant percentage of those companies (57.6%) have products on the market, although business plans based on development and licensing of intellectual property are widespread. Large companies typically are focusing more on applications and many have early stage R&D subsidiaries and/or research collaborations with small businesses or start-ups. Members of the NNAP observe a similarity between nanotechnology and the biotechnology industry in the 1980s and 1990s, suggesting that future acquisitions and consolidations are likely.

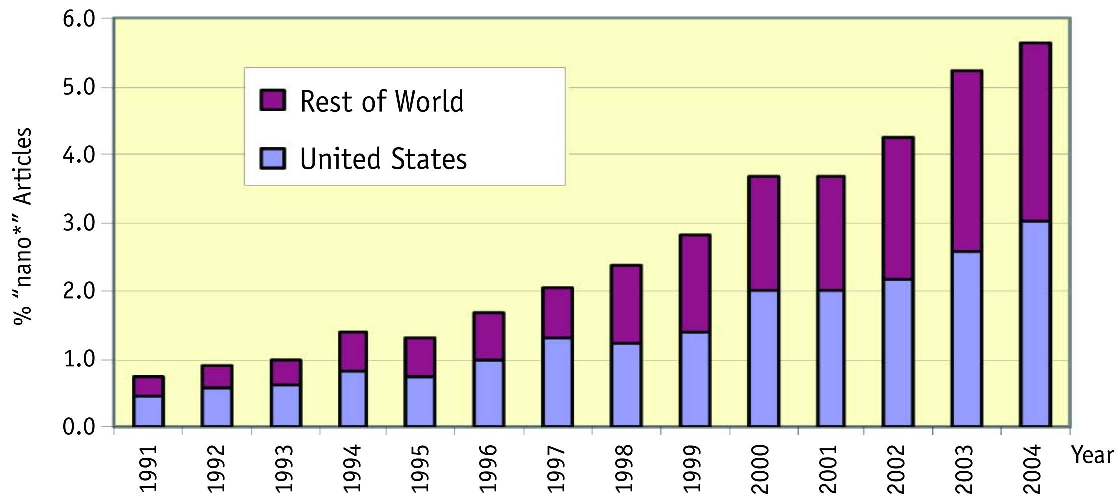
2. Research Output

In addition to judging United States competitiveness by comparing investments worldwide, the NNAP sought to compare research output. However, it is important to keep in mind that patents and publications are based on research that was performed one or more years prior to submission, with additional time elapsed between the submission of the research and its publication. Just as research spending precedes discovery and innovation, these measures lag behind.

2A. Publication Output

One metric often used to gauge scientific leadership is the number of peer-reviewed scientific articles. Figure 2 shows the results of a search of one of the principal databases of scientific literature, the Institute for Scientific Information (ISI) Web of Science a searchable database of about 5400 professional journals, using the keyword "nano*." The chart shows an escalation in the total number of publications since 1989, and especially since 2000. Although the number of publications from the United States has grown throughout the period, the percentage of publications originating from the United States has declined from approximately 40% in the early 1990s to less than 30% in 2004. In a similar study, Zucker and Darby (2005) show that the United States is dominant in terms of the number of nanotechnology research articles published, accounting for more than twice the number published by the country with the next-highest number, China. However, Zucker and Darby also note that the U.S. share is decreasing. They summarize: "Taken as a whole these data confirm that the strength and depth of the American science base points to the United States being the dominant player in nanotechnology for some time to come, while the United States also faces significant and increasing international competition."

Figure 3.
Total Percentage of Articles in *Science, Nature,* and *Physical Review Letters* Identified by a Keyword Search on "nano*"



Source: J. Murday, U.S. Naval Research Laboratory

Whereas the total number of publications is an indicator of the quantity of research output, a better indicator of the *quality* of the output is represented by publication in the most highly regarded and widely read scientific journals. A search of three high impact journals, *Science, Nature, and Physical Review Letters*, shows a 100% increase in the percentage of articles related to nanotechnology in these journals. Among these publications, the United States has produced an even larger fraction—over 50%—of the nanotechnology-related articles (Figure 3). These data show, however, as did those from the broader selection of publications, that there is a steady increase in the percentage that originates from other countries.

2B. Patent Output

Another metric commonly used to gauge leadership in technology innovation, and one that is perhaps more indicative of movement toward a commercial application, is the number of patents and patent applications. A study by Huang et al. (2004) reveals the rapid growth of nanotechnology-related patents. Based on a search of the full text of patents in the U.S. Patent and Trademark Office (USPTO) database using a list of nanotechnology-related keywords, over 8,600 nanotechnology-related patents were issued in 2003, an increase of about 50% over the number issued in 2000. The analysis pointed to strong U.S. leadership in the number of patents issued. U.S. entities accounted for over 60% of nanotechnology patents recorded in the USPTO database during the years 1976 to 2003. In addition, among the patents identified by the study, U.S. patents received the most citations by subsequently filed patents, another indication of technology leadership. Overall, the five countries receiving the highest number of nanotechnology-related patents in 2003 were the U.S. (5,228), Japan (926), Germany (684), Canada (244) and France (183). The number of nanotechnology-related patents issued by the USPTO to assignees in other countries, especially the Netherlands, Korea, Ireland, and China, is likewise increasing.

Because a full-text search finds patents that mention nanotechnology-related terms in the background section of the patent, even though the patented invention itself does not necessarily meet the definition of nanotechnology, Huang et al. also performed a search of just the patent title and claims. The results of this search for the years between 1990 and 2003 (shown in Figure 4) show trends that are similar to those indicated by the broader full-text search.

Nanocrystalline Synthetic Bone is Stronger and Heals Faster

Every year, orthopedic surgeons will implant medical devices into millions of Americans to mend broken bones, repair ligaments and tendons, and relieve pain in backs, hips and knees. However, even the best materials and devices used today for such procedures are a compromise. Metal screws and pins can loosen or permanently weaken the surrounding bone while ordinary fillers or cements can be very slow to—or may never—fully heal.

About half the weight of natural bone is the mineral hydroxyapatite, which makes a synthetic version of the mineral an obvious candidate for bone repair or replacement. Hydroxyapatite is in fact highly biocompatible. Bone cells attach to it and grow, and thereby encourage the healing process. But when manufactured using conventional methods, it forms a ceramic material with relatively large crystals compared to those in bones. The larger crystal size makes the synthetic material structurally weaker and less biocompatible than natural bone. Ceramic hydroxyapatite is made of many individual crystals packed together, and one way to make the material stronger and more biocompatible is by reducing the size of individual crystals.

Research performed at MIT, and supported in part by the Office of Naval Research, has led to a technique for producing very pure, dense hydroxyapatite with crystals that are less than 100 nanometers across, similar to the size of hydroxyapatite crystals found in natural bone. This synthetic bone nanomaterial more closely matches the strength of natural bone and, when used to fill voids caused by injury or disease, allows bones to heal faster and more completely than when coarser hydroxyapatite is used.

In 2001, Angstrom Medica was founded to develop structural synthetic bone nanomaterials for medical use. Since then, the company has received several SBIR grants from the National Science Foundation and the National Institutes of Health and raised nearly $4 million in venture capital. In February 2005, Angstrom Medica received FDA approval to market its material for use as a bone void filler, making it the first engineered nanomaterial specifically cleared by FDA for medical use.

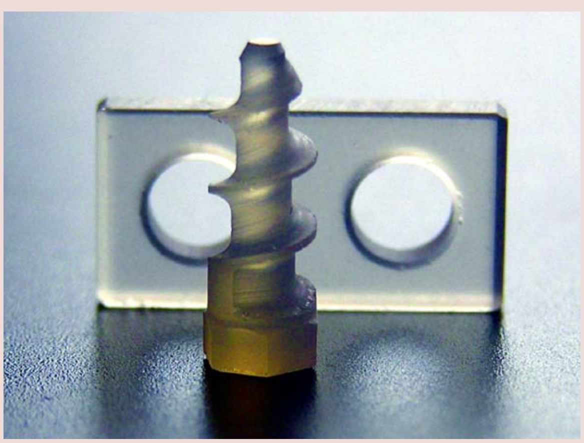
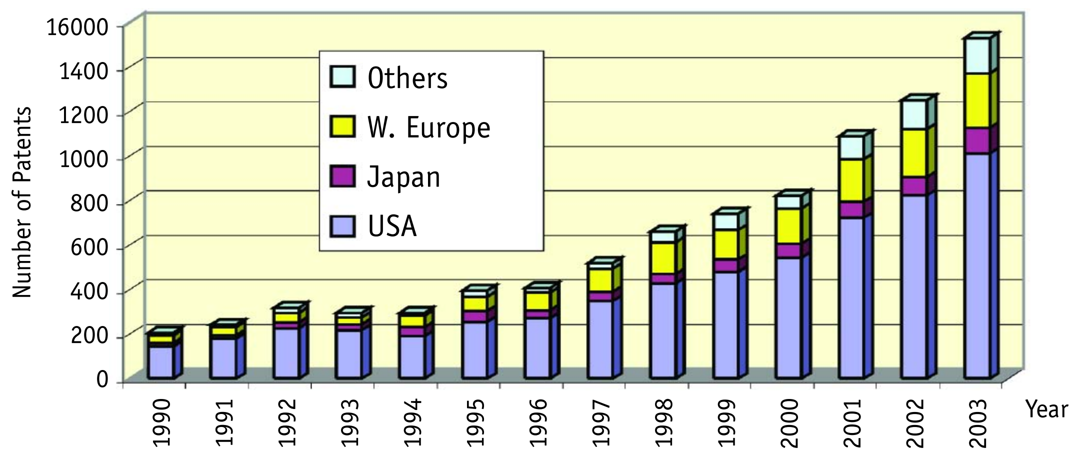


Photo courtesy of Angstrom Medica

Angstrom Medica plans to take advantage of the mechanical strength of its dense, nanocrystalline hydroxyapatite to make orthopedic pins and screws (see photo) for applications like anchoring repaired ligaments, fusing spinal vertebrae, or pinning broken bones. Unlike metal screws, nanocrystalline hydroxyapatite implants should integrate fully with the natural bone, leaving it as good as new. And, as a side benefit, they won't set off the metal detectors at the airport!

Figure 4.

Number of Nanotechnology-related Patents Identified by a Search of Titles and Claims of Patents in the USPTO Database



Source: Huang, Z., H. Chen, Z.-K. Chen, and M. Roco. 2004. *International Nanotechnology Development in 2003: Country, Institution, and Technology Field Analysis based on USPTO Patent Database. Journal of Nanoparticle Research,* 6:325-354.

3. Research Areas of Focus

The preceding sections indicate that the United States has a leadership position in terms of total investment, research publications, and patents related to nanotechnology. In addition to these overall measures, an accurate assessment of U.S. competitiveness requires the identification of countries that have adopted a strategy of making targeted investments, thereby positioning themselves to be leaders in a key industry or platform technology.

3A. Broad International Survey

In June 2004, NSF sponsored an international meeting on responsible nanotechnology research and development at which 25 countries and the European Union were represented. Attendees were asked to provide estimates of government funding and areas of particular research interest. Results of this survey indicated that some nations have broad research programs, like the United States, whereas others have opted to make targeted research investments. Table 3 shows the key areas in which various countries are focusing their nanotechnology efforts according to the survey responses. These countries appear to be investing especially in materials/manufacturing, biotechnology, and electronics.

3B. Asia

According to reports from the Asian Technology Information Program (ATIP), which tracks activity among Asian Pacific nations, China is especially strong in nanomaterials development. China's nanomaterials research focus, its low cost of doing business, its talented labor pool, and its potentially large domestic market, could provide incentive for further investment by foreign corporations seeking to capitalize on nanomaterials development (ATIP 2003; ATIP 2004). Other Asian countries are likewise focusing nanotechnology research efforts on industries in which they already hold a comparative advantage. According to ATIP, Korea is focusing on nanoelectronics with strong industry participation, Taiwan is targeting nanoelectronics, and Singapore has a particular emphasis on nanobiotechnology. Taiwan's National Science Council, which administers government funding for Taiwan's nanotechnology effort, plans to establish three technology research parks;

Table 3.

Focus Areas of Government Investments in Nanotechnology

Country	Materials/ Manufact.	Devices (including Electronics & Optics)	Energy & Environment	Biotech/ Medical	Instrument Development	Education
Argentina	X					
Australia	X	X	X	X		
Austria						
Belgium	X	X		X		
Brazil	X	X		X		
Taiwan	X	X		X		
Czech Republic	X	X		X		
European Union*	X	X	X	X	X	X
France	X			X		
Germany	X	X		X	X	
India	X	X		X	X	X
Ireland	X	X	X	X		
Israel	X			X		
Italy	X	X		X	X	
Japan	X	X	X	X	X	
Korea	X	X				
Mexico	X					
Netherlands	X	X		X	X	
New Zealand	X					
Romania	X			X		
South Africa	X		X	X		
Switzerland	X	X		X	X	
United Kingdom	X	X		X		
United States	X	X	X	X	X	X

Source: June 2004 International Dialogue on Responsible Research and Development of Nanotechnology, http://www.nanoandthepoor.org/international.php

Note *: While the EU as a whole is pursuing a broad program, individual EU countries (also shown here) have more targeted areas of research.

two would focus on nanoelectronics research. Though Japan has the strongest government support for nanotechnology research in the region, with broad scope, its recognized strength is in infrastructure and instrumentation. Japan also is focused particularly on the commercialization of nanotechnology; recently a number of new initiatives were launched to assist Japanese businesses and to develop strategies aimed at creating new nanotechnology-related industries. As part of a larger S&T strategy, the Japanese government has included the "development of new devices using nanotechnology" as one of five "leading projects" aimed at revitalizing the Japanese economy.

Table 4.
German Federal Funding by Priority Sector (in Millions of Euros)

	2002	2003	2004	2005
Nanoelectronics	19.9	25.0	44.7	46.2
Nanomaterials	19.2	20.3	32.7	38.1
Optical Science & Engineering	18.5	25.2	26.0	26.0
Microsystems Eng	7.0	7.0	9.4	10.2
Nanobiology	4.6	5.4	5.0	3.1
Communications	4.3	4.0	3.6	3.4
Other	0.4	1.3	2.4	2.2
Totals	**73.9**	**88.2**	**123.8**	**129.2**

Source: Roos, U. 2004. Germany's Nanotechnology Strategy. Berlin: British Embassy Berlin.

3C. Europe

In Europe, efforts exist at both at the national level, with a number of individual countries pursuing targeted research, and at the European Commission (EC) level, with a more broad-based program. For example the EC, under its 6th Framework Programme for Research and Technological Development, committed about 350 million euros for nanotechnology funding in 2003, which represents a third of the overall European expenditure. In a recent communication (Commission of the European Communities 2004), the European Commission endorsed a more coordinated approach to nanotechnology R&D across EU countries while acknowledging the multiple individual country programs that already exist. Germany's strategic investment can be traced to the early 1990s, when nanotechnology was identified as a field with substantial promise. As a result of sector forecasting studies commissioned by the government, over the years Germany has developed a strategy to prioritize the majority of its Federal funding toward nanoelectronics, nanoscale materials, and optical science and engineering (OECD 2002; see also Table 4). In addition to funding for R&D, German public funding is targeting infrastructure development, including research centers at various geographic locations. While the EU as a whole appears to be competing for broad nanotechnology research leadership, some of the targeted research being conducted in particular EU countries could also provide competitive advantages in particular technologies or industry sectors. NNAP recommends the close monitoring of the EU's coordinated effort and the nanotechnology initiatives of individual EU countries.

4. Areas of Opportunity

The preceding sections provide an overview of the research activity taking place around the world. To gain insight into the areas of opportunity, the NNAP members believe that it is also useful to assess the disciplines and industry sectors in which that activity is occurring.

4A. Publications

A review of the ISI database of research publications reveals that by far the largest number of articles related to nanotechnology published from 1981 to 2001 was on the subject of semiconductors (Zucker and Darby 2005). More recently, however, the number of articles related to nanotechnology and biology, medicine, chemistry, and multidisciplinary categories have grown substantially. According to Zucker and Darby, the number of publications about nanotechnology in relation to information technology also has grown.

Nano-light Bulb up to Ten Times More Efficient

Electricity accounts for about one-third of all energy consumed in the United States, and about one-fifth of all electric energy is used for lighting. But today's lighting is remarkably inefficient. Incandescent light bulbs only convert about 5% of the electricity they draw into visible light, wasting the rest as heat. Fluorescent lights, while better, are still only about 25% efficient. By comparison, a new home furnace is typically 80% efficient, and electric motors can reach 95% efficiency. Enormous opportunities exist, therefore, for saving energy through more efficient lighting.

Semiconductor-based light emitting diodes, or LEDs, can produce light much more efficiently. Early LEDs converted about 50% of electricity into light—10 times better than incandescent bulbs—but the light was a single color or wavelength and not suitable for general illumination. Developing cost-effective LEDs that produce white light—that is, light with many different wavelengths—has been a major challenge.

Researchers at the Department of Energy's Sandia National Laboratories have demonstrated a white light source with LED efficiency. The device uses a conventional LED emitting near-ultraviolet (410 nm) light to illuminate a range of nanosized semiconductor particles, or "quantum dots." The dots in turn emit light of many different colors. By mixing different sized quantum dots it is possible to create a device that produces light of any desired color, including white, as shown in the figure at the bottom left. Today, researchers are working to increase the lifetimes of these high-efficiency white-light LEDs to make them commercially viable.

The quantum leap forward in energy efficient lighting offered by white-light LEDs can substantially impact the nation's energy consumption. If enough existing lights were replaced by LEDs to cut in half the amount of electricity used for lighting, it would reduce energy use by the amount of energy produced by 50 nuclear power plants.

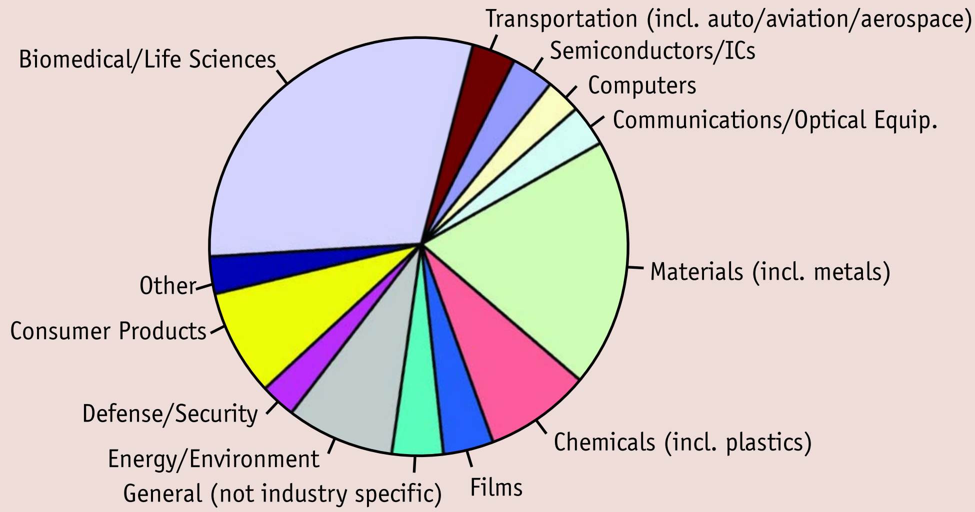
Courtesy of J. Simmons, Sandia National Laboratories

4B. Patents

Based on a search of the USPTO database (Huang et al. 2004), the total number of nanotechnology-related patents increased by 217% from 1996 to 2003, contrasting with an overall increase in patents during the same period of 57%. From 1976 to 2003, about 30% of nanotechnology patents were in the chemical/catalysts/pharmaceuticals industries, 15% were in the electronics industry, and about 10% were in the materials industry. From 1997 to 2003, the chemical/catalysts/pharmaceutical sectors were observed to have the most significant growth of nanotechnology patenting activity.

Figure 5.

Target Industries for Companies Involved in R&D, Manufacture, Sale, and Use of Nanotechnology in 2004 (Total Number of Companies = 599)



Source: EmTech Research 2005

In 2003, four of the five top assignees for nanotechnology patents in 2003 were electronics companies, although the field of chemistry (molecular biology and microbiology) had the greatest number of nanotechnology patents both in 2003 and in previous years. Other technological fields that experienced rapid growth in patenting activity in 2003 were those relating to transistors and other solid-state devices, semiconductor device manufacturing, optical waveguides, and electric lamp and discharge (Huang et al. 2004).

More recently, according to an EmTech Research (2005) survey of approximately 600 companies involved in R&D, manufacture, sale, or use of nanotechnology, the top three companies based on the number of nanotechnology-related patents issued were IBM, Intel, and L'Oreal. Other companies that ranked highly were large, technology-based businesses.

4C. Private Sector Activity

It seems reasonable to expect that the private sector would invest in nanotechnology R&D in those areas in which relatively near-term commercial applications are forthcoming. According to the EmTech Research survey of nanotechnology suppliers (EmTech Research 2005), the two largest target industries are biomedical/life sciences (including drug diagnosis, analysis, delivery, and discovery; medical tools and materials; and genomics and proteomics research) and materials (including metals). If chemicals, plastics and films are also counted as materials, this is the single largest area. Despite strong activity in biotechnology and materials, the diversity of business activity—ranging from energy to consumer products—is just as notable.

The companies included in Figure 5 range in size, with the largest number being either very small (<10 employees) or large (>1000 employees). Small companies depend on funding from both public and private sources, including venture capital. A separate survey by Lux Research estimates that the distribution of approximately $1.1 billion in venture capital funding for nanotechnology invested between 1998 and 2004 has been predominantly in electronics and semiconductors (41%) and nanobiotechnology (40%). Other sectors include specialty chemicals and nanomaterials (14%) and instrumentation (5%) (Lux Research Inc. 2004).

4D. TAG-Identified Areas of Opportunity

As part of its review, the NNAP surveyed its TAG members to gain insight into what areas of research those experts thought were likely to yield high impact advances. Below is a selection of the near-, mid-, and long-term areas in which TAG members felt nanotechnology would make a significant impact.

Near-term (1-5 years)

- Nanocomposites with greatly improved strength-to-weight ratio, toughness, and other characteristics
- Nanomembranes and filters for water purification, desalination, and other applications
- Improved catalysts with one or more orders of magnitude less precious metal
- Sensitive, selective, reliable solid-state chemical and biological sensors
- Point-of-care medical diagnostic devices
- Long-lasting rechargeable batteries

Mid-term (5-10 years)

- Targeted drug therapies
- Enhanced medical imaging
- High efficiency, cost effective solar cells
- Improved fuel cells
- Efficient technology for water-to-hydrogen conversion
- Carbon sequestration

Long-term (20+ years)

- Drug delivery through cell walls
- Molecular electronics
- All-optical information processing
- Neural prosthetics for treating paralysis, blindness, and other conditions
- Conversion of energy from thermal and chemical sources in the environment

The opportunities identified by the TAG suggest the group's enthusiasm about the potential for technologies that will improve the quality of life for all by providing clean water, affordable energy, and better healthcare.

5. Other Leadership Factors

An additional concern worth mentioning when considering U.S. leadership in nanotechnology, and one that PCAST has studied extensively over the past year, is the relative decline in the number of U.S. undergraduate and graduate degrees in science, technology, engineering and math (STEM) fields. PCAST's June 2004 Report, *Sustaining the Nation's Innovation Ecosystem: Maintaining the Strength of Our Science and Engineering Capabilities* (PCAST 2004) outlines data that raise serious concerns about the pace at which other countries, particularly industrialized Asian nations, are educating their citizens in STEM-related fields.

For example, in China over 39% of undergraduate degrees in 2001 were in engineering, compared with 5% in the United States. The numbers indicate that China is producing over three times as many trained engineers as the United States. Similarly, at the post-graduate level, the number of Asian citizens awarded degrees in natural science and engineering is significantly increasing, whereas the number of comparable U.S. degrees has declined in recent years. The increase in STEM talent, especially in Asia, coupled with significantly lower wage structures, threatens to lead to greater pressure, not only on U.S.-based high-tech manufacturing, but even on leading-edge R&D. While it is unclear how this shift will impact nanotechnology specifically, it is worth taking steps to ensure that the pool of U.S. nanotechnology researchers and technical workers remains strong. In fact, nanotechnology experts from the TAG who are currently engaged in university-based nanotechnology research particularly emphasized the need for high-quality U.S. students to carry out future nanotechnology research.

6. Conclusions

By reviewing the history of nanotechnology R&D funding, it is clear that the United States has been the leader in nanotechnology up to this point. Early recognition of the potential benefits of a coordinated nanotechnology R&D initiative, along with strong financial commitment across the Federal agencies, has enabled the United States to establish this leadership position. Measures of research output in the form of patents and publications further demonstrate U.S. leadership.

Despite the optimistic numbers, the trends in all categories—investment, publications, and patents—show steady erosion in the percentage lead of the United States over time. The Federal budget for nanotechnology R&D has begun to level, whereas the cumulative investment worldwide continues to grow. The NNAP notes that programmatic investments in a given area such as nanotechnology, whether by the United States or by other nations, cannot indefinitely continue their rapid increase. The significant increases in nanotechnology funding recently made by many other nations (and regions) may reflect efforts to catch-up to the United States. Nevertheless, the NNI should monitor worldwide investment and activities and remain cognizant of the U.S. competitive position; the NNAP certainly will continue to do so. And in any event, if the United States is to maintain its leadership in nanoscale science, engineering, and technology within current tight fiscal constraints, as well as to capitalize on the resulting innovations to achieve economic and other benefits, the NNI must continue to ensure that every dollar is well spent.

CHAPTER 2: Is This Money Well Spent and the Program Well Managed?

Whereas the preceding chapter scanned the global activity for the purposes of assessing the U.S. strength in nanotechnology R&D compared to other nations, this chapter looks inward to determine if the U.S. Federal investment of over $4 billion from 2001 through 2005 has been worthwhile, and whether the management of the NNI will lead to wise investments in the future.

1. NNI Strategic Plan and Management

1A. Vision, Goals & Funding

From the outset, the NNI has been a multidisciplinary program with the following key elements:

- Basic research aimed at fundamental knowledge creation
- Applied research targeted at applications in which nanotechnology is expected to have an impact
- Infrastructure in the form of facilities, equipment and instrumentation
- Education for students of all ages, teachers, and the public, including workforce training
- Societal implications, including environmental, health, economic, ethical, legal, and other issues

In December 2004, the NNI released an updated Strategic Plan (NSTC 2004) describing the vision and goals of the Initiative, and the strategies by which those goals are to be achieved. The vision as stated in the NNI Strategic Plan is "a future in which the ability to understand and control matter on the nanoscale leads to a revolution in technology and industry." The plan identifies four goals that must be accomplished in order to make the vision a reality:

1) Maintain a world-class research and development program aimed at realizing the full potential of nanotechnology
2) Facilitate transfer of new technologies into products for economic growth, jobs and other public benefit
3) Develop educational resources, a skilled workforce and the supporting infrastructure and tools to advance nanotechnology
4) Support responsible development of nanotechnology

These high-level goals directly or indirectly incorporate all of the original program elements listed above.

In addition, the Strategic Plan defines major subject areas of investment, or "Program Component Areas" (PCAs). According to the Plan, the PCAs relate to areas of investment that are critical to accomplishing the goals, cutting across the interests and needs of the participating agencies. The PCAs are:

1) Fundamental nanoscale phenomena and processes
2) Nanomaterials
3) Nanoscale devices and systems
4) Instrumentation research, metrology, and standards for nanotechnology
5) Nanomanufacturing
6) Major research facilities and instrumentation acquisition
7) Societal dimensions

Table 5.

Relationships Between Program Component Areas and the Overarching NNI Goals

Program Component Areas:	Goal 1: Maintain a world-class research and development program aimed at realizing the full potential of nanotechnology	Goal 2: Facilitate transfer of new technologies into products for economic growth, jobs, and other public benefit	Goal 3: Develop educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology	Goal 4: Support responsible development of nanotechnology
Fundamental Nanoscale Phenomena and Processes	critical to goal	secondary relevance	primary relevance	secondary relevance
Nanomaterials	critical to goal	secondary relevance	secondary relevance	secondary relevance
Nanoscale Devices and Systems	primary relevance	critical to goal	secondary relevance	secondary relevance
Instrumentation Research, Metrology, and Standards for Nanotechnology	secondary relevance	critical to goal	secondary relevance	secondary relevance
Nanomanufacturing	secondary relevance	critical to goal	primary relevance	primary relevance
Major Research Facilities and Instrumentation Acquisition	primary relevance	primary relevance	critical to goal	secondary relevance
Societal Dimensions	secondary relevance	secondary relevance	primary relevance	critical to goal

critical to goal
primary relevance
secondary relevance

Source: Nanoscale Science, Engineering, and Technology Subcommittee (NSET). 2004. *The National Nanotechnology Initiative: Strategic Plan.* Washington, D.C. December 2004.

The PCAs (which are defined in the Appendix) appear to provide a rational means by which the NNI investment can be categorized. Progress in each PCA is related to some degree to the achievement of the four goals as shown in Table 5. The fact that each PCA includes activities that take place within multiple agencies (as shown in Table 6) can and should result in discoveries by one agency that benefit others. Although the NNAP members believe that these PCAs can serve to focus and manage the overall investment appropriately, the Panel notes that this grouping is silent with respect to certain areas that are expected to play a significant role, in particular research at the interface of nanotechnology and biology (e.g., adaptation of biological processes for synthesis of nanostructured nonbiologic material) and research in advanced computational science for theoretical modeling and simulation of nanoscale materials and processes. Although these areas do not necessarily need to be considered as separate PCAs in their own right, the NNAP suggests that the NNI emphasize their importance within the existing PCA framework.

The NNI Strategic Plan states that "advancement may be expedited by grouping together work in a particular PCA that is taking place within multiple agencies." The NNAP agrees with this statement. To ensure that such advancement not only may but will be expedited, the NNAP recommends that the NSET Subcommittee perform a government-wide review of the work being performed within each PCA.

1B. Programmatic and Funding Balance

As previously noted, the NNI today involves over $1 billion annually in research funding that is distributed to many agencies. One of the challenges, and indeed a central reason for having a coordinated Federal research effort, is to ensure balance across the program. In the case of the NNI, balance does not refer simply to the distribution of investments among the PCAs. It also means balance between short- and long-term research, between research focused on fundamental discovery and on development of applications, and between R&D aimed primarily at advancing the technology versus research that is focused on understanding the environmental, health, and other societal implications of the new technology.

These distinctions illustrate the complexity and diversity of the NNI, qualities that offer many opportunities for investment and management. In the NNAP's view the NSET Subcommittee, in its coordination of the NNI, has been aggressive in grappling with these issues of balance. In the course of developing the Strategic Plan, the NSET Subcommittee has not only carried out internal planning activities, but also sought input from various stakeholders outside the Government through a variety of means, including open workshops.

The NNAP members believe that the NNI Strategic Plan demonstrates an appropriate approach to balancing the various aspects of the program. In particular, NNI agencies are moving responsibly to increase support for research into the environmental and health effects of nanomaterials relative to the investments in support of technological advancement. Likewise, the Strategic Plan also demonstrates an appreciation of the importance of actively transitioning research results into commercial applications.

Based on the NNI 2006 Supplement to the President's Budget (NSTC 2005a), the NNAP members believe the FY 2006 budget represents a reasonable distribution of funding among PCA categories and across participating research agencies, with the following caveats.

First, the NNAP is aware of concern among nanotechnology experts, including TAG members, about the level of participation by agencies that are expected to be substantially impacted by nanotechnology in the future, including the U.S. Department of Agriculture (USDA), the Department of Transportation (DOT), and the Department of Homeland Security (DHS). The NNAP members agree that nanotechnology research is relevant and important to the mission of these agencies, and encourage the NNI to promote awareness within the agencies of the initiative and of nanotechnology solutions to agency needs.

Second, the NNAP notes that the request for $11 million for USDA nanotechnology R&D in FY 2006 is a significant increase from $3 million to be spent in FY 2005. The NNAP members are pleased to learn that in addition to the Cooperative State Research, Education, and Extension Service of the USDA, the Forest Service has plans to develop R&D programs in nanotechnology.

Finally, whereas USDA appears to be growing its nanotechnology R&D program, DOT and DHS do not appear to be doing so. The NNAP is concerned that DHS, in particular—with its need for advanced technology solutions for sensors and materials—is investing only $1 million in FY 2005 and 2006. The NNAP encourages the NNI to reach out to agencies like DHS and DOT to further the NNI's goal of Government-wide coordination of nanotechnology R&D.

Table 6.

Relationships Between Program Component Areas and NNI Agency Missions, Interests, and Needs

● - Primary   □ - Secondary

Shading indicates agencies with budgets for nanotechnology R&D in FY 2005.

	Fundamental Nanoscale Phenomena and Processes	Nanomaterials	Nanoscale Devices and Systems	Instrumentation Research, Metrology, and Standards for Nanotechnology	Nanomanufacturing	Major Research Facilities and Instrumentation Acquisition	Societal Dimensions
CPSC	□	□	●	●			●
DHS	●		●	●		□	
DOC (BIS)	□	●	●	●	□		
DOC (NIST)	□	□	□	●	●	□	□
DOC (TA)	□	□	□	□	●	□	●
DOC (USPTO)		●	●	●	●		
DOD	□	●	●	□	●	□	□
DOE	●	●	□	□	□	●	□
DOJ			●				
DOS							●
DOT	●	□	●		●		
DOTreas		●	●				
EPA	□	●	●	□	●		●
HHS (FDA)		□	●				●
HHS (NIH)	●	□	●	□	□		□
HHS (NIOSH)		□			□		●
IC	□	●	●		□		□
ITC		●	●		●		●
NASA	□	●	●		□	□	
NRC			●				
NSF	●	●	□	□	●	●	●
USDA	□	●	●		□		●

Source: Nanoscale Science, Engineering, and Technology Subcommittee (NSET). 2004. *The National Nanotechnology Initiative: Strategic Plan.* Washington, D.C. December 2004.

Quantum Dots Glow Brightly to Assist Surgeons and Aid Medical Research

In cancer surgery, after doctors remove a tumor, they also remove nearby lymph nodes and examine them for signs of malignancy. The nodes connected most directly to the tumor-affected area are called "sentinel nodes," and if they are cancer-free it is a good indication that the disease has not spread. But it can be tricky to find the sentinel node for a particular tumor.

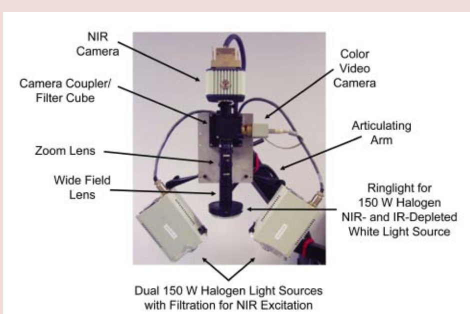
The current method for identifying sentinel lymph nodes is to inject a radioactive tracer and a visible dye near the tumor. A radiation detector locates the node and the dye provides confirmation during surgery. But pinpointing the radiation is not always accurate and the procedure requires considerable experience on the part of the doctor.

A new method has been developed by researchers at Harvard Medical School (funded by NIH) using semiconductor nanoparticles—or "quantum dots" (QDs)—which may make it much easier to find and remove sentinel lymph nodes. QDs are fluorescent, emitting light at a particular wavelength depending on their size. By tailoring the size of the QDs to approximately 15-20 nanometers, they emit light in the near infrared, a wavelength that passes harmlessly through the body, allowing the light to be detected using an infrared camera from outside the lymph node and even outside the body. The QD size must also be small enough to flow through the lymph system, but still be trapped by the nodes.

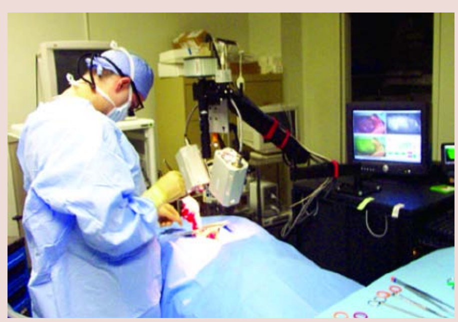
Not only do QDs eliminate the need for the use of radioactive materials, they are brighter and much longer lasting and can be sized for more efficient concentration by the lymph nodes, compared to currently available fluorescent dyes. In early studies on pigs, surgeons found the QDs make locating the sentinel lymph node much easier.

In other research at Emory University and the Georgia Institute of Technology, QDs have been attached to antibodies that bind specifically to prostate tumors in mice. These types of experiments are first steps in being able to image, identify, and ultimately treat cancers with a single agent.

The brightness and staying power of QDs also make them useful in research for imaging at the single molecule level and for tracking processes in animals or in cellular experiments over longer time periods.



QD imaging system, including visible and infrared light sources and visible and infrared cameras.



Use of the QD imaging system during animal surgery.

The photographs above are published with permission from: An Operational Near-Infrared Flourescence Imaging System Prototype for Large Animal Surgery, *Technology in Cancer Research and Treatment*, volume 2, page 558, 2003, Adenine Press, http://www.tcrt.org.

1C. Cautionary Thoughts

While the general approach to managing and funding the NNI in terms of goals and priorities seems sound, the NNAP would like to provide a few cautionary thoughts as the program moves forward:

- ***Flexibility.*** Because nanotechnology generally is in the early stages of development and deployment, it is appropriate to pursue many avenues of opportunity. At the same time, it is important to remain flexible and not to allow "institutions" to develop around specific research funding areas. Constraints on the levels of Federal funding can be expected to continue, and for the NNI to succeed priorities must be made and real opportunities pursued, even if that means scaling back or eliminating lesser priorities as the program moves forward. The overarching goal of scientific and engineering excellence is what must be remembered.

- ***Technology Transfer.*** Recognizing the increasing levels of activity by industries and by the States, the NNI should foster the greatest practical interaction among these stakeholders to stimulate innovation while protecting worker and public health and safety. While the Federal Government supports technology transfer, it must not at the same time lose sight of its primary responsibility: to advance the basic research surrounding nanotechnology.

- ***Societal Implications***. The NNI program is appropriately aggressive in its approach to understanding and addressing the societal implications and the environmental and health effects of nanotechnology. Because research into legal, ethical, economic, and other societal effects does not require costly instrumentation, the funding required will be smaller in comparison to components where such instrumentation is a necessity. Nevertheless, such societal research is critical. The NNAP members believe that the budget that is currently directed to societal issues—approximately 8%—appears appropriate.

- ***Leveraging.*** To maximize the value of NNI efforts aimed at each of the four goals, the NSET Subcommittee should pursue interactions and partnerships with other Government and non-government organizations with related or overlapping goals and interests. Such organizations include professional societies that have educational activities, interagency groups focused on environment or manufacturing, and agencies that have not been previously engaged, such as the Departments of Education and Labor.

1D. Grand Challenges

The concept of "grand challenges" as a means of guiding and focusing the Federal R&D program on a few targeted opportunities has been widely discussed. Opinions vary among the members of the TAG. Some members argue that nanotechnology is not yet mature enough for the program to be focused on just a few applications. Others believe that such focus is precisely what is necessary to ensure the most rapid progress toward opportunities that are within 5 to 10 years' reach. In its current form, the NNI Strategic Plan does not include specific grand challenges, but rather highlights areas of application that are supported by R&D in multiple PCAs.

After considering a number of grand challenge options, the NNAP members believe that nanotechnology is at too early a stage and too diverse to be pigeonholed into a few grand challenges. The role of the Federal Government today should be to invest broadly in the best ideas for advancing knowledge in support of the NNI vision. That being said, the NNAP encourages the individual agencies, within their own nanotechnology R&D programs, to identify performance-based targets. A good example of such an approach is the Cancer Nanotechnology Plan developed by the National Cancer Institute (NCI) (http://nano.cancer.gov/alliance_cancer_nanotechnology_plan.asp). This plan identifies key areas of opportunity in which nanotechnology can address the NCI's vision of eliminating suffering and death from cancer, as well as establishes milestones for measuring progress in each area.

1E. Management

The NNI Strategic Plan outlines the management structure under which the NNI operates. The various Government and non-government organizations with a role in the NNI, and their relationships, are shown in Figure 6. As described briefly in the introduction of this report, the NSET Subcommittee of the NSTC Committee on Technology is responsible for planning, coordinating, and implementing NNI programs and activities. Under the NSET Subcommittee, there are currently four interagency working groups focused on specific issues:

- ***Nanotechnology Environmental and Health Implications (NEHI) Working Group.*** This working group brings together representatives from agencies that support nanotechnology R&D and those with responsibility for regulating the manufacture, sale, or use of materials and other products based on nanotechnology. The purposes of the working group are to facilitate the exchange of information about the environmental and health implications of nanotechnology among research and regulatory agencies, and to identify research needed to support regulatory decision-making.

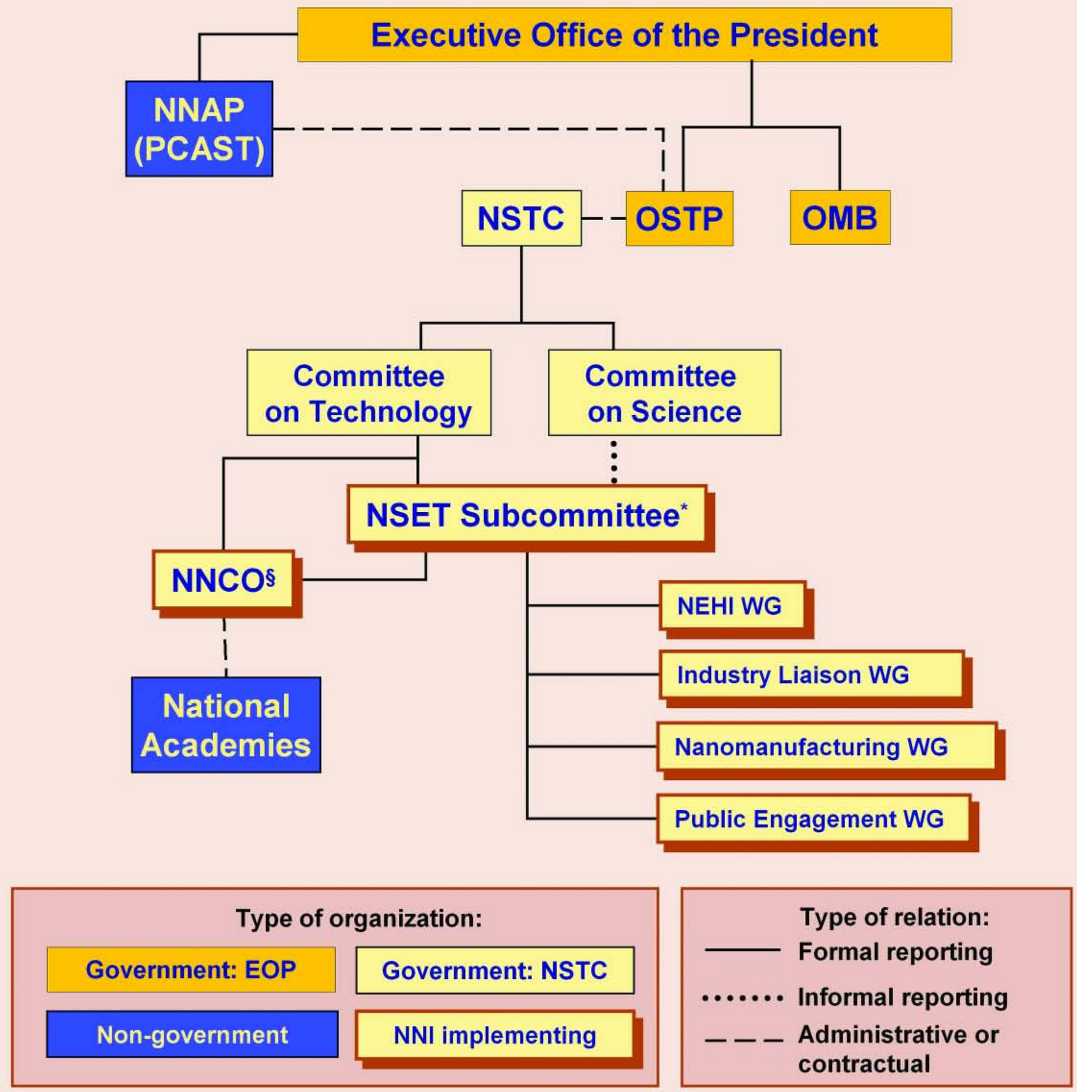
- ***Industry Liaison Working Group.*** This group works with industry representatives to establish channels through which the NNI provides the industry with information on its R&D activities, while the industry in turn offers suggestions to the NNI on how it might best support pre-competitive R&D that meets industry needs. Liaison activities already have been initiated with representatives from the semiconductor, chemical, aerospace, biotechnology, and automotive industries.

- ***Manufacturing Working Group.*** This group was established to coordinate activities related to reliable, scaled up manufacture of nanoscale materials, components, and products. Activities in this area currently are taking place primarily within NSF, the Department of Defense, and the National Institute of Standards and Technology (NIST).

- ***Nanotechnology Public Engagement Group.*** This group was recently established to develop approaches by which the NNI can communicate more effectively with the public. The NNI recognizes that most members of the general public know little about nanotechnology. As research results proceed to the marketplace, it is important that the public becomes more informed about what nanotechnology is—and what it is not.

National Nanotechnology Coordination Office. Due to the scope of the NNI and the interagency coordination activities, a National Nanotechnology Coordination Office (NNCO) was established in 2001 to provide technical and administrative support. The NNCO was made statutory by the Act. A particularly important function of the NNCO is as a conduit for information. It serves as the point of contact on Federal nanotechnology activities for both non-government parties and Government agencies that are not participating in the NNI. It also has responsibilities for public engagement and maintains the NNI website (www.nano.gov).

Figure 6.
Organizations with a Role in the NNI and Their Relationships



* NSET Subcommittee member departments and agencies:
CPSC; DHS; DOD; DOE; DOC (BIS, NIST, USPTO, TA); DOJ; DOS; DOT; DOTreas; EPA, HHS (FDA, NIH, NIOSH); ITC; ITIC; NASA; NRC; NSF; USDA; DOEd

§ NNCO provides support to, and works on behalf of, the NSET Subcommittee; the NNCO Director reports to the White House Co-Chair of the Committee on Technology.

Source: NSTC 2004

2. NNI Accomplishments

The United States has invested heavily in nanotechnology R&D over the past several years. It is valid to ask what we have obtained from our investment and what opportunities are ahead in the short and long term.

Accomplishments of the NNI include:

- *Advanced the foundational knowledge for control of matter at the nanoscale* with over 2500 active research projects in 2004 at more than 500 universities, Government labs, and other research institutions in all 50 States.

- *"Created an interdisciplinary nanotechnology community,"* according to the NSF Committee of Visitors, an outside review panel, in 2004.

- *Built up an infrastructure* of over 35 nanotechnology research centers, networks, and user facilities.

- *Promoted understanding of societal implications and applications* through the investment of approximately 8% of the NNI budget for research related primarily to the environment, health, safety, and other societal concerns. The amount is greater if the portion of research that is related to, but not primarily directed at, such concerns is also included.

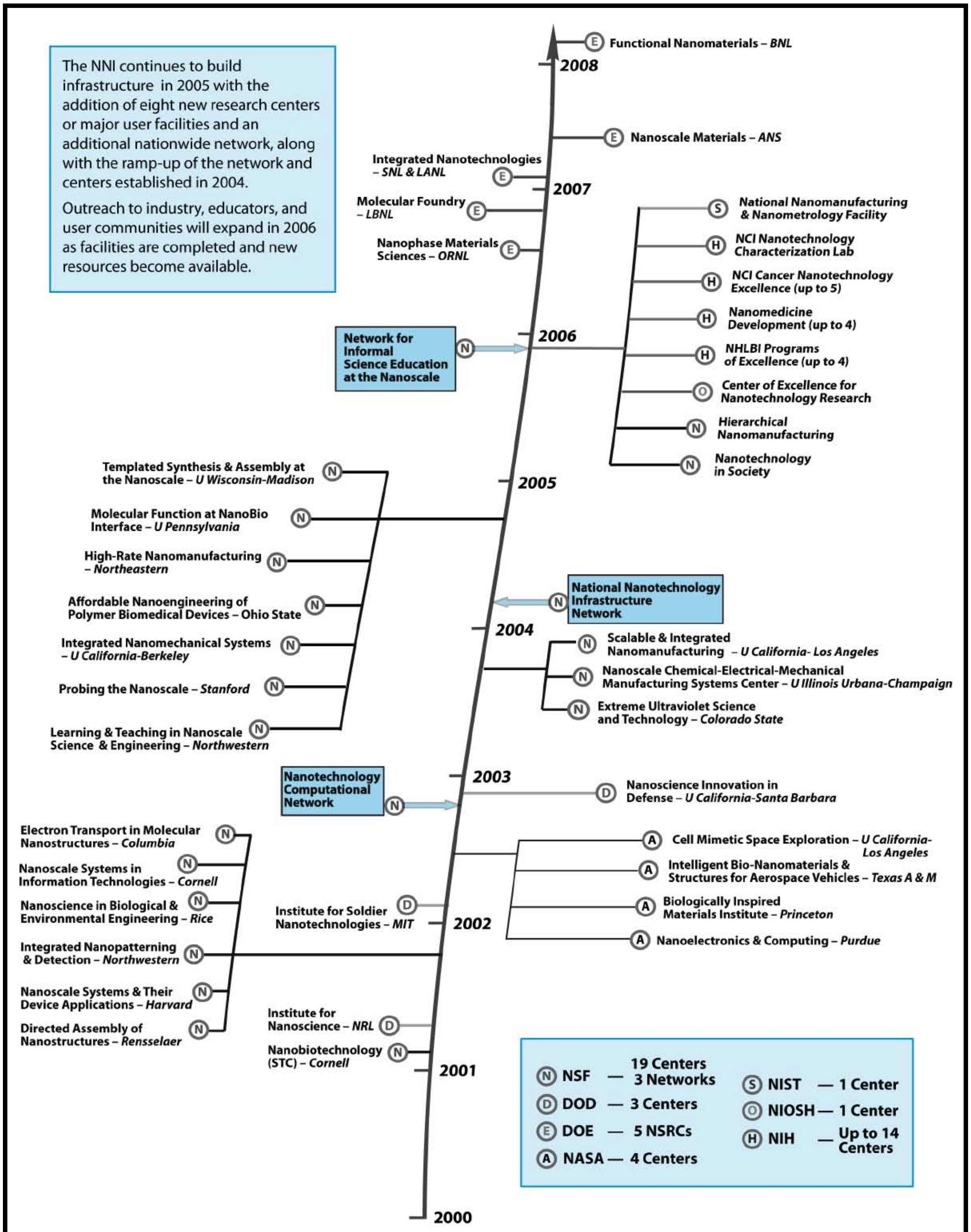
- *Established nanotechnology education programs* to reach students, not only in graduate schools but also in undergraduate, high school, and middle school. These programs involved over 10,000 graduate students and teachers in 2004 alone.

- *Supported public outreach* via a regularly updated website (www.nano.gov), which has become a major resource for researchers, educators, the press, and the public.

Over the past several years, a substantial commitment has been made toward the development of an infrastructure that includes both well-equipped user facilities designed to support widespread nanotechnology R&D and research centers that promote multidisciplinary approaches to focused areas. The NNAP notes that the user facilities and research centers provide opportunities for researchers from academia, industry, and Government laboratories to interact. This interaction will not only advance nanotechnology, but will also promote understanding among these communities and will enhance the transfer of technologies into commercial applications. Figure 7 shows the infrastructure that currently exists, is planned, or is under construction.

User Facilities. The NNI supports geographically distributed user facilities that provide researchers from academia, Government, and industry with broad access to expertise and advanced instrumentation for the fabrication, characterization, and modeling and simulation of nanoscale and nanostructured materials, devices, and systems. The Federal Government's investment in such expensive and advanced facilities and equipment enables researchers to share access to state-of-the-art tools that are otherwise too costly for individual researchers and many smaller institutions.

Figure 7.
NNI User Facilities and Research Centers



Source: NSTC 2005a

NNI user facilities include the NSF-funded National Nanotechnology Infrastructure Network (NNIN) and the Network for Computational Nanotechnology (NCN). The NNIN is a network of 13 partner universities that provides fabrication and instrumentation, equipment, and expertise. The 7-member NCN supports computational research and education, as well as Internet-accessible modeling and simulation applications and algorithms. Also nearing completion are five user facilities that will be collocated with large-scale facilities at Department of Energy (DOE) laboratories. These DOE Nanoscale Science Research Centers (NSRCs) will be available to all researchers on a merit-reviewed basis.

The NNAP views Federal investment in user facilities and computational capabilities that are made available to the broader U.S. research community to be wise investments. The NNI should seek to make the availability of such facilities and capabilities widely known and should ensure that such facilities are adequately maintained and staffed.

Research Centers. In addition to user facilities that serve the broader research community, the NNI is investing in a number of centers of excellence for multidisciplinary research in focused areas. To date, nearly two dozen such centers have been established (see Figure 7) and several more are to be awarded in 2005. Typically, each center, although led by a single university, involves researchers from multiple universities, with partners from industry, and sometimes from Federal laboratories as well. These centers provide valuable opportunities for researchers from various disciplines to work cooperatively on a focused research topic. In addition, by integrating researchers from academia, industry, and Government, the centers create a "hothouse" environment for ideas and innovation, as well as enhance the transition of basic research into commercial applications.

Members of the TAG differ on the optimum number of centers, and even on whether the research results at such centers are superior to the results that might otherwise be obtained by small research teams. Whereas the traditional model of investment in individual investigators is perhaps ideal for the support of curiosity (or knowledge-driven) research, the multidisciplinary, multi-investigator research center approach can lead to more rapid and systematic advancement.

Over the past decade or more, NSF has gradually increased the fraction of its agency-wide funding that is spent on centers vs. individual investigators or small research groups. Today, the agency invests roughly 20% in centers across the agency and within its NNI portfolio. The NNAP members believe that nanotechnology research is particularly multidisciplinary in nature and therefore may benefit more from investment in large centers than would many other technologies.

Although NSF, with its broad mission to advance knowledge, supports multidisciplinary centers, there may be an even more compelling case for mission-oriented NNI agencies such as the Department of Defense and the National Aeronautics and Space Administration (NASA) to consider a greater use of application-oriented research centers. Nevertheless, the establishment of centers across NNI should be carefully managed to avoid unnecessary duplication, and a balance should be maintained between research to be done in centers and that to be done by smaller research teams.

3. Conclusions

The NNAP members believe that the money invested by the Federal Government in nanotechnology has been wisely spent. Research advances are diverse and abundant, as disclosed in patents and publications and at numerous conferences and workshops. Despite a growing number of products that incorporate nanotechnology, in general, our fundamental understanding of nanoscale processes and behaviors is at a very early stage, and many applications will not be developed until well into the future. It is critical, therefore, that the Federal Government sustain its investment to ensure that the United States continues to be a leader in this emerging technology and reaps the resulting benefits.

CHAPTER 3: Are We Addressing Societal Concerns and Potential Risks?

The development and application of any new technology has societal effects. For example, advances in assistive technologies have enabled people with disabilities to participate in and contribute to their communities and workplaces in ways not previously possible. New technologies, however, can displace older ones, leading to a parallel shift in job opportunities; because new jobs potentially require different skills, such changes pose challenges for workforce training and the educational system. Unintended hazardous effects to the environment and public health also impact society. Finally, advances in technology often raise ethical questions, such as effects on personal privacy, medical ethics, and access to benefits.

The NNI has recognized the need to address each of these areas. Its efforts in this area are focused and coordinated under the Program Component Area on Societal Dimensions. In the FY 2006 budget, $82 million (8% of the total NNI budget) is requested within this PCA.

Details of the NNAP's evaluation of NNI activities to assess and address societal implications and risks are provided below.

1. Environmental, Health, and Safety

The possibility of unintended and undesirable consequences depends on two factors—hazard and exposure. Although researchers must be cognizant of potential hazards when working with new materials having unknown properties, these activities pose little risk to the public or the environment. As new technologies begin to find application in manufacturing processes and in commercial products, however, the potential risks beyond the lab environment must be understood. The NNAP notes that many technologies and products have associated risks that are successfully managed in order to gain their benefits—for example, gasoline, electricity, and medical X-rays.

The state of knowledge with respect to the actual risks of nanotechnology is incomplete. The NNI is funding research within several agencies to develop a broad understanding of the environmental and health effects of nanotechnology, in particular those nanomaterials that show the most promise for commercial use. The NNAP draws special attention to the ongoing research by the National Toxicology Program (an interagency program within the Department of Health and Human Services) to determine the toxicity of specific nanomaterials, and by the National Institute for Occupational Safety and Health to ensure worker safety. The NNAP members believe that the greatest likelihood of exposure to nanomaterials is during manufacture, and therefore agree with the prioritization of research on potential hazards from workplace exposure.

Of the total amount to be spent on researching the societal dimensions and impact of nanotechnology, the NNI plans to invest about half of the NNI budget allocated to this PCA for FY 2006, or 4% of the total budget, for R&D that is aimed primarily at understanding and addressing the potential risks posed by nanotechnology to health and the environment. This amount does not include substantial research that has a different primary focus but that nonetheless extends our knowledge of health and environmental effects of nanomaterials. Many projects funded by the National Institutes of Health fall into this category. For example, research on the use of nanoparticles for medical imaging would likely include a basic biocompatibility evaluation. In order to estimate the level of this secondary contribution, the NNAP has engaged the Science and Technology Policy Institute to conduct a survey of NIH-funded nanotechnology research projects.

The Federal Government has a role not only in funding research on environmental and health effects, but in setting appropriate standards, guidelines, and regulations to protect the public and the environment. The NNAP members are pleased to note the formal establishment of the Nanotechnology Environmental and Health Implications Working Group under the NSET Subcommittee. The working group has enabled exchange of information among research and regulatory agencies and has brought together a group that can both identify the research needed in support of regulatory decision-making and implement those priorities into the R&D program.

2. Education and Workforce Preparation

The widespread application of nanotechnology in coming decades means that the United States will need trained workers in many fields, including future researchers in every technical discipline, skilled technicians for jobs in various industries, and teachers at all levels. The pipeline that produces new researchers, technicians, and science teachers is fed by a stream of primary and secondary students. The exciting prospects offered by nanotechnology are attracting students of all ages to learn more.

The need to provide and support a range of education and training activities is an integral part of the NNI. The principal mechanism by which the NNI provides education is through research grants to university researchers. These grants support graduate and postdoctoral training at the cutting edge of nanoscale science, engineering, and technology R&D.

The National Science Foundation is the lead NNI agency for education-related programs beyond graduate training through research grants. The agency plans to invest about $28 million in FY 2006 for nanotechnology educational programs, including curriculum development in universities, the integration of research and education, distance learning, and courses and tutorials by professional societies. In addition, NSF-funded university-based centers are required to provide educational and outreach services to a broad audience, for example to teachers, the broader university community, or the public.

NSF is funding two activities focused specifically on nanotechnology education. First, the agency is funding the Nanotechnology Center for Learning and Teaching at Northwestern University to develop scientist-educators at the middle school, high school, and undergraduate levels. The center also will serve as a clearinghouse for curricular materials, instructional methods, and activities in nanotechnology education. More than 12,000 students and teachers are expected to be involved in NSF's nanotechnology education programs in FY 2006.

Second, in an effort to improve informal education—that is, learning outside of traditional classroom settings—NSF plans to award a grant in 2005 for the establishment of a network that links science museums and other informal science education organizations with nanoscale science and engineering research organizations. The goal of this network is to foster public awareness and understanding of, and engagement with, nanoscale science, engineering, and technology.

Taken together, these efforts are expected to help grow the workforce that will be needed to fill the anticipated demand. However, the NNAP members strongly believe that more needs to be done to bolster the number of STEM graduates and teachers and encourage the NNI to continue to build upon the existing programs.

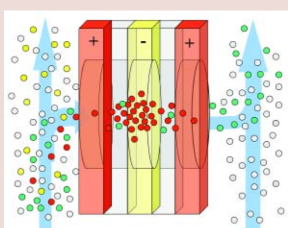
Nanoengineered Membranes Generate Clean Water, Save Energy, and Recycle Resources

Access to clean water is a public health issue of global proportions. In the developing world, 80% of all disease is water-related, and providing access to clean water is perhaps the single most important step to improving health. In some areas of developed countries like the Western United States, agricultural practices and other activities contaminate scarce water supplies. In California alone 4,000 water wells have been shut down due to nitrate contamination from farms, feedlots, and septic tanks. Reverse osmosis and other existing methods for producing clean water are too inefficient and costly for widespread use.

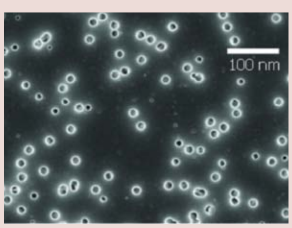
With support from the Department of Energy (DOE) through Laboratory Directed Research and Development funding, researchers at Lawrence Livermore National Laboratory (LLNL) are nanoengineering membrane systems using sophisticated computer modeling and advanced manufacturing technology. At the heart of the devices are electrically conductive membranes with tightly controlled pore sizes of just a few nanometers (see figures below).

By requiring less energy and by removing only targeted pollutants while leaving behind benign or beneficial compounds, nanoporous membrane systems reduce treatment costs by at least half compared to conventional technologies. LLNL is focusing on systems that remove nitrate, perchlorate, arsenic, and selenium, but the technology can be tailored to extract many other contaminants as well. Application of these new membrane technologies can add millions of acre-feet of low-cost water to the Western United States, where water shortages are becoming acute.

The same technology can be used to recycle resources and minimize waste in industrial processes. DOE estimates that replacing energy-inefficient processes used in industry today, including evaporation and distillation, with selective nanomembrane technologies could save one “quad” or 10^{15} BTUs, the equivalent of 1% of total U.S. energy use.



Schematic showing system with membranes of engineered nanopores (left) in electrically conductive materials. System selectively removes target species, allowing low-cost treatment of water containing toxic substances such as arsenic, or pathogens such as viruses.



Field emission scanning electron micrograph of a “smart” membrane with pores drilled to 10 nanometers in diameter—the size needed for nitrate ions to pass through. Nitrate is a major drinking water contaminant in agricultural areas.

Graphics courtesy of William Bourcier, LLNL

3. Ethical, Legal, and Other Societal Implications

Nanotechnology, like biotechnology, has the potential to require individuals, corporations, and governments to make decisions that have ethical, legal, and other societal implications. To address such issues, the NNI must actively engage scholars who represent disciplines that might not have been previously engaged in nanotechnology-related research. Moreover, these efforts should be integrated with conventional scientific and engineering research programs so that the people who develop nanotechnology are more fully aware of the societal implications of their work.

4. Public Engagement

In the United States, the public is generally very supportive of the Federal Government's investment in scientific research. In 2001, 81% of NSF survey respondents agreed with the statement "Even if it brings no immediate benefits, scientific research that advances the frontiers of knowledge is necessary and should be supported by the Federal Government" (NSB 2002). To sustain this support, the scientific community and the Federal agencies that fund scientific research must communicate more directly with the public, not through surrogates such as the entertainment industry.

Through the NNI website and through outreach activities at the NSF-funded centers and DOE user facilities, the NNI has established channels to communicate with members of various stakeholder groups, including the broader public. In addition, the NSET Subcommittee recently formed a subgroup focused on public engagement activities. The NNAP will follow the group's progress. For its own part the NNAP has held open meetings focusing on nanotechnology issues, which have provided the public with several opportunities to provide input.

5. Conclusions

The members of the NNAP compliment the NNI for recognizing, early on, that nanotechnology can have potentially broad societal implications—both positive and negative—and for taking steps to understand and, where necessary, to address these implications. The NNAP members believe that the level of funding for research related to societal aspects of nanotechnology is adequate at this time but that the NNI must ensure that the results are disseminated appropriately. In particular, information on environmental or health effects should be shared, especially with those who have regulatory responsibilities.

In addition, the NNAP cannot emphasize too strongly the importance of building the education infrastructure that will be needed to support the development and application of nanotechnology. Although not generally included as a "societal concern" when policymakers and others discuss nanotechnology, education should be an element of the discussion. The NNI has many excellent programs in this area, which should be held up as a model for other parts of the Federal R&D enterprise.

CHAPTER 4: How Can We Do Better?

Since its inception, the NNI has done a very good job of organizing the pertinent Federal Government agencies around the nanotechnology topic, establishing a robust national research infrastructure, and—through the NSET Subcommittee and the NNCO—coordinating and tracking programmatic activity. With 22 different participating agencies, each with its own distinct mission, these accomplishments deserve high praise.

The NNI's success has contributed to increased levels of public attention and to more acute international competition, and thus to new challenges. The NNI initially provided the means to spur and organize agency participation. Although it continues to serve this purpose by steadily engaging additional agencies, in the future NNI will increasingly be called upon to show progress and demonstrate real added value as well.

The NNAP members are impressed with the NNI program in general, and offer the following recommendations to further strengthen it in light of expected fiscal constraints. In addition to program management and funding issues, a number of other issues have emerged that warrant special consideration; these are outlined below along with the Panel's recommendations.

1. Program Investment Areas and Funding Levels

Upon reviewing the NNI Strategic Plan issued in December 2004, NNAP members believe that, overall, the Plan provides an appropriate framework under which to implement a broadly based Federal R&D program. The Program Component Areas are appropriate for the program at this time; however, the NNAP recommends that PCAs be assessed periodically to ensure that they adequately cover and describe the entire scope of the NNI R&D portfolio. To accelerate progress in the various PCAs, the NNAP further recommends that the NNI: (1) review activities Government-wide, and (2) identify one or more research targets within each PCA.

The Administration has made nanotechnology an R&D priority. The NNAP members believe that it is critical that the United States maintain a leadership position in nanotechnology and therefore recommend continued robust funding for the NNI.

Beyond this fundamental endorsement, the NNAP also recommends several additional items for NNI consideration, as indicated in the following sections.

2. Technology Transfer

The Federal Government is developing strategies to assist U.S. companies in accelerating the commercial development of nanotechnology, particularly in areas where commercial development complements U.S. Government requirements. Today, most nanotechnology products on the market are produced by large businesses and are evolutionary in nature—although with real performance improvements (e.g., powders for composites and coatings and nanostructured semiconductor devices). Although efforts are being made to accelerate the transition of nanotechnology into practical use, nanotechnology is still primarily "nanoscience"—that is, the technological developments are at a very early stage. The time to commercialization for many of the resulting technologies is estimated to be a decade or more. Startup companies are forming, but in most cases, their products are still under development.

Nanotechnology start-ups and other industry players commonly appeal for funding to transition research into the prototyping and product development stages. There is disagreement about the point in the development cycle at which the Government should hand off to the private sector. Although funding for nanotechnology product development may be appropriate to meet specific agency mission requirements (for instance biological sensors for the Departments of Homeland Security and Defense), there is an ongoing policy debate regarding whether the U.S. Government should fund commercial product development that is not directly tied to Government requirements. Many would argue that if a yet-to-be developed product had true commercial appeal, commercial investors would step up to fund this transition. Others argue that, particularly for novel technologies like nanotechnology, the Federal Government has an interest in helping to accelerate commercial development in order to ensure U.S. economic leadership in this area.

PCAST has studied the issue of technology transfer extensively over the past several years, and takes the position that while the Federal Government can take steps to help promote technology transfer, the primary responsibility for funding product manufacturing should be left to the private sector with appropriate assistance from State and local governments. Indeed, private networks to help manufacture new nanotechnology products are forming (see, for example, the MEMS and Nanotechnology Exchange at: http://www.mems-exchange.org). Furthermore, States are investing heavily in nanotechnology as part of their respective economic development strategies.

2A. Federal Government Role

It is the opinion of the NNAP that the first and most important responsibility of the Federal Government with respect to nanotechnology is to fund the basic research that will form the intellectual foundation for eventual commercial development and exploitation. In other words, the United States needs great science and great engineering. The Federal Government has a rich history of funding basic research, which has resulted in discoveries that underlie many entrepreneurial and economic success stories. It is critical that the United States continue this tradition in the area of nanotechnology. While the intense international competitive pressure makes it tempting to "rush to market," the leadership position of the United States in nanotechnology depends heavily on the intellectual property amassed through a commitment to building and supporting a base of fundamental knowledge.

The NNAP members strongly believe that, at this stage in the development of nanotechnology research, the best way to ensure U.S. economic leadership in nanotechnology is for the Federal Government to continue focusing on and funding basic nanotechnology research, including support for advanced instrumentation and infrastructure. This is not to say that the Federal Government should ignore opportunities for research that is to be transitioned for commercial gain. Existing programs can provide assistance in this area. The Small Business Innovation Research (SBIR) and the Small Business Technology Transfer (STTR) programs are available at U.S. Government research agencies to fund the critical early stages of technology development, including nanotechnology. According to the NNI FY 2006 Supplement to the President's Budget (NSTC 2005a), several agencies within NNI specify nanotechnology as a focus area in their SBIR solicitations. These grants are often highly leveraged by the recipients, serving to catalyze additional State and private funding. Government agencies pursuing nanotechnology research should encourage promising nanotechnology technology development projects through established programs, such as SBIR and STTR.

In the past the Federal Government has played a vital role in the development of new technologies by being an "early adopter" customer. That is, the Government's willingness to pay a premium price up front for leading-edge technology that offers improved performance, such as advanced semiconductor electronics in the 1960s, eventually led to the development of affordable, reliable consumer products that formed the basis of an important consumer industry. The Federal Government, through its mission agencies, should look for opportunities to develop and use, in support of those missions, products that arise from Federal nanotechnology research.

2B. Federal—Industry Interaction

In addition to utilizing programs such as SBIR and STTR, the NNAP members believe the NNI can and should interact with industry to ensure communication of private sector nanotechnology research needs, as well as to provide industry insight into the latest Federal nanotechnology research breakthroughs. The NNAP endorses the approach the NNI has taken in establishing liaison activities with various industry sectors and encourages expanding such activities to other sectors where appropriate.

2C. Federal—State Interaction

Although the Federal Government's efforts have been focused appropriately on nanotechnology research, it is noteworthy that many States have recognized the economic benefits that might be reaped by investing in coordinated regional initiatives (e.g., business incubators, research centers, or research consortia) to capitalize on the results of the Federally funded nanotechnology research.

The NNAP's examinations of the nature of successful innovation have demonstrated that State governments and local and regional organizations can and do play a vital role. State and local governments can play a crucial role in helping to promote commercialization of Federal nanotechnology research, and the NNI should aggressively extend its outreach and planning activities to the States.

The NNAP members applaud the NSET Subcommittee and the Department of Commerce for sponsoring a workshop on regional, State, and local initiatives in nanotechnology in the Fall of 2003. The NNAP recommends continued interaction with States through additional conferences, workshops, and other communication to assist their progress, to ensure they are fully aware of available NNI resources such as user facilities, and to seek additional mechanisms by which technology transfer may take place.

3. Program Management

The NNAP offers a number of program management observations and recommendations:

3A. NSET/NNCO Structure and Functions

The NNAP endorses the current NNI program management structure. The NNAP finds that the NSET Subcommittee is engaged and is committed to fulfilling its obligations under the Act. The NNAP also finds that the NNCO provides appropriate support to the NSET Subcommittee in the administrative functioning of the NNI program. Communication among those responsible for coordination of the NNI occurs via regular meetings of the NSET Subcommittee. The active involvement of OSTP and OMB further helps to ensure that NNI addresses Government-wide priorities. Formation of subgroups to address specific topics (i.e., environmental and health issues, industry liaison, nanomanufacturing, and public engagement) has facilitated important activities in those areas. This type of focused interagency exchange is helpful in addressing some of the more pertinent issues relating to nanotechnology R&D, and should be continued.

As nanotechnology becomes integrated in more Federal agencies, it will be even more important for the NSET Subcommittee to retain the flexibility needed to add, delete, or alter the subjects or composition of these interagency working groups to ensure that the NNI continues to focus on the most salient issues and that the growth at the Subcommittee level does not impede the accomplishment of interagency coordination. The NSET Subcommittee has been successful in addressing specific areas through the formation of topical subgroups. Given the growing level of activities taking place outside the United States, the Subcommittee should consider establishing a group to track international activities and to identify opportunities for collaboration, for example in the area of environmental and health effects.

3B. Infrastructure and Knowledge Management

The NNI has made great strides in its effort to establish a geographically distributed infrastructure of instrumentation, expertise, and facilities. In addition, the investment in a diverse portfolio of research has resulted in greater knowledge of nanoscale processes and phenomena and of ways in which that knowledge might be put to practical use. Much of that knowledge is represented in publications, patent applications, and other documents. To maximize the likelihood that good ideas for nanotechnology R&D are acted upon, the NNI should consider means by which it can collect and share information about instrumentation and facilities that are available to the broad research community. More challenging, but also valuable, would be for the NNI to develop a system for tracking and making available information about published results and technologies that are available for commercialization.

3C. Streamlined NNI Grant Reporting

At the researcher level, the NNAP has detected an issue that the NSET Subcommittee should address. Many of the key principal investigators (PIs), whether part of a center or not, have grants from many agencies in support of their work. Each agency requires, in many cases, individual reports. The NSET Subcommittee should look for ways to streamline the reporting requirements on individual PIs so that maximum reporting efficiency is achieved.

3D. Coordination with Other Interagency Groups

In addition to addressing specific issues through formation of subgroups, the NSET Subcommittee should proactively engage other interagency groups that have overlapping interests and activities. An example of an interagency group that has overlap is the NSTC Interagency Working Group on Manufacturing Research and Development, which has identified nanomanufacturing as an area for focused manufacturing R&D. Activities by such groups clearly need to be coordinated with the NNI. Similarly, the NSET Subcommittee's NEHI Working Group should be engaged at the appropriate level with the NSTC Subcommittee on Health and the Environment.

3E. Involvement by Other Agencies

The NNAP recommends that the NNI take steps to involve other agencies in NNI coordination activities where appropriate. In particular, as the NNI activities around education and workforce development continue to grow, it will be critical to engage further the Departments of Education and Labor. The Department of Education has programs specifically aimed at improving STEM education that could benefit from NNI-funded research on education and development of educational materials. Similarly, the Department of Labor has workforce preparedness programs that would benefit from better understanding of nanotechnology-enabled industries and their needs.

4. Societal Implications

An important aspect of exploring any new technology is to consider the impacts, both positive and negative, on society. Since its inception, the NNI has been considering the societal implications associated with nanotechnology, including implications for the environment, health, the workforce, the law, and ethics. Support for the continued advancement of nanotechnology research, and eventual integration of nanotechnology into consumer products and useful applications, will depend heavily on the public's acceptance of nanotechnology. Governments around the world must take a proactive stance to ensure that environmental, health, and safety concerns are addressed as nanotechnology research and development moves forward in order to assure the public that nanotechnology products will be safe.

The NNI's role in addressing societal concerns is primarily one of coordination and communication. The program, through the NSET Subcommittee, should coordinate with the agencies that have the responsibility and authority for protecting the environment and the public. The NNAP members believe that, at this time, the emphasis should be placed especially on ensuring workplace safety where nanomaterials are manufactured or used, because such places are where the greatest likelihood of exposure exists. Moreover, because such concerns reach beyond borders, the NNI should also coordinate with agencies and organizations that are responsible for representing the United States in international forums, including the State Department, OSTP, and others.

In addition to its coordinating role, the NNI, through the NNCO, should vigorously communicate with various stakeholders and the public about the Government's efforts to address societal concerns. Without such communication, public trust may dissipate and concerns based on information from other sources, including the entertainment industry, may become dominant.

Finally, there is an expanding need for activities that are focused on ethical, legal, and other societal implications beyond just the environmental and health effects. The NNI should participate in appropriate dialogues with stakeholders beyond the research and technical communities.

5. Education/Workforce Preparation

For nanotechnology to continue developing into more than just a "research project," the education and workforce preparation infrastructure must be improved. Through grants to universities, undergraduate and graduate students receive the education and training that will allow them to become the next generation of researchers. However, to ensure that adequate numbers of skilled technicians and STEM educators are available for jobs in both nanotechnology-related industry and education, the NNAP reiterates its suggestion that the NNI interact more strongly with the Departments of Education and Labor. High-quality STEM education at all levels, beginning with the primary grades, is critical to remaining competitive in nanotechnology research and in related industries. Regarding continuing education and professional development, the NNI should expand its interaction with professional societies that have continuing education as a mission in order to promote the development of training opportunities for mid-career professionals.

6. NNAP Report Schedule

Based on the rapid pace of research and the high degree of uncertainty regarding commercial outcomes, regulations, and societal impacts, the NNAP members believe the schedule for updating the NNI Strategic Plan every three years is appropriate. The NNAP had the opportunity to participate in the NSET Subcommittee planning process and looks forward to a continued close relationship. In order to provide timely input to the NSET Subcommittee, the NNAP recommends that the schedule for its review be adjusted to not less frequently than every three years to parallel the schedule for updating the NNI Strategic Plan, with an offset of one year to allow the Plan to incorporate NNAP recommendations. That is, the next NNAP review should be in two years (one year before the next scheduled update of the NNI Strategic Plan), and thereafter, reviews should be made every three years.

CHAPTER 5: Concluding Remarks and the NNAP's Future Areas of Focus

In summary, the NNAP supports the NNI's high-level vision and goals, and the investment strategy by which those are to be achieved. The Panel members feels that the program can be strengthened by extending its interaction with industry, State and regional economic developers, and internationally, where appropriate.

This report of the NNAP has focused on the U.S. competitive position. To date, the NNI has helped to bring the United States to a global leadership position in nanotechnology, but that status is being aggressively challenged by other nations, and the United States cannot rest on its laurels. In support of continued monitoring in this area, the NNAP has chartered a study by STPI to develop the means by which investments by various nations may be normalized to allow for more accurate and thus informative “apples to apples” comparisons.

The NNAP will, as part of the Act's mandate, report periodically with a basic program assessment. Beyond this, the NNAP also intends to explore other areas of concern in greater depth. As this report is being finalized, and pending other developments that must be addressed, attention will next be focused among the following issues:

- Commercialization and technology transfer;
- Education and training, including whether the U.S. will have an adequate workforce to take advantage of the discoveries and innovations occurring in nanotechnology;
- Environmental health and safety, including Federal programs in environmental, health, and safety assessment and interagency and international coordination;
- The linkage between the Federal expenditures on Nanotechnology R&D and the Nation's national security and economic growth objectives; and
- Continued monitoring and updating of the United States’ competitive posture.

APPENDIX - NNI Program Component Areas

The following text is excerpted from the NNI supplement to the President's FY 2006 Budget.

Program Component Areas (PCAs) are defined by the Act as major subject areas under which related NNI projects and activities are grouped. Whereas the NNI goals embody the vision of the initiative and provide structure for its strategy and plans, the PCAs relate to areas of investment that are critical to accomplishing those goals. These areas cut across the interests and needs of the participating agencies and indicate where advancement may be expedited through coordination of work by multiple agencies. The PCAs are intended to provide a means by which the NSET Subcommittee, as the interagency coordinating body; the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB); Congress; and others may be informed of and direct the relative investment in these key areas. The PCAs also provide a structure by which the agencies funding R&D can better direct and coordinate their activities. Agency plans for each PCA will be included in the annual NNI supplement to the President's budget, commencing with this report for 2006. The seven PCAs are defined as follows:

1. Fundamental Nanoscale Phenomena and Processes

Discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biological, and engineering sciences that occur at the nanoscale. Elucidation of scientific and engineering principles related to nanoscale structures, processes, and mechanisms.

2. Nanomaterials

Research aimed at discovery of novel nanoscale and nanostructured materials and at a comprehensive understanding of the properties of nanomaterials (ranging across length scales, and including interface interactions). R&D leading to the ability to design and synthesize, in a controlled manner, nanostructured materials with targeted properties.

3. Nanoscale Devices and Systems

R&D that applies the principles of nanoscale science and engineering to create novel, or to improve existing, devices and systems. Includes the incorporation of nanoscale or nanostructured materials to achieve improved performance or new functionality. To meet this definition, the enabling science and technology must be at the nanoscale, but the systems and devices themselves are not restricted to that size.

4. Instrumentation Research, Metrology, and Standards for Nanotechnology

R&D pertaining to the tools needed to advance nanotechnology research and commercialization, including next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems. Also includes R&D and other activities related to development of standards, including standards for nomenclature, materials, characterization and testing, and manufacture.

5. Nanomanufacturing

R&D aimed at enabling scaled-up, reliable, cost-effective manufacturing of nanoscale materials, structures, devices, and systems. Includes R&D and integration of ultra-miniaturized top-down processes and increasingly complex bottom-up or self-assembly processes.

6. Major Research Facilities and Instrumentation Acquisition

Establishment of user facilities, acquisition of major instrumentation, and other activities that develop, support, or enhance the Nation's scientific infrastructure for the conduct of nanoscale science, engineering, and technology research and development. Includes ongoing operation of user facilities and networks.

7. Societal Dimensions

Various research and other activities that address the broad implications of nanotechnology to society, including benefits and risks, such as:

- Research directed at environmental, health, and safety implications of nanotechnology development and risk assessment of such impacts**
- Education
- Research on the ethical, legal, and societal implications of nanotechnology.

**Environmental, health, and safety (EHS) research and development (R&D) on the EHS implications of nanotechnology includes efforts whose primary purpose is to understand and address potential risks to health and to the environment posed by this technology. Potential risks encompass those resulting from human, animal, or environmental exposure to nanoproducts – here defined as engineered nanoscale materials, nanostructured materials, or nanotechnology-based devices, and their byproducts.

GLOSSARY

ATIP	Asian Technology Information Program
BIS	Bureau of Industry and Security
CPSC	Consumer Product Safety Commission
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOJ	Department of Justice
DOS	Department of State
DOT	Department of Transportation
DOTreas	Department of Treasury
EC	European Commission
EHS	Environmental health and safety
EPA	Environmental Protection Agency
EU	European Union
FDA	Food and Drug Administration
FFRDC	Federally Funded Research and Development Center
FY	Fiscal Year
ISI	Institute for Scientific Information
ITC	International Trade Commission
ITIC	Intelligence Technology Innovation Center
MEMS	Microelectromechanical Systems
NASA	National Aeronautics and Space Administration
NCI	National Cancer Institute
NCN	Network for Computational Nanotechnology
NEHI	Nanotechnology Environment and Health Implications (NSET working group)

NIH	National Institutes of Health
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NNAP	National Nanotechnology Advisory Panel
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NNIN	National Nanotechnology Infrastructure Network
NRC	National Research Council (National Academies)
NRC	Nuclear Regulatory Commission
NSET	Nanoscale Science, Engineering, and Technology Subcommittee (NSTC)
NSF	National Science Foundation
NSRC	Nanoscale Science Research Center
NSTC	National Science and Technology Council
ONAMI	Oregon Nanoscience and Microtechnologies Institute
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PCA	Program Component Area
PCAST	President's Council of Advisors on Science and Technology
PI	Principal Investigator
SBIR	Small Business Innovation Research Program
STEM	Science, technology, engineering, and math
STPI	Science and Technology Policy Institute
STTR	Small Business Technology Transfer Program
TA	Technology Administration
TAG	Technical Advisory Group
USPTO	United States Patent and Trademark Office
USDA	United States Department of Agriculture

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