THE NATIONAL NANOTECHNOLOGY INITIATIVE

Strategic Plan

December 2007

Prepared by
Subcommittee on Nanoscale Science, Engineering, and Technology
Committee on Technology
National Science and Technology Council

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The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development enterprise. A primary objective of the NSTC is establishing clear national goals for Federal science and technology investments. The NSTC prepares research and development strategies that are coordinated across Federal agencies to form investment packages aimed at accomplishing multiple national goals. The work of the NSTC is organized under four committees: Science, Technology, Environment and Natural Resources, and Homeland and National Security. Each of these committees oversees subcommittees and working groups focused on different aspects of science and technology. More information is available at www.ostp.gov/nstc.

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The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee is the interagency body responsible for coordination of the National Nanotechnology Initiative (NNI). It is a subcommittee of the NSTC's Committee on Technology. The National Nanotechnology Coordination Office provides technical and administrative support to the NSET Subcommittee and assists the subcommittee in preparing planning, budget, and assessment documents for the NNI. More information is available at www.nano.gov.

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About this Document

This document is the strategic plan for the NNI. It describes the NNI vision and goals and the strategies by which those goals are to be achieved. The plan includes a description of the NNI investment strategy and the program component areas called for by the 21st Century Nanotechnology Research and Development Act of 2003. This plan updates and replaces the NNI Strategic Plan of December 2004.

Cover

Central square image: A scanning tunneling microscope image showing closed chains of C_{60} molecules, represented by the light-colored lines, around islands of silver on a flat, clean surface of silver. A scanning tunneling microscope maps the topography of a surface, and in many experiments, single atoms and molecules can be resolved. For example, the enlarged view shown as a circular blow-up above the upper left corner of the central square image reveals individual C_{60} molecules within the chain. These images were used to study how silver islands and C_{60} chains change over time. Image from: Metal-molecule interface fluctuations, C. G. Tao et al., *Nano Letters* **7**, 1495 (2007). Copyright 2007, American Chemical Society. Reprinted here with permission. Images provided by C. G. Tao and E. D. Williams, University of Maryland. Background image: Idealized representation of the STM image, superimposed on an idealized representation of a flat silver surface. Cover design by Nicolle Rager Fuller, Sayo Arts, Washington, DC.

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NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
Washington, D.C. 20502

December 20, 2007

Dear Colleagues:

Advances in nanotechnology—the ability to see, measure, and control matter at the scale of atoms and molecules—are leading to novel applications in areas ranging from aerospace to agriculture. The broad spectrum of practical and beneficial uses of nanotechnology is built on a foundation of basic research in materials, chemistry, biology, physics, and engineering supported by the National Nanotechnology Initiative (NNI).

Now in its eighth year, the NNI expedites the responsible discovery and development of nanotechnology with the ultimate goal of improving the Nation's economy and the quality of life for all citizens. Today, the NNI involves 25 Federal agencies with diverse missions and expertise. The NNI agencies coordinate their nanotechnology-related activities in order to leverage their investments and facilitate progress in areas of individual and joint interest. The inherently multidisciplinary nature of nanotechnology is especially well served by such a multi-agency approach.

This NNI Strategic Plan outlines the goals and priorities of the initiative and describes approaches for achieving them. The plan supports leading edge research, sustains the extensive infrastructure of facilities, seeks to facilitate technology transfer, and addresses environmental, health, and societal concerns.

This document updates the first NNI Strategic Plan issued in 2004. It reflects progress in the science and in the management and coordination of such a broad effort that involves not only multiple agencies, but also industry, academia, and the public. In particular, the plan benefited from reviews of the NNI by the President's Council of Advisors on Science and Technology (PCAST) and the National Research Council. These outside reviews have provided valuable and complementary recommendations that have strengthened the initiative.

With the implementation of this plan, the United States will remain at the forefront of nanoscale science and engineering and a leader in achieving the economic benefits offered by the emerging technology.

Sincerely,

John H. Marburger, III
Director

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Vision and Goals

The vision of the National Nanotechnology Initiative (NNI) is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society.

The National Nanotechnology Initiative expedites the discovery, development, and deployment of nanoscale science and technology to serve the public good, through a program of coordinated research and development aligned with the missions of the participating agencies. In order to realize the NNI vision, the participating agencies are working collectively toward the following four goals:

Goal 1: Advance a world-class nanotechnology research and development program.

The NNI ensures United States leadership in nanotechnology research and development by stimulating discovery and innovation. This program expands the boundaries of knowledge and develops technologies through a comprehensive program of research and development. The NNI agencies invest at the frontiers and intersections of many disciplines, including biology, chemistry, engineering, materials science, and physics. The interest in nanotechnology arises from its potential to significantly impact numerous fields, including aerospace, agriculture, energy, the environment, healthcare, information technology, homeland security, national defense, and transportation systems.

Goal 2: Foster the transfer of new technologies into products for commercial and public benefit.

Nanotechnology contributes to United States competitiveness by improving existing products and processes and by creating new ones. The NNI implements strategies that maximize the economic benefits of its investments in nanotechnology, based on understanding the fundamental science and responsibly translating this knowledge into practical applications.

Goal 3: Develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology.

A skilled science and engineering workforce, leading-edge instrumentation, and state-of-the-art facilities are essential to advancing nanotechnology research and development. Educational programs and resources are required to produce the next generation of nanotechnologists, that is, the researchers, inventors, engineers, and technicians who drive discovery, innovation, industry, and manufacturing.

Goal 4: Support responsible development of nanotechnology.

The NNI aims to maximize the benefits of nanotechnology and at the same time to develop an understanding of potential risks and to develop the means to manage them. Specifically, the NNI pursues a program of research, education, and communication focused on environmental, health, safety, and broader societal dimensions of nanotechnology development.

NNI Participating Agencies (Fiscal Year 2008)

Federal Agencies with Budgets Dedicated to Nanotechnology Research and Development

Cooperative State Research, Education, and Extension Service (CSREES, U.S. Department of Agriculture)
Department of Defense (DOD)
Department of Energy (DOE)
Department of Homeland Security (DHS)
Department of Justice (DOJ)
Department of Transportation (DOT)
Environmental Protection Agency (EPA)
Forest Service (FS, U.S. Department of Agriculture)
National Aeronautics and Space Administration (NASA)
National Institute for Occupational Safety and Health (NIOSH, Department of Health and Human Services)
National Institute of Standards and Technology (NIST, Department of Commerce)
National Institutes of Health (NIH, Department of Health and Human Services)
National Science Foundation (NSF)

Other Participating Agencies

Bureau of Industry and Security (BIS, Department of Commerce)
Consumer Product Safety Commission (CPSC)
Department of Education (DOEd)
Department of Labor (DOL)
Department of State (DOS)
Department of the Treasury (DOTreas)
Food and Drug Administration (FDA, Department of Health and Human Services)
Intelligence Advanced Research Projects Activity (IARPA, representing the intelligence community)
International Trade Commission (ITC)
Nuclear Regulatory Commission (NRC)
U.S. Geological Survey (USGS, Department of the Interior)
U.S. Patent and Trademark Office (USPTO, Department of Commerce)

Introduction

The ability to image, measure, model, and manipulate matter on the nanoscale is leading to new technologies that will impact virtually every sector of our economy and our daily lives. Nanoscale science, engineering, and technology are enabling promising new materials and applications across many fields including healthcare, electronics, aeronautics, and energy. Realizing these possibilities requires continued research and accelerated innovation. The United States has been and is now the recognized leader in nanotechnology research and development (R&D), but this lead cannot be assumed to be permanent. Thus, the National Nanotechnology Initiative (NNI) is as important as ever to ensuring U.S. leadership in nanotechnology R&D.

The NNI has created a thriving nanoscale science and engineering R&D environment within the United States. As a result, scientific understanding of nanometer-scale phenomena has expanded enormously. An extensive network of R&D centers is already established. Commercialization resulting from NNI-supported research is growing. Yet exploiting the full value that nanotechnology offers depends on sustained R&D. Barriers to innovation and technology transfer need to be lowered. Researchers, educators, and technicians with new skills are required. Furthermore, nanotechnology must be developed responsibly.

Many indicators point towards the increasing importance of nanotechnology to the scientific and engineering communities. For example, several nanotechnology-specific journals have been launched by professional societies. The work published in these journals details the remarkable progress that has been made towards understanding nanoscale phenomena and controlling matter at nanoscale dimensions. Much of this research was executed at the nearly seventy research centers and user facilities established and supported through the NNI, beginning with the Nanobiotechnology Center at Cornell University in 2001 and continuing through the opening in May 2007 of the Center for Functional Nanomaterials at Brookhaven National Laboratory.

The NNI and nanotechnology itself are still young, and translating an emerging technology into economically viable products usually takes decades. Yet, already the nanotechnology innovation and development process has begun. For example, to date more than 4800 patents have been identified under the nanotechnology classification created by the U.S. Patent and Trademark Office, many of which draw upon NNI-supported research.

About the NNI

The National Nanotechnology Initiative is the program established in fiscal year 2001 to coordinate Federal nanotechnology R&D. The NNI provides a vision of the long-term opportunities and benefits of nanotechnology. By serving as a central locus for communication, cooperation, and collaboration for all Federal agencies that wish to participate, the NNI brings together the expertise needed to guide and support the advancement of this broad and complex field. The NNI creates a framework for a comprehensive nanotechnology R&D program by

What is Nanotechnology?

Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.

A nanometer is one-billionth of a meter. A sheet of paper is about 100,000 nanometers thick; a single gold atom is about a third of a nanometer in diameter. Dimensions between approximately 1 and 100 nanometers are known as the nanoscale. Unusual physical, chemical, and biological properties can emerge in materials at the nanoscale. These properties may differ in important ways from the properties of bulk materials and single atoms or molecules.

establishing shared goals, priorities, and strategies, and it provides avenues for each individual agency to leverage the resources of all participating agencies.

Today the NNI consists of the individual and cooperative nanotechnology-related activities of twenty-five Federal agencies with a range of research and regulatory roles and responsibilities. Thirteen of the participating agencies have R&D budgets that relate to nanotechnology, with the reported NNI budget representing the collective sum of these. The NNI as a program does not fund research; however, it informs and influences the Federal budget and planning processes through its member agencies.

About this Plan

Given the dynamic nature of the field, a periodic reexamination of the NNI Strategic Plan is essential. The 21st Century Nanotechnology Research and Development Act of 2003 calls for the NNI Strategic Plan to be updated every third year; the plan presented here updates and replaces the December 2004 plan. A number of inputs guided this update. Independent reviews of the NNI by the President's Council of Advisors on Science and Technology and the National Research Council of the National Academies have been strongly supportive of the NNI, its strategies, and its operations. Each review has offered specific recommendations for improving the NNI. Additional input has come from topical workshops sponsored by the NNI (see list in Appendix A). In these workshops, academic, government, and industry experts developed research recommendations for a variety of application areas, considered societal implications of nanotechnology, and addressed economic development strategies.

This plan, guided by a review of the recommendations mentioned above, represents the consensus of the participating agencies as to the goals and priorities of the NNI. The plan provides a framework within which each agency will carry out its own mission-related nanotechnology programs and that will sustain coordination of interagency activities. In addition to specifying high-level goals, the plan identifies activities aimed at accomplishing those goals. The plan also identifies major subject areas, or program component areas, in which investments are needed to ensure the success of the initiative. Finally, the plan identifies a number of representative high-impact application opportunities and critical research needs that cut across the NNI program component areas and that align with the competencies and missions of participating agencies.

This strategic plan presents an overview of the NNI and will facilitate achievement of the NNI vision by offering guidance for agency leaders, program managers, and the research community in their nanotechnology R&D investments and activities.

Program Component Areas

Program component areas (PCAs) are major subject areas under which are grouped related projects and activities. They provide an organizational framework for categorizing the activities of the NNI. Progress in these areas is critical to achieving the NNI's goals and to realizing its vision. The investment related to each PCA is reported in the annual NNI supplement to the President's Budget.

The eight program component areas of the NNI are defined as follows:

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.

Nanomaterials: Research aimed at the 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.

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.

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.

Nanomanufacturing: R&D aimed at enabling scaled-up, reliable, and 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.

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 R&D. Includes ongoing operation of user facilities and networks.

Environment, Health, and Safety: Research primarily directed at understanding the environmental, health, and safety impacts of nanotechnology development and corresponding risk assessment, risk management, and methods for risk mitigation.

Education and Societal Dimensions: Education-related activities such as development of materials for schools, undergraduate programs, technical training, and public communication, including outreach and engagement. Research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, workforce, educational, ethical, and legal implications.

The 2004 NNI Strategic Plan defined seven PCAs, including a Societal Dimensions PCA. To better understand and manage the NNI investment, the Societal Dimensions PCA defined in the 2004 plan is divided into two in this updated plan: the Environment, Health, and Safety PCA and the Education and Societal Dimensions PCA described above.

Relationship to Goals and Agencies

The PCAs represent areas of investment necessary to achieving the NNI goals. Table 1 qualitatively indicates the relative strength of the relationships between the PCAs and NNI goals. Note that the projects and activities in one or more PCAs are critical to the progress of each goal. In addition to their relationship to the NNI goals, the PCAs are strongly correlated with the missions of the agencies participating in the NNI.

The PCAs cut across the interests and activities of the participating agencies and represent areas where achieving the goals of the NNI can be expedited through interagency coordination. Table 2 shows for each participating agency which PCAs have the strongest relationships to the agency's mission, interests, and needs. For agencies with budgets for nanotechnology R&D, the strength of the relationship shown in Table 2 roughly correlates with the level of investment. For those agencies that do not have nanotechnology R&D budgets, there are nevertheless strong connections with agency missions. For example, the Food and Drug Administration (FDA) regulates a wide range of products, including foods, cosmetics, drugs, medical devices, and veterinary products, some of which utilize nanotechnology or contain nanomaterials. Thus, for the FDA to fulfill its regulatory mission, the science for understanding biological interactions of nanoscale materials must be developed and related scientific issues must be resolved.

Table 1. Relationships between the PCAs and NNI Goals

Relevance: critical / primary / secondary

PCA \ GOAL	Goal 1: Advance a world-class nanotechnology research and development program	Goal 2: Foster the transfer of new technologies into products for commercial and public benefit	Goal 3: Develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology	Goal 4: Support responsible development of nanotechnology
Fundamental Nanoscale Phenomena & Processes	critical	secondary	primary	secondary
Nanomaterials	critical	secondary	primary	secondary
Nanoscale Devices & Systems	primary	critical	secondary	secondary
Instrumentation Research, Metrology, & Standards	secondary	critical	secondary	primary
Nanomanufacturing	primary	critical	primary	secondary
Major Research Facilities & Instrumentation Acquisition	secondary	primary	critical	secondary
Environment, Health, & Safety	primary	secondary	primary	critical
Education & Societal Dimensions	secondary	secondary	primary	critical

Table 2. Relationships between the PCAs and the Missions, Interests, and Needs of NNI Agencies

■ – Primary □ – Secondary

PCA / Agency*	Fundamental Nanoscale Phenomena & Processes	Nanomaterials	Nanoscale Devices & Systems	Instrumentation Research, Metrology, & Standards	Nanomanufacturing	Major Research Facilities & Instrumentation Acquisition	Environment, Health, & Safety	Education & Societal Dimensions
BIS (DOC)	□	■	■	■	□			
CPSC	□	□	■	■	□		■	□
CSREES (USDA)	□	■	■	□	□		□	■
DOD	■	■	■	□	■	□	□	□
DOEd							□	■
DOE	■	■	□	□	□	■	□	□
DHS	■		■	■		□		
DOJ			■					
DOL		□			□		■	■
DOS	□	□	□	□	□	□	■	■
DOT	■	□	■		■		■	
DOTreas		■	■					
EPA	□	■	■	□	■		■	□
FDA (HHS)	□	□	■	□	□		■	
FS (USDA)	□	■	■	□	■		□	
IARPA	□	■	■		□			
ITC		■	■		■			
NASA	□	■	■		□	□		
NIH (HHS)	■	□	■	□			■	□
NIOSH (HHS)		□			□		■	□
NIST (DOC)	■	■	□	■	■	□	□	
NRC				■				
NSF	■	■	□	□	■	■	■	■
USGS (DOI)	■			■			■	
USPTO (DOC)		■	■	■	■			

*A glossary of abbreviations is provided in Appendix B.

Strategy and Plans:
Research and Development in the National Interest

This section describes the strategy and plans for realizing the NNI vision in the context of the four NNI goals.

Goal 1: Advance a world-class research and development program

Strategic elements to achieve this goal include investing in multiple R&D pathways, mapping the leading edge of nanotechnology R&D, coordinating investments across agencies, and encouraging collaborations and other interactions.

R&D Investment Pathways

The NNI expands the boundaries of knowledge and develops technologies through a comprehensive program of R&D. This program invests at the frontiers and intersections of many disciplines, including biology, chemistry, engineering, materials science, and physics. Activities targeted toward this goal include support for fundamental research, use-inspired research, application research, and technology development. The research program of the NNI continues to be executed through a mix of single investigators, multi-investigator and team efforts, centers, and user facilities. Each plays an important role in the discovery and innovation process.

Single investigators. Research directed by single investigators is a key component of the NNI R&D portfolio and is considered critical to the continuing development of new concepts that can lead to breakthroughs in nanotechnology. Funding of individual investigators allows the NNI to support a broad range of ideas, including exploratory proposals that, if successful, could lead to major advances.

Multi-investigator and team efforts. Research at the frontiers and intersections of traditional disciplines enables rapid progress both in understanding nanoscale phenomena and in developing nanotechnology applications. Consequently, funding of multidisciplinary teams that bring a range of expertise to bear on a particular research topic or technology problem is a hallmark of the NNI effort. Participating agencies employ a variety of mechanisms for this type of investment.

Centers. The NNI member agencies invest substantial resources in large multidisciplinary research centers (see Figure 1, p. 12). Compared to multi-investigator research teams, these centers have a broader scope and bring together a larger group of researchers with diverse scientific expertise. Some centers have leveraged the Federal investment to obtain laboratories, instrumentation, and equipment from other sources, thus providing even more extensive opportunities and support for nanotechnology R&D.

User facilities and networks. These facilities make advanced experimental and theoretical capabilities accessible to researchers from academia, industry, and government laboratories. They bring together suites of complementary tools, including specialized, one-of-a-kind instruments, to cover a wide range of nanotechnology research, from materials synthesis through modeling. The scientific and technical staffs at these facilities are a vital component of this infrastructure, as they represent the expertise that is needed to most effectively utilize these capabilities.

Mapping the Leading Edge: Stimulating Concepts & Refining Ideas

Fostering a world-class program of research and development requires identifying challenges, recognizing opportunities, and stimulating new ideas. An effective means for mapping the leading edge of R&D is to develop a snapshot of the state of the art and use this to forecast future research directions. Towards this end, the NNI will sponsor topical and strategy-setting workshops. Such workshops bring together experts from academia, government, and industry to identify opportunities and needs, to suggest mechanisms to address these opportunities and needs, and to recommend strategies by which agency investments can be leveraged and coordinated. Current areas of common interest across several agencies that will be subjects of future workshops are:

- Sensors and nanoelectronics
- Energy
- Fate and transport of nanomaterials
- Medical and health applications

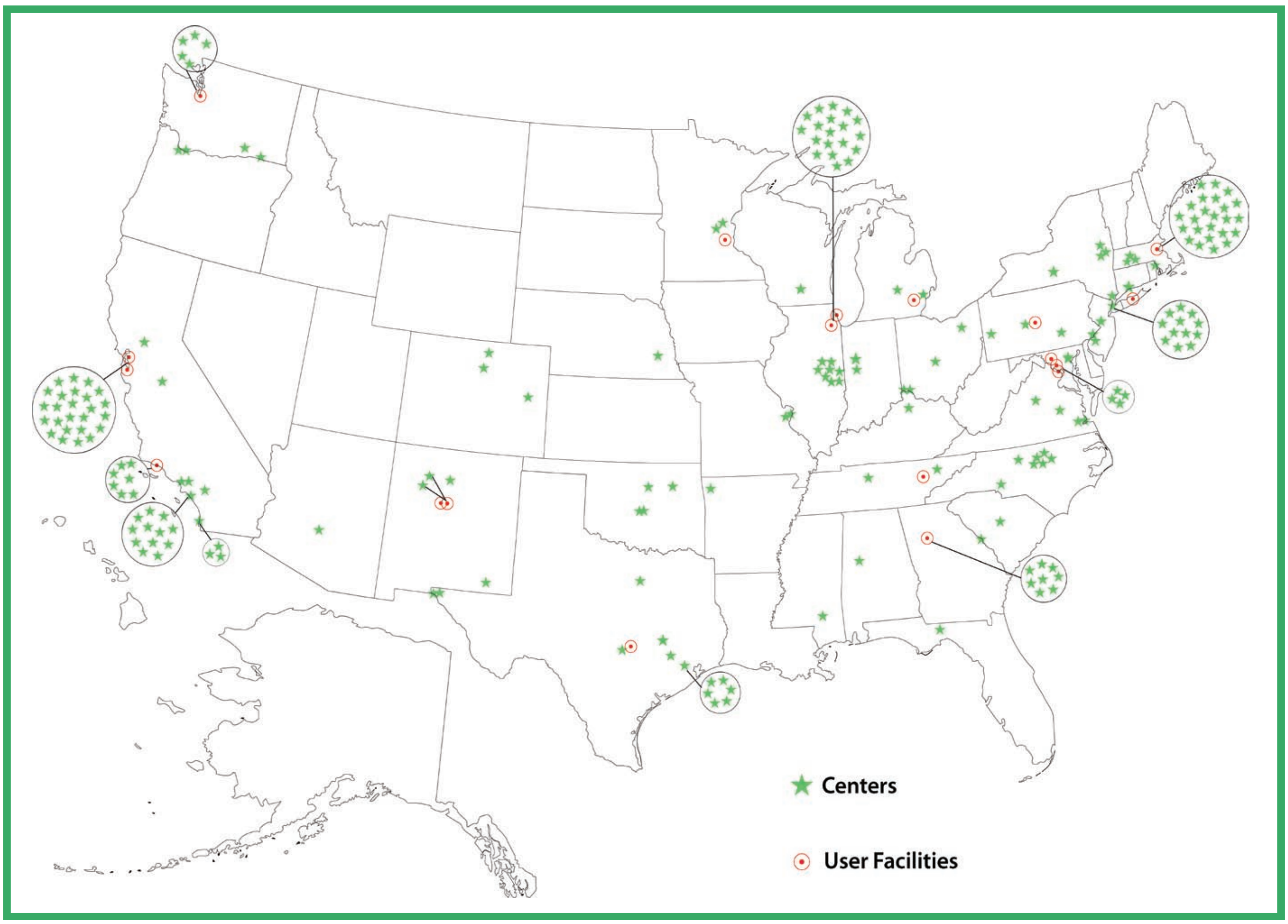
Coordinating Investment

No single agency within the Federal Government has the mission or breadth of expertise to fully exploit the opportunities nanotechnology presents, to execute all the requisite research, or to provide all the necessary standards and reference data. Thus, in certain key areas, it is essential to coordinate the NNI research and development programs across multiple agencies. Often, this synergistic route is the only feasible approach. Even in areas principally of interest to a handful of agencies, benefits can be derived from formulating programs from a broader interagency perspective.

An example of this coordinated approach comes from the NNI-led study of the environmental, health, and safety implications of engineered nanoscale materials. Here, certain agencies are funding the fundamental research required to understand underlying processes, other agencies are developing instruments for field measurements, and still other agencies provide the standards necessary to operate those instruments properly. Ultimately, other policy-setting and regulatory agencies will use the information from this research to assist industry and government in developing responsible guidelines for nanotechnology research and development.

Successful coordination of the Federal Government's nanotechnology R&D investment requires shared priorities. In order to communicate areas of common interest across the Government, leaders from the budget, legislative affairs, and other appropriate offices of all NNI agencies will be invited to the workshops discussed in the previous section. Each workshop will include opportunities for agency representatives to discuss further means for coordinating the Federal nanotechnology R&D effort. In order to further

Figure 1. NNI-sponsored Centers and User Facilities (December 2007)



facilitate a coordinated, interagency investment, the workshop participants will be asked to develop a list of priority research opportunities, challenges, and needs. The resulting list will be distributed to all the agencies participating in the NNI as an aid in formulating solicitations and collaborations. Additionally, members of the public will be invited to take part in these workshops as observers and to participate in associated engagement activities to discuss topics raised in the workshop that they find of interest and importance. The perspectives collected from these public engagement activities will be additional input to the NNI decision-making process.

Collaborations & Interactions

Recognizing the interdisciplinary nature of nanotechnology and the unique areas of expertise at the various Federal science agencies, the NNI agencies plan to explore opportunities for exchange of scientists across Federal agencies. Such exchanges enhance interagency connections in areas of mutual interest and expand the perspectives of Federal scientists. Scientists with this kind of experience are better equipped to assist their home agencies in furthering their research programs and provide their host agencies with fresh perspectives. The NNI will seek to facilitate targeted, cost-neutral sabbatical-type exchanges between agencies. The possibility of similar exchanges with industry will be investigated, where appropriate. International opportunities for collaboration and other interactions will be pursued, through participation in multilateral organizations and through existing science and technology agreements with other countries. NNI member agencies also benefit from international benchmarking activities and the sharing of programmatic R&D information.

To promote and expand interagency interactions, the NNI will facilitate communications concerning ongoing and planned nanotechnology activities among the member agencies. Multiple perspectives add value to many NNI activities, such as conferences and workshops, and the participation of multiple agencies in such activities strengthens and enhances the Federal nanotechnology R&D enterprise.

Goal 2: Foster the transfer of new technologies into products for commercial and public benefit

In order to realize the benefits of a world-class R&D program, the NNI seeks to enhance the transfer of research results into practical applications. The technology transfer process involves partnerships between the entities that support and perform research and those with the capacity to commercialize new technologies. Advances in nanotechnology already are impacting many industry sectors.

The NNI will foster technology transfer by engaging in a coordinated way with key industry sectors and will collect and exchange information and ideas regarding each sector's technology needs. Recognizing that entrepreneurs play a large role in innovation, the NNI also seeks to provide small businesses and start-ups with access to the results of NNI-funded research. In general, the NNI will help create a business environment conducive to responsible development of nanotechnology by businesses of all sizes. Partners in this undertaking include international, regional, state, and local organizations promoting nanotechnology development, as well as professional societies, trade associations, and other nongovernmental organizations.

Coordinated Engagement with Industry

The NNI will continue to work across industry sectors to gather input and feedback on Federal research priorities and activities in order to promote commercialization for public benefit. Industry liaison groups that include government and private sector representatives promote the exchange of information on NNI research programs and industry needs. Current liaison groups with the electronics, forest products, chemical industries, and the industry research management community will continue. The formation of comparable groups with other industry sectors is under consideration.

Engagement with industry at all stages of the innovation process will aid the diffusion of nanotechnology from the laboratory to the marketplace. Interaction with industry through liaison groups and at NNI workshops helps NNI agencies to identify pre-competitive research that will be most useful in addressing industry needs.

Industry participation in the review of research proposals provides valuable input. Therefore, NNI agency proposal review panel members include representatives from industry, when appropriate and possible. In addition, participation of industry representatives, when appropriate and possible, on external review boards for NNI centers, networks, and user facilities ensures that those entities remain responsive to industry needs and promotes awareness of NNI infrastructure within the business community. Finally, industry cooperation will be essential to measuring the impact of nanotechnology in the commercial sector, for example, in collecting information regarding revenues, employment, patents, and licensing.

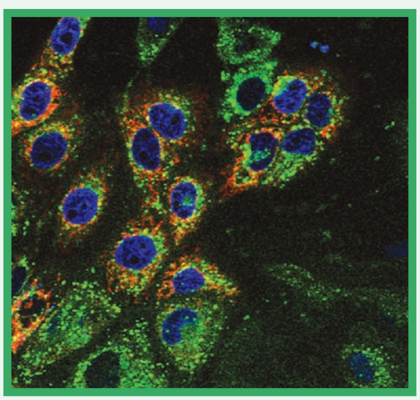
NNI agencies will continue to make use of existing mechanisms for technology transfer and commercial development, such as the Small Business Innovation Research (SBIR) program, the Small Business Technology Transfer (STTR) program, and the Manufacturing Technology (MANTECH) program. These programs are not specifically aimed at nanotechnology; however, agencies may highlight topics of interest to stimulate proposals in certain areas.

NNI Agencies Collaborate to Speed Development of Cancer Therapies

Nanotechnology Characterization Laboratory

A key promise of nanotechnology is for improved healthcare, including potentially revolutionary treatments for cancer. As with many nanotechnology opportunities, realizing this promise requires expertise across multiple scientific disciplines. To meet this challenge, the National Cancer Institute (NCI), working in concert with the National Institute of Standards and Technology (NIST) and the Food and Drug Administration (FDA), established the Nanotechnology Characterization Laboratory (NCL) to accelerate the development and translation of nanoscale materials and devices into cancer therapies.

The NCL performs and standardizes preclinical characterization of nanoparticle-based platforms intended for cancer therapeutics and diagnostics. This characterization service is available to researchers from academia, government, and industry, and the data can be used in support of an Investigational New Drug filing with the FDA. The NCL also provides infrastructure support to the NCI Alliance for Nanotechnology in Cancer and serves as a national resource and knowledge base for the cancer and nanotechnology research communities.



Optical confocal microscopy image of fullerenes (green) in porcine kidney cells. This method is part of an investigation of the internalization and subcellular distribution of fullerenes in cells. The nuclei of the cells have been dyed blue; the mitochondria are dyed orange in the image.
(Courtesy of NCL.)

NCI, NIST, and FDA each bring unique expertise to this partnership. The NCI focuses on research directed at identifying the causes of cancer and related diseases. Its scientists investigate the many factors that contribute to human cancers; identify new targets for cancer diagnosis, treatment, and prevention; and perform state-of-the-art characterization of nanoparticle-based platforms. NIST brings state-of-the-art physical and chemical measurement instrumentation and expertise to the partnership. NIST scientists develop measurement methods, assay protocols, models, and standards for physical and chemical characterization of nanoparticles, and also apply measurement tools to characterize the physical properties of nanoparticle-based platforms submitted to the NCL. FDA reviewers are expert at evaluating safety and efficacy, and the FDA has a commitment to developing mechanisms for facilitated review of new medical technology. All three agencies support the NCL's efforts to markedly accelerate the development of nanotechnology-based products benefiting cancer patients, reduce risks associated with this development, and encourage private-sector investment in this promising area of technology. This is one example of the NNI working towards the deployment of nanotechnology for public benefit.

Creating a Favorable Business Environment

Federal agencies can make important contributions to promoting a business environment that supports the transfer of nanotechnology R&D into products that benefit the public.

Protection of intellectual property is particularly important at the early stages of technology development. The U.S. Patent and Trademark Office (USPTO) continues to improve its ability to assess inventions that are based on advances in nanotechnology. The USPTO is developing a knowledgeable corps of patent examiners and is adding detailed structure to its patent classification for nanotechnology to aid the examination process.

In addition to impacting development of nanotechnology-enabled products and processes through intellectual property protections, the Federal Government also affects related businesses through regulation. Federal agencies that have responsibilities for oversight of nanotechnology-based products are active participants in the NNI. In carrying out their responsibilities, the regulatory agencies seek to ensure that companies comply with existing regulations, which may include developing guidance, as appropriate, for applying those regulations to nanotechnology-based products and disseminating that information.

As with any developing area, new information will become available over time, and additional research and new approaches may be required. Cooperative efforts among research agencies, regulators, and industry can

NNI Partnerships Accelerate Discovery of a New Logic Switch

Public-Private Partnership Supporting Nanoelectronics Innovation

Experts maintain that new technology and engineering approaches are necessary for the continued vitality of the information technology industry. Nanoelectronics, the application of nanotechnology to make electronic circuits, offers revolutionary alternatives to the component technology used in existing computer circuits.

Understanding the need for transformational long-range basic research in this area, the Semiconductor Research Corporation, an industry-led research consortium, has formed the Nanoelectronics Research Initiative (NRI). The NRI has the mission of developing nanotechnology-based computing devices to succeed existing semiconductor technologies. As a result of work among experts from industry, academia, and government, the NRI has identified multiple high-priority research targets, the most pressing of which is the invention of a new logic switch by 2020.

Recognizing the importance of this industry sector, two NNI agencies, the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST), have formed public-private partnerships with the NRI to support research in nanoelectronics with the goal of developing radically new, yet practical, successors to the components currently used in electronics and computer circuits. NSF, NIST, and the industry members of the NRI each provide funding to support research towards that goal. The research is conducted through university-based centers. Project selection is done by a panel of technical experts.

Concept of a switch made from a graphene sheet. Here a molecular quantum dot (center, white) is connected to graphene electrodes through narrow constrictions. A coplanar graphene side gate (dark green) controls charge flow through the switch. Reproduced by permission from *Physics Today*, © 2007 American Institute of Physics.

These government-industry-academic partnerships blend the discovery mission of NSF, the technology innovation mission of NIST, the practical perspective of industry, and the technical expertise of U.S. universities to address a nanotechnology research and development priority. It is one example of the creative methods the NNI uses to accelerate research that contributes to the Nation's economic competitiveness.

ensure that environmental, health, and safety risks are assessed and managed, and that data gaps are addressed in a prioritized fashion that stimulates innovation, while at the same time safeguarding public welfare. The sharing of non-proprietary information on the physical and chemical properties of nanomaterials will greatly facilitate this process.

Providing channels for communication among government agencies, companies, industry groups, and the public is an additional strategic element. Such communication will provide industry with current information to support responsible development of nanotechnology and will inform the public about risks and benefits of nanotechnology for individuals, society, and the environment.

Creating an international trade environment favorable to commercialization of nanotechnology is an important thrust of the NNI. Research strategies and guidelines regarding environmental, health, and safety aspects of nanotechnology and trade-related standards development are coordinated through U.S. participation in nanotechnology activities sponsored by the Organisation for Economic Co-operation and Development, the International Organization for Standardization, and other international organizations. Supporting the development of standards for nomenclature and terminology, measurement and characterization, and guidelines for handling and processing of nanomaterials will help to create a business environment in which U.S. companies have paths to bringing their products to international as well as domestic markets.

Beyond the Federal Program

In addition to coordinating and leading the Federal Government's nanotechnology R&D program, the NNI also engages with other governmental and nongovernmental organizations interested in the potential of nanotechnology to support U.S. competitiveness and promote the public good.

A number of regional organizations and state and local governments recognize the economic potential of nanotechnology and have begun to take steps to create nanotechnology-based clusters, that is, concentrations of universities, investors, and interrelated businesses with common manufacturing processes, customers, and suppliers. Because nanotechnology has the potential to impact almost every industry, whether high-tech or low-tech, there are opportunities for leveraging NNI R&D investments in every region. The NNI will support and foster these efforts by working with national, state, and regional groups, for example, to facilitate communication between local nanotechnology initiatives and to identify barriers to commercialization.

Goal 3: Develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology

A solid educational foundation, a skilled workforce, and a state-of-the-art R&D infrastructure are essential to the success of the NNI. Nanoscale science, engineering, and technology programs and other technology education programs and resources are required to produce a new generation of researchers and inventors working at the nanoscale. Educational programs continue to be developed with NNI support for all levels, including K-12 schools, community colleges, vocational schools, and major research universities. Building on this foundation, additional measures must be executed to develop and maintain a skilled nanotechnology workforce.

The supporting physical infrastructure, that is, highly specialized buildings and equipment, also is important. The NNI has created a network of interdisciplinary research centers and user facilities with modern equipment for nanometer-scale science and engineering research (see Figure 1, p. 12). Federal funding of state-of-the-art research facilities make these capital-intensive facilities accessible to researchers from all sectors. Additional facilities not specifically funded by the NNI, but which nevertheless support nanoscale science, engineering, and technology research, include synchrotron light sources and neutron-scattering facilities. In many instances, NNI user facilities and centers are located at, or near, these other facilities.

Nanotechnology Education

The NNI research centers, user facilities, and university-based research projects are designed and developed to foster multidisciplinary education, offer opportunities for teacher training, and stimulate the development of curricula and instructional materials. The NNI also provides hands-on training of technicians, undergraduates, graduate students, and postdoctoral researchers at universities, Federal laboratories, and other institutions.

In the future, the NNI member agencies will build on this investment by sustaining support for educational programs at all levels. Examples of specific efforts by the NNI member agencies to support and encourage the development, evaluation, and dissemination of educational materials for a broad cross-section of users and stakeholders include the following:

- Enhancing existing programs designed to develop middle school, high school, and undergraduate scientist-educators who can effectively introduce nanotechnology concepts into schools.
- Developing educational modules that incorporate nanotechnology into curricula for the many disciplines contributing to nanotechnology.
- Fostering international exchanges of students and researchers working in nanotechnology-related fields.
- Putting opportunities in place that bring together nanotechnology researchers from NNI-funded centers and user facilities to work with educational researchers and teachers, for example, through summer visiting research fellowships for teachers and undergraduate students.

The Nanoscale Science Research Centers

Department of Energy User Facilities for Nanoscience Research

To accelerate synthesis, processing, fabrication, and analysis at the nanoscale, the Department of Energy's Office of Science has established five new Nanoscale Science Research Centers (NSRCs) since 2006. Each center houses particular expertise and instrumentation in a limited number of focused scientific themes. These centers are designed to be user facilities for interdisciplinary research at the nanoscale, serving as the basis for a national program that encompasses new science, new tools, and new computing capabilities. User access is allocated based on peer merit review of submitted proposals.

The NSRCs are each located in new, custom-designed space, and each supports a broad array of state-of-the-art capabilities, including sophisticated cleanrooms, high-power computational resources, laboratories for nanofabrication, and one-of-a-kind, signature instruments. They are co-located with preexisting Department of Energy user facilities. This allows the NSRCs and their users to take advantage of complementary capabilities at the national laboratories, including the neutron scattering centers, synchrotron light sources, and electron microscopy user facilities. This is one example of the U.S. nanotechnology infrastructure supported by NNI agencies.

Developing a Nanotechnology Workforce

A skilled workforce is essential to realizing the NNI vision. This workforce must include nanotechnology researchers, technicians, manufacturing engineers, and production workers. To develop this workforce, the NNI will build on the educational programs described above by promoting partnerships between industry, educators, and the Federally funded R&D system. Such partnerships will aim to provide access to training programs for careers in nanotechnology-related industrial sectors. Examples of activities the NNI will support and encourage include the following:

- Using Department of Labor funded career centers and other appropriate public venues to distribute information on nanotechnology and the career opportunities this field offers.
- Developing training programs that encourage workers to pursue nanotechnology-related career opportunities.
- Providing information on nanotechnology-related training opportunities on the NNI website.
- Assessing human resource issues, including workforce training, by comparisons with other countries through international benchmarking exercises.

Nanoscience Research for Defense and Dual-Use Technologies

Department of Defense Facilities for Nanotechnology Research

Air Force, Army, and Navy research laboratories have developed unique and complementary approaches for fostering nanoscience research directed towards understanding and exploiting the unique properties that some engineered nanoscale materials exhibit. The Air Force Research Laboratory Nanotechnology Initiative, the Army Research Laboratory Nanoelectronics Laboratory, and the Naval Research Laboratory Institute for Nanoscience have led this effort.

Each of the service laboratories maintains analytical and materials growth capabilities that make it possible to fabricate and test advanced nanotechnology-enabled devices. Each laboratory has different areas of specialization, ranging from microelectromechanical systems to biological and chemical sensors, from biologically inspired nanomaterials to ultra-high vacuum approaches for fabricating nanomaterials. This expertise covers a wide range of applications that are expected to be important to future defense technologies.

The Air Force Research Laboratory's Nanotechnology Initiative and associated programs have expanded the existing Air Force materials processing and characterization infrastructure. Research at these facilities accelerates the development of engineered nanoscale materials that address diverse aerospace challenges, including improved electro-optic sensors, composite materials for morphing vehicles, alternative energy generation and storage concepts, and improved propellants.

The Army Research Laboratory's nanoelectronics facilities provide world-class processing and characterization equipment for nanotechnology investigations, particularly for the development of nanoelectronic devices and test instruments. In particular, the Specialty Electronic Material and Sensors Cleanroom (SEMASC) is the Army's most extensive sensor prototyping laboratory, with a full suite of specialized etch, deposition, characterization, and photolithography tools. This user facility is open to all Army researchers, as well as to external university, industry, and government partners.

The Naval Research Laboratory's Institute for Nanoscience brings together scientists with disparate training and backgrounds to attack common goals at the intersection of their respective fields at the nanoscale. The institute's Nanoscience Research Laboratory includes a cleanroom with a full complement of advanced fabrication and metrology tools and vibration-isolated, controlled-environment laboratories for the most sensitive systems, such as transmission electron microscopes and scanning probe microscopes.

Full Utilization of the NNI Infrastructure

The extensive infrastructure established by the NNI over the past seven years includes centers and user facilities supporting research on nanomanufacturing and nanoscale characterization, synthesis, simulation, and modeling. This infrastructure is well-suited to supporting the prototyping and demonstration stages of nanotechnology development. The NNI will support and encourage efforts to keep these facilities fully staffed and readily accessible to nanotechnology researchers from academia, industry, and government. The NNI agencies are committed to promoting broad access to user facilities by all sectors, especially by small businesses. Future activities include development of an inventory of major tools and facilities, continued development of user training for these facilities, and efforts to publicize the availability of these resources. The NNI agencies will also evaluate these existing infrastructure and equipment investments, considering possible new needs for the long term. In the near term, however, the focus will be on maximizing the utility and utilization of the substantial infrastructure already in place.

Some specific activities that the NNI agencies will support in order to enhance utilization of NNI infrastructure include the following:

- Developing a means to increase awareness among the nanotechnology research community of the services that are available at the various user facilities and of opportunities for collaboration with researchers at the NNI research centers.
- Developing and disseminating a database of major equipment available at NNI user facilities.
- Providing expert staff to advise, collaborate, and, when appropriate, to operate or train users to operate available equipment.
- Upgrading instrumentation in order to maintain state-of-the-art facilities and equipment.
- Coordinating information exchanges among centers, networks, and user facilities funded by NNI member agencies; for example, information relating to practices for the safe handling of nanomaterials.

Goal 4: Support responsible development of nanotechnology

Responsible development of nanotechnology entails research toward understanding the public health and safety and environmental implications of nanotechnology, as well as research toward promising, highly beneficial uses of the technology. Such an approach recognizes the value of supporting basic research to develop nanotechnology as well as research to address environmental, health, and safety concerns related to the use of the technology.

Responsible development of nanotechnology also entails establishing channels of communication with relevant stakeholders, in terms of both providing information and seeking input. Such communication allows the public and the NNI agencies to make well-informed decisions and builds trust among all stakeholders. Implicit in this approach is the recognition that public understanding and acceptance of nanotechnology and its applications are necessary components of successful commercialization.

The broad implications of nanotechnology for society can be grouped into two categories, namely (1) environmental, health, and safety (EHS) implications, and (2) societal dimensions. The NNI has made and will continue to make research in both these areas a priority. The implications of nanotechnology extend beyond borders, so international cooperation is an important part of the NNI strategy for responsible development in both of these categories.

Environmental, Health, & Safety Implications

The NNI's strategic approach to addressing the potential environmental, health, and safety implications of nanotechnology consists of comprehensive planning, research coordination, leveraging of forefront science through collaboration, and periodic review of EHS research needs and directions. This research strategy enables the NNI to identify new research needs and to pursue appropriate paths to meet those needs. Iterating the planning, research, and review cycle over the long term will provide the highest-quality information and data for government regulators, the public, and industry, helping to ensure that nanotechnology-enabled products are brought to the market responsibly.

The NNI agencies have funded high-priority, foundational nanotechnology EHS research since the inception of the initiative, and they continue to support a diverse and growing research portfolio. This broad portfolio is leveraged through the other investments of the various NNI agencies, along with the investments of industry and those of other countries.

The NNI has completed a first comprehensive assessment of EHS research and information needs and ongoing activities. Government subject matter experts led this assessment, informed by inputs from program managers, funding decision makers, and the public. Additional input was gained through U.S. participation in parallel international efforts. The process involved research, regulatory, and other Federal agencies, and thus promoted communication of needs, capabilities, and priorities between those communities. This activity provides the basis for current NNI planning and guidance activities in this area.

The information collected during the process just described was used to establish EHS research needs for engineered nanoscale materials, and a priorities document has been published. Documents such as this provide guidance to those who implement necessary research, that is, Federal agencies, industry, academia, and other relevant groups. A document that describes the NNI strategy for addressing the identified priorities for nanotechnology-related EHS research is in preparation.

The NNI plans to conduct periodic reviews of the needs, priorities, and strategies for nanotechnology EHS research. These reviews will establish whether new developments or discoveries require that research directions and goals should be changed or redirected. This approach to planning and implementing continuing nanotechnology EHS research will enable the NNI to adapt to the dynamic aspects of research and discovery and to pursue the most promising paths for addressing newly identified research needs. This approach takes advantage of the full depth of the Federal Government's resources and expertise and minimizes the pursuit of unnecessary and duplicative paths of research.

Societal Dimensions

Nanotechnology, like other new areas of technology, will impact society in ways that may be difficult to predict. The NNI supports ongoing research pertaining to ethical, legal, and societal implications (ELSI) of nanotechnology, in order to better understand its societal ramifications, to encourage the distribution and exchange of insights from leading experts in this area, and to develop avenues for societal input into nanotechnology development. As part of this effort, NSF supports two research centers focused on the study of the societal dimensions of nanotechnology.

The NNI also promotes public outreach, engagement, and communication of research findings, including those related to understanding societal dimensions of nanotechnology. An important tool that has been and will continue to be used in this effort is the NNI website, www.nano.gov. This is a major vehicle for providing information ranging from research news to funding opportunities. The website is linked to sites that host educational resources, safety databases, and other nanotechnology-related information. There will also be continued support for efforts to educate the public through means such as those currently led by the NSF-funded Nanoscale Informal Science Education (NISE) Network, which is a combination of exhibits and resources aimed at educating the public about nanotechnology. Another example of public education and outreach is the National Institute of Environmental Health Sciences' Nanotechnology Webinar series. This program brings the public, industrial hygienists, and public health advocates into a web-based dialogue with nanotechnology subject matter experts. Other outreach efforts, such as media roundtables, will also continue, and the NNI will explore ways of building capacity for public engagement, using vehicles such as web dialogues.

NNI Agencies Leveraging Resources

Joint Funding of Research on Potential EHS Implications

The National Nanotechnology Initiative (NNI) supports collaborations among multidisciplinary research groups and across agencies. NNI agencies jointly fund research on potential environmental, health, and safety implications of nanotechnology. Below are examples of how the agencies of the NNI share resources and work together to achieve common objectives.

- The Environmental Protection Agency (EPA) initiated, with subsequent support from the Department of Energy (DOE) and the National Science Foundation (NSF), funding for research that focuses on investigating the environmental and biological fate, transport, and transformation and exposure/bioavailability of engineered nanoscale materials. This research program encourages international collaborations, which are critical for an integrated and comprehensive approach toward understanding the impact that engineered nanomaterials may have on humans and ecosystems. This EPA-led program began in fiscal year 2005; participation of other agencies has varied from year-to-year.
- The Army Engineer Research and Development Center is conducting research that focuses on the characterization, fate and transport, toxicology, and modeling of engineered nanoscale materials specifically related to militarily relevant nanotechnologies. The goal of this research is to provide technology developers with tools for "smart" development and use of engineered nanomaterials. This research has strong connections to other Federal agencies, including the Air Force, EPA, U.S. Geological Survey, and the National Institute for Occupational Safety and Health (NIOSH). Funding began in fiscal year 2006.
- The National Institute of Environmental Health Sciences (NIEHS) of the National Institutes of Health (NIH) is partnering with EPA and NIOSH, as well as with five other institutes at NIH, to support research that investigates the systemic, cellular, and molecular responses to manufactured nanoscale materials. This program began in fiscal year 2007.
- NSF and EPA have issued a joint funding solicitation for proposals to create a Center for Environmental Implications of Nanotechnology. This center will conduct research and education on the implications of nanotechnology for the environment and living systems at all scales. The center will address interactions of naturally derived, incidental, and engineered nanoscale and nanostructured materials, devices, and systems with the living world. Funding is planned to begin in fiscal year 2008.

High-Impact Application Opportunities and Critical Research Needs

The power of nanotechnology is rooted in its potential to transform and revolutionize multiple technology and industry sectors, including aerospace, agriculture, biotechnology, homeland security and national defense, energy, environmental improvement, information technology, medicine, and transportation. Discovery in some of these areas has advanced to the point where it is now possible to identify high-impact application opportunities for nanotechnology and areas where critical research will significantly advance these potential applications.

Specific examples of these opportunities and needs are given on the pages that follow this introduction. These examples illustrate a few of the potential benefits that nanotechnology offers. They are of interest to a wide variety of NNI member agencies. These examples are derived in part from ideas generated at NNI-sponsored topical workshops, at which experts from academia, industry, and government examined a particular aspect of nanotechnology in detail (see Appendix A for a list of these workshops).

Each example lists interested NNI agencies. Many of the NNI agencies that fund nanotechnology R&D have supported, and will continue to support, the foundational scientific research and technology development that will ultimately meet the research needs and lead to the applications described here. One or two agencies often have a particularly strong connection to a given application area. Agencies with mission-driven needs pursue nanotechnology applications that address their individual requirements. In many cases, however, multiple agencies have an interest in an application, be it from a research, regulatory, or policy perspective. In some cases, coordinated research across agencies is necessary in order to realize an application opportunity or meet a research need. The relationships between the agencies and selected application areas are summarized in Table 3.

The application and research needs discussed here are visionary, yet realistic. The time horizon for realizing these goals is long-range, ten years or more. Because scientific research and product development is never formulaic, it is likely—indeed, it is probable—that research and discovery will lead in unanticipated directions. Transforming discovery into products is a complex process for any technology and typically takes decades; this will be no different for nanotechnology.

The most effective means to achieve the potential of the nanotechnology application opportunities discussed here will be to pursue a variety of technical approaches. Similarly, a wide breadth of collaboration often will be required.

The high-impact application opportunities given on the following pages, although not comprehensive, are examples of the important national needs and major industry sectors on which nanotechnology could have an impact. Equally, the critical needs are only some of the important advances required to move nanotechnology to its next phases. It must be emphasized that this is just an illustrative sampling. Other important nanotechnology R&D priorities will—and must—be pursued.

Table 3. NNI Agency Contributions to Selected Nanotechnology Application Areas

● – Central Role ○ – Supporting Role

Application Area / Agency*	CPSC	CSREES	DOD	DOE	DHS	DOJ	DOL	DOT	EPA	FDA	FS	IARPA	ITC	NASA	NIH	NIOSH	NIST	NSF
Aerospace			●	○	○			○				○	○	●			○	○
Agriculture & Food		●	○	○	○	○			○	●	○							○
National Defense & Homeland Security		○	●	○	●	○			○	○		●	○	○	○	○	○	○
Energy		○	●	●	○				○		○	○	○	○			○	○
Environmental Applications	○	○	○	○	○		●		●	○	○				○	○	○	●
Information Technologies			●	○	○							○	○	○	○		○	●
Medicine & Health	○	○	○	○			●		●	●				○	●	○	○	○
Transportation & Civil Infrastructure			○	○	○			●	○		○						○	○

*A glossary of abbreviations is provided in Appendix B.

Early Detection of Life-Threatening Diseases

Rapid, Multiplexed Detection of Disease Markers

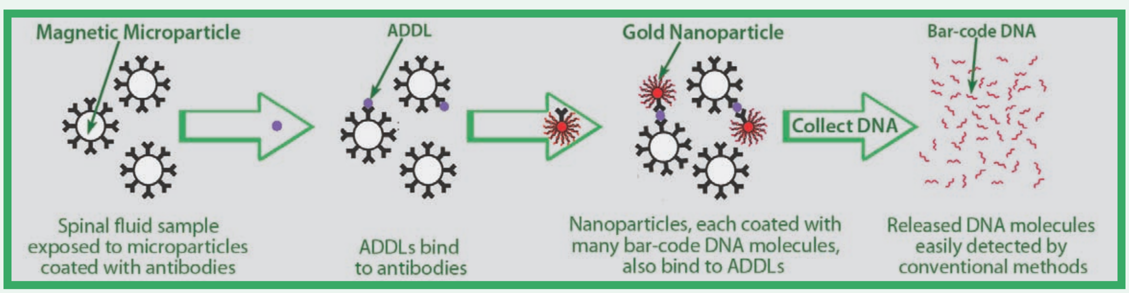
Interested Agencies: CSREES, DOD, FDA, NIH, NIST, NSF

Early detection of a life threatening disease, such as a cancer, or rapid and accurate detection of a life-threatening exposure, such as to a chemical or biological agent, can make a difference between death and survival. Similar technological approaches can be used to detect the molecular signatures of disease, an environmental exposure, or the presence of toxins or microorganisms in food. However, current detection methods often require multiple steps, do not provide data in real time, are not quantitative, and have limited sensitivity and specificity. Nanotechnology has the potential to overcome the limitations of current approaches and thereby advance the diagnosis and treatment of life-threatening diseases, enhance our national security, and improve food safety.

To make rapid, accurate, real-time detection possible, a number of advances will be required. The molecular signatures of disease, also called biomarkers, and biological threats are often present at concentrations that are too low to be measured by current technology, so new devices will need improved sensitivity. Additionally, many sensors are not able to measure multiple parameters simultaneously. This multiplexing capability is needed to distinguish one disease or exposure from another and will improve the specificity and accuracy of the disease or exposure identification. Ideally, these devices should be capable of measuring large numbers of markers simultaneously on a single, easily obtainable tissue sample, such as breath, sweat, or saliva, be portable, and be easy to use in a doctor's office or by a first responder.

One example of a promising new medical approach that uses bionanotechnology is the bio-barcode assay for the detection of disease-related proteins or DNA in tissue samples. In its first application, the bio-barcode assay uses gold nanoparticles to amplify and detect amyloid beta-derived diffusible ligands (ADDLs), a molecular signature for early-stage Alzheimer's disease. This method is a million times more sensitive than the current point-of-care diagnostic tests, specific for molecular signatures of disease, and quantitative.

Other promising medical diagnostics using nanotechnology include methods to detect infectious agents and improved diagnostic imaging systems to examine tissues and organs for disease diagnosis, such as computed tomography and magnetic resonance imaging. Looking further down the road, many of these imaging agents could be coupled with targeted drug delivery.



Schematic presentation of the bio-barcode amplification and magnetic collection process for detecting the presence of ADDL, a molecular signature of early-stage Alzheimer's disease, using gold nanoparticles coated with DNA. Adapted from *Proc. Natl. Acad. Sci. USA*; original image © 2005 National Academy of Sciences, all rights reserved.

Knowing It's Safe

Exposure Measurements for Engineered Nanoscale Materials

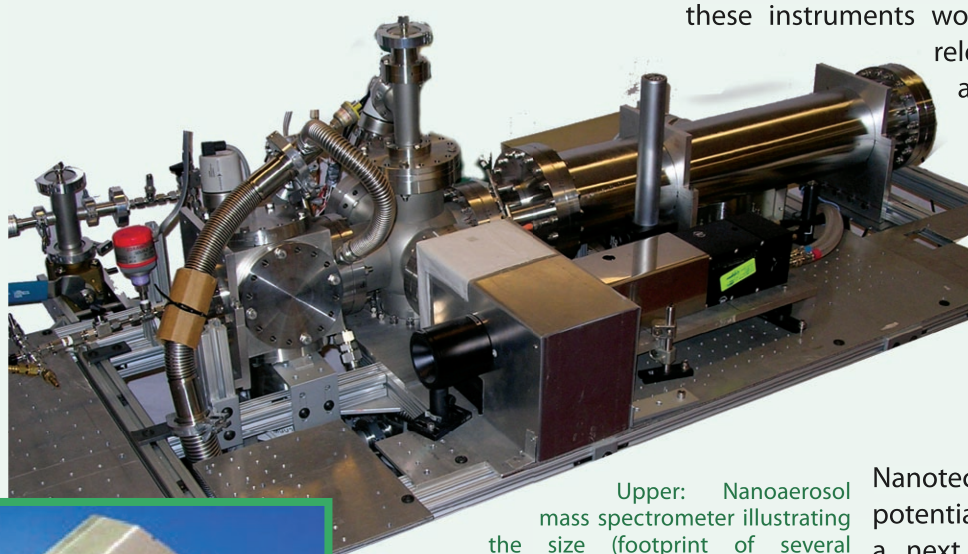
Interested Agencies: CPSC, DOD, DOE, DOL, DOT, EPA, FDA, NIH, NIOSH, NIST, NSF, USGS

Knowing the concentration and types of engineered nanoscale materials in the air, in water, and on surfaces is essential to evaluating the potential impacts on workers, consumers, the public, and the environment.

Definitive methods for identifying engineered nanoscale materials in the environment are neither well developed nor readily available. Presently, estimating exposure to and concentrations of nanomaterials is possible only for a limited number of material types. The results of these measurements are often inaccurate, and the process is cumbersome and typically involves collecting samples in the field for subsequent analysis in the lab. The instruments used in these analyses incorporate sophisticated technologies and methods, such as electron energy-loss spectrometry, that require expert operators to collect the data and interpret the results. Moreover, a single instrument may cost hundreds of thousands of dollars and be capable of measuring only one or two of the many parameters of interest, for example average size or elemental composition. Even these limited measurements can take hours, if not days, to complete.

For exposure and concentration measurements of engineered nanoscale materials to become feasible, existing methods for measuring the relevant parameters must be simplified and refined and new approaches must be developed. For these measurements to become practical, the instruments will need to be affordable, portable, and work in the field, and provide exposure and concentration information in real time. Ideally, these instruments would also measure several relevant parameters, such as size distribution, shape, charge state, and chemical composition. Such instrumentation would greatly facilitate risk assessment analyses and would facilitate the development of appropriate exposure mitigation programs.

Nanotechnology itself could potentially provide platforms for a next generation of analytical instruments, perhaps through the development of high-density, multianalyte sensor arrays.



Upper: Nanoaerosol mass spectrometer illustrating the size (footprint of several square feet) and complexity of current instrumentation for measuring nanoparticles in the atmosphere (courtesy of M. V. Johnston, University of Delaware). Lower left: Concept of a future-generation instrument (courtesy of Sandia National Laboratory).

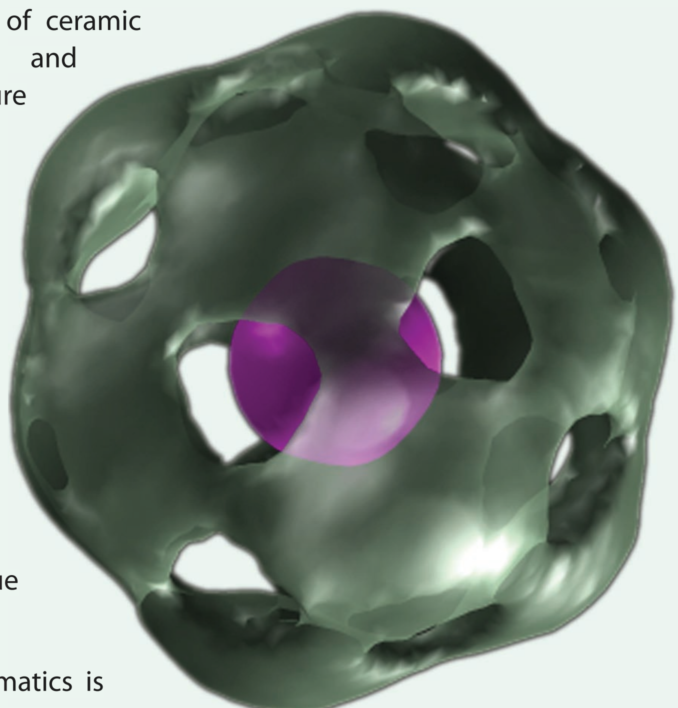
Letting Nature Do the Work

Nanobiotechnology

Interested Agencies: CSREES, DOD, DOE, FDA, NASA, NIH, NSF

A key challenge for nanotechnology is the fabrication and assembly of nanometer-scale materials, devices, and systems. Biology performs these functions in living cells, which in many respects act as integrated nanomanufacturing factories. A cell includes nanomaterials (proteins, membranes, etc.), nanodevices (motor proteins, ion channels, etc.), and even functional nanosystems (e.g., mitochondria) that are created from individual molecules by hierarchical self-assembly. Biological capabilities can be harnessed directly, borrowed, or taken as inspiration for future nanomanufacturing.

Naturally occurring nanostructured organisms such as diatoms have been converted from silica into a range of ceramic nanomaterials with new properties. Cells and viruses can also be engineered to manufacture or assemble nanomaterials. Certain bacteria naturally produce magnetic nanoparticles and have already been engineered to produce nanoparticles coated with specific proteins. Researchers have used biological methods to discover viruses that can be used as scaffolds for selective attachment and growth of semiconductor nanoparticles, and have produced the first virus-assembled nanoelectrode and virus-assembled battery. Scientists are also learning from processes organisms use to create complex inorganic nanostructures, including those with unique chemical, optical, and mechanical properties.



An image, reconstructed from transmission electron micrographs, of a biologically inspired complex composed of a semiconductor quantum dot encapsulated in a protein shell. Reproduced by permission from *Nano Letters*, © 2006 American Chemical Society.

Progress in genomics, proteomics, and bioinformatics is rapidly expanding our understanding of how the genetic code enables cells to turn molecules into nanostructures and nanosystems. Harnessing this biological knowledge will enable flexible, scalable, and affordable nanomanufacturing for the pharmaceutical, biochemical, nanoelectronics, and materials industries.

Safe and Affordable Water

Nanotechnology-Based Water Purification and Testing

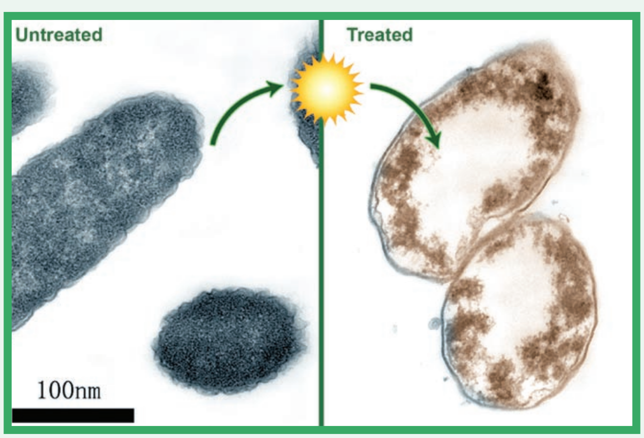
Interested Agencies: CSRESS, DOD, DOE, DOS, EPA, NASA, NIH, NSF, USGS

Clean water is a basic necessity for people and animals and vital to agriculture. The worldwide supply of potable water is limited and demand is increasing. Disease-causing organisms often contaminate water in less developed parts of the world. Gasoline additives, dry cleaning chemicals, and agricultural pesticides sometimes foul the water supply in industrialized countries. Water pumped from deep aquifers often contains high levels of contaminants such as iron, manganese, and even arsenic, or has high salinity.

Many different technologies already exist for removing various contaminants from water, including distillation, chlorination, ultraviolet irradiation, and selective membrane filtration. Each has its drawbacks. Most are energy-intensive. Some generate byproducts that have unfavorable environmental and health impacts.

Nanotechnology could help meet the need for safe, affordable water through inexpensive water purification and rapid, low-cost detection of impurities. Solutions are likely to come from many directions. Some may be applied locally while others will be best suited to central treatment facilities. Nanostructured mixed metal oxides can destroy biological toxins in water through photocatalysis and oxidation. Coatings made from nanomaterials minimize biofilm fouling, a problem with existing membrane technologies.

Progress has already been made. Experiments with palladium-doped iron nanoparticles have demonstrated the capability to remove organic contaminants from groundwater. Magnetite nanoparticles have shown promise for removing arsenic from drinking water. Sensors based on nanostructured surfaces have been used to detect metals, biotoxins, and organic compounds accurately and rapidly. These sensors also could be incorporated into sophisticated control systems for sensing and then treating specific contaminants.



Transmission electron microscope micrograph showing the destruction of *E. coli* bacteria in water using visible light, a process made possible by the presence of nanoscale titanium oxide (courtesy of J-K. Shang and B. M. Pianfetti, University of Illinois at Urbana-Champaign).

Nanotechnology-based membrane materials, impurity-scavenging nanoparticles, and portable devices for on-site detection and diagnosis of contaminants are priorities in water purification research. It will be important to investigate the scale-up of low-impact manufacturing processes for these new systems. Finally, it will be important to ensure that there are no unwanted environmental and health impacts of engineered nanomaterials used in the new purification processes.

Smarter Computers

Future Information Processing Technology from Nanotechnology

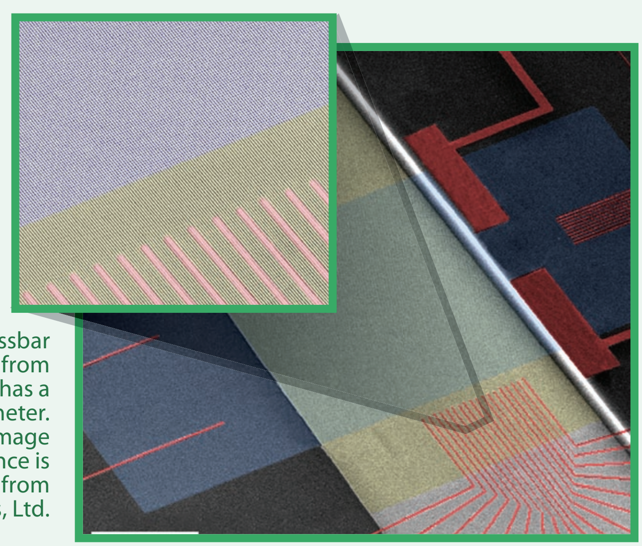
Interested Agencies: DOD, DOE, DOT, FDA, NASA, NIH, NIST, NSF

Computers and other advanced electronic systems are at the foundation of our Nation's technological and economic strength. Complex natural phenomena such as climate patterns are modeled using advanced computers. Airplanes and car engines are designed with sophisticated information technology systems. Three-dimensional diagnostic images of human organs are constructed by computers coupled to imaging technologies.

Complementary metal-oxide semiconductor field-effect transistor (CMOS-FET) technology is the engine that propels modern computers and electronics. Historically, CMOS-FETs have gotten smaller, year after year. This has meant that more components can be fit onto a computer chip, one reason why computers and other electronic systems have gotten ever more powerful over time. As individual circuit components approach nanoscale dimensions, however, conventional electronic devices become unreliable and waste too much power, both of which will eventually limit the ability to miniaturize.

Nanotechnology offers new approaches for continuing improvements in information technology. One of the most anticipated developments will be discovery of a replacement for the logic switch around which today's computers are designed, that is, the CMOS-FET. Ideally, future nanotechnology-enabled logic switches will provide increased performance while using significantly less electrical power, will be integrable with existing fabrication processes, and will lead to computers with much higher component densities.

Controlling the structure of matter at the nanoscale will enable future electronic devices that will operate more efficiently at much lower power than existing devices and systems. Graphene, a flat sheet-like molecule made of carbon atoms, offers an example. Electrons can travel great distances in sheets of graphene, resulting in less waste heat. Moreover, depending on how a graphene sheet is oriented, it can act either as a conductor or a semiconductor, two essential components in an electronic circuit. These characteristics offer the potential advantage of being able to create energy-efficient, multicomponent devices from a single sheet of graphene. There are numerous other areas where nanotechnology can contribute to the continued improvement of information technology systems. These include the use of nanostructured materials for better thermal management and superior dielectric properties.



Scanning electron microscope images of a nanowire crossbar memory circuit, in which the memory elements are made from overlaying silicon and titanium nanowires. This circuit has a memory element density of 100 billion bits per square centimeter. Lower right: Image of entire circuit. Upper left: Magnified image of nanowire crossbar memory junctions. Wire-to-wire distance is approximately 33 nm. Reproduced by permission from *Nature*, © 2007 Macmillan Publishers, Ltd.

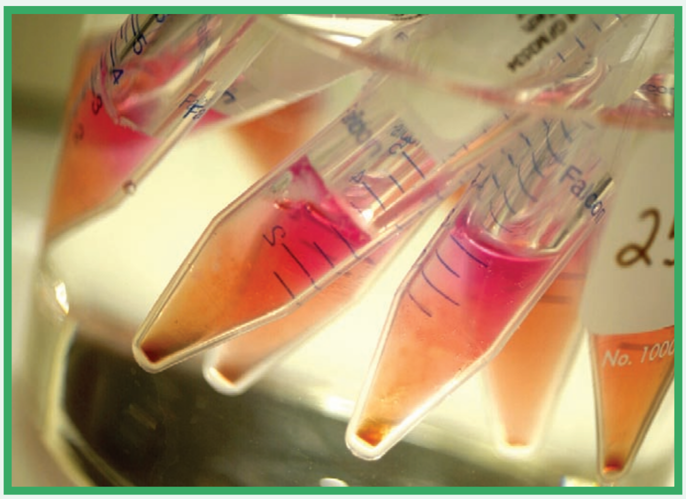
Nanotoxicology: Doing it by the Numbers

Predicting Toxicity Before Manufacturing

Interested Agencies: CPSC, DOD, DOE, DOL, DOT, EPA, FDA, NIOSH, NIH, NIST, NSF

The behavior of engineered nanoscale materials in biological systems is directly related to the physical and chemical properties of that material. The rapidly increasing number of nanomaterials in development and manufacture, as well as the exquisite sensitivity of a material to its biological microenvironment, makes it difficult to predict biocompatibility or toxicity in humans and the environment. Currently, decisions to proceed to manufacture or to release products for commercial use are based on laboratory assessments of toxicity.

Conventional toxicity assessment often employs a tiered system of assays. A material that gives positive indications of toxicity in the first-tier assessment is then analyzed more rigorously in a dose-response model. These data, plus exposure measurements from the exposure site, are analyzed, and an estimate of risk is calculated. These analyses are frequently time-, nanomaterial-, and equipment-intensive. Computational models that predict biological and environmental response of a new material based on knowledge of structurally similar materials have been developed for several classes of chemicals.



Vials of quantum dots and blood plasma following centrifugation, part of a study of the effects of quantum dots on immune cell function. Such studies are used to evaluate the safety of nanomaterials in humans. Computational methods could augment or replace these time-consuming and expensive laboratory tests. (Image courtesy of NCL).

Development of similar predictive models for nanomaterials will require a thorough understanding of the biological interaction of a few well-characterized standard nanomaterials in well-characterized biological and environmental systems. These data would be used to define basic structure-activity relationships and would serve as the basis for creating models that predict the biological and environmental response of new or more complex nanomaterials. Development of the computational components of a predictive model would occur in parallel with the biology studies and require translation of the models for chemicals to nanoparticles and complex three-dimensional nanoscale structures.

The ability to predict biological and environmental response to nanomaterials through a computational model and to adjust physical and chemical parameters of the materials early in product research and development has the potential to shorten the time for toxicity testing from several weeks to a matter of hours. It will also provide a labor and cost benefit to the manufacturer, new tools for risk assessment by regulatory agencies, and protection of humans and the environment from harmful exposures.

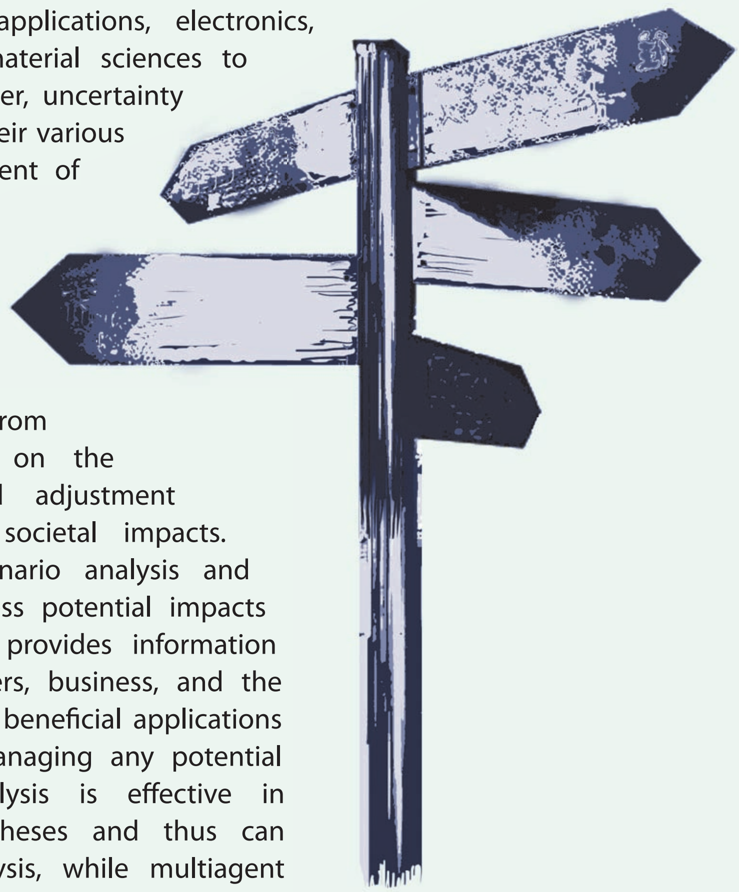
Could, Would, or Should?

Societal Dimensions of Nanoscale Science & Technology

Interested Agencies: CPSC, CSREES, DOE, DOL, FDA, NASA, NIH, NSF

Nanotechnology is a science in motion. Anticipating the societal impact of nanotechnology requires balancing uncritical expectations and fears with values and issues raised by ethical, legal, and societal discussions regarding its development and applications.

Potential applications of nanotechnology are expected in a wide range of fields, from agriculture and food, biomedical applications, electronics, energy, environmental remediation, and material sciences to computing and other technologies. However, uncertainty surrounding some future applications and their various potential impacts could hamper development of nanotechnology.



The research challenge will be to identify and, to the extent possible, quantify potential societal developments (social, economic, workforce, educational, ethical, and legal) that could result from discoveries in nanotechnology. Research on the processes of innovation, diffusion, and adjustment will generate information on potential societal impacts. Additionally, modeling tools, such as scenario analysis and multiagent modeling, can be used to assess potential impacts and resulting societal interactions. This provides information concerning potential impacts to policy makers, business, and the public, allowing for the development of beneficial applications of nanotechnology, while reducing and managing any potential unintended consequences. Scenario analysis is effective in identifying issues and researching hypotheses and thus can be an effective tool for theoretical analysis, while multiagent modeling is akin to scenario analysis, but is carried out through computer simulation.

It could prove interesting to compare the history of nanotechnology with the history of other technologies, such as the Internet, genetically modified organisms, aircraft, stem cells, and computers, to draw lessons that might be relevant. Alternative histories, for instance, can be built using such familiar technologies as the automobile. How might today's society approach its introduction were it being developed now? How would society attempt to avoid unintended impacts?

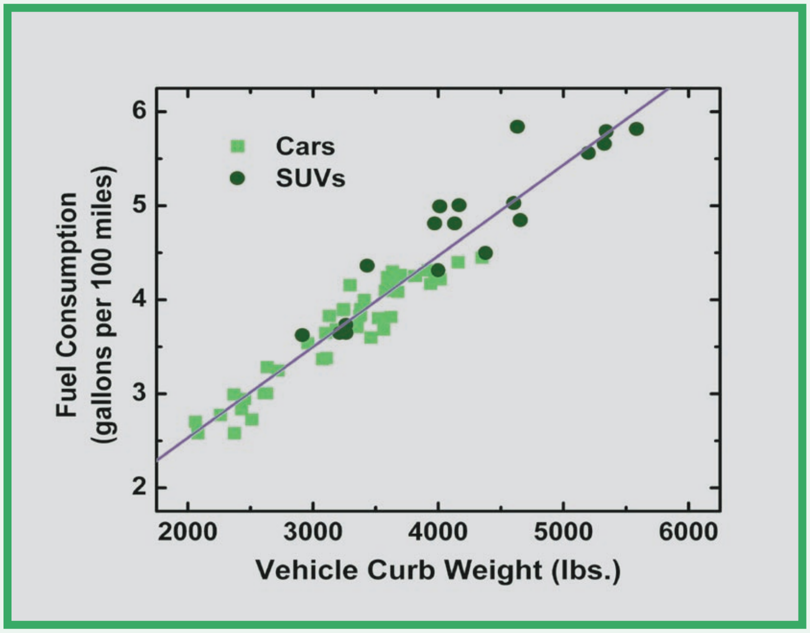
More Energy-Efficient Transportation

Lightweight Magnetic and Structural Nanomaterials

Interested Agencies: DOD, DOE, DOT, EPA, NASA, NIH, NIST, NSF

A study by the National Academies, titled *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, found that reducing the weight of a vehicle by twenty percent results in a fifteen percent reduction in fuel consumption. A few specific examples illustrate the importance and magnitude of this relationship between vehicle weight and transportation fuel efficiency. AirTran recently installed carbon-fiber-based seats in its 737-700 Series aircraft, which shaved 19.4 pounds from each row of seating and is estimated to result in fuel savings of $2,000 per year per aircraft. Boeing estimates that weight savings due to use of carbon fiber composite materials in its new 787 aircraft will increase fuel efficiency by as much as twenty percent. Such reduction in fuel consumption for transportation has the additional benefit of reduced outputs of greenhouse gases.

Nanotechnology offer possibilities for production of new strong and lightweight materials that also may exhibit superior magnetic and mechanical properties. These materials could result in weight reduction in transportation vehicles. For example, calculations predict that nanocomposite magnets could have magnetic strengths twice as high as those of the best commercial magnets in use today. These magnetic materials could significantly reduce electric motor weight and size in hybrid automobiles, railway systems, and subways. Application of nanostructured composite materials may also allow designers to reduce the weight of structural components without compromising stiffness or other properties that are essential for passenger safety.



Relationship of fuel consumption rate to vehicle weight for a representative set of vehicles used in the United States. Data from: *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, National Academy Press (Washington, DC: 2002)

To realize the potential of nanotechnology-based materials, key scientific and technological barriers must be overcome. Improved synthesis and processing techniques must be developed to enable bulk fabrication of nanomaterials, to ensure high quality and purity of the nanomaterials, and to control their structure at the nanoscale.

Better Measurements

Reference Materials for Commerce and Safety Monitoring

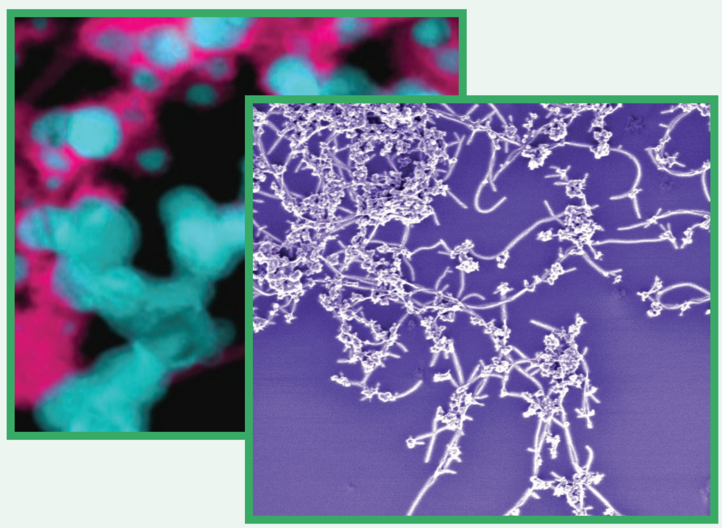
Interested Agencies: CPSC, EPA, DOD, DOL, FDA, NIH, NIOSH, NIST, USGS

The chemical composition and physical characteristics of today's engineered nanoscale materials can vary substantially between batches and from vendor to vendor. Products manufactured from such variable starting materials have inconsistent performance characteristics. Health and safety testing studies yield seemingly variable results. Accurate calibration of environmental monitoring systems is difficult.

A suite of reference standards (stable materials with rigorously characterized chemical and physical properties) could help to eliminate these problems. Reference standards are used in laboratories to perform instrument calibrations, by manufacturers to verify the composition or properties of their products, and in clinical laboratories to validate the accuracy of specific measurements. Material standards with property values that have been determined using established and definitive methods are essential in the validation of new measurement methods.

Standards are needed for engineered nanoscale materials. Different groups or classes of standards will be needed by different sectors. For example, materials necessary for performance evaluations in manufacturing may consist of nanocomposites or nanoclays relevant to a particular industry. Materials needed for toxicology and ecotoxicology research include titanium dioxide, zinc oxide, and carbon nanotubes. However, significant R&D is needed on many fronts. Pure samples are needed. The critical and relevant physical parameters (size, shape, composition, etc.) must be identified. Reliable methods of distributing these standards must be established. Instruments with the ability to determine the elemental composition, location, and chemical state of all atoms in nanomaterials must be developed.

Creating a suite of standards for engineered nanoscale materials will require a coordinated interagency research effort. Multiple NNI agencies will need to be involved in developing and validating instrumentation and methods. Agencies with needs to measure specific materials will play a role in selecting material for which standards will be developed. The research-sponsoring agencies will be critical to funding studies that identify relevant chemical and properties for standardization. Regulatory agencies will have an essential role in describing the use of these standards, for example in environmental and workplace monitoring settings.



Lower right: Electron micrograph of a carbon nanotube sample showing how the sample contains significant impurities such as metallic particles and other forms of carbon. Field width is approximately 4 µm. Upper left: Electron energy loss spectrometry reveal metallic impurities (pink) and along with carbon (light blue). Field width is approximately 100 nm. (Images courtesy of NIST.)

Energy Security

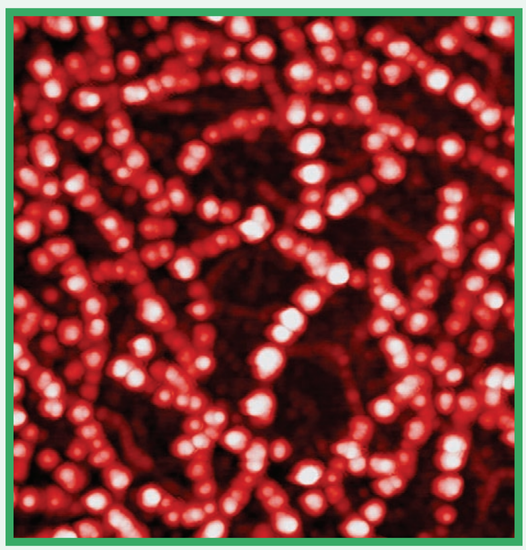
Meeting the Energy Challenge

Interested Agencies: CSREES, DOE, DOD, NASA, NSF

The world demand for energy is expected to double by the year 2050. The difficulty of meeting this demand is compounded by the growing need to protect our environment. To resolve this challenge and provide secure energy resources, energy efficiency must be increased and new "clean" energy sources developed.

Nanotechnology may provide novel solutions to these challenges. At the root of the opportunities nanoscience offers in energy research is a simple fact: many of the elementary steps in the storage and conversion of energy take place on the nanoscale. Furthermore, new functionalities of nanoscale materials emerge from high surface area, quantum size effects, high aspect ratio, reduced dimensionality, and intimate connectivity. The properties of engineered nanoscale materials, as well as the techniques used to image, measure, and manipulate these materials, create new opportunities for energy technologies.

Nanomaterials offer new ways to store and transform energy and to control catalytic activity. Photovoltaic cells made of nanoscale semiconductors offer several mechanisms to enhance the efficiency and reduce the cost of solar energy. For example, nanomaterials can be designed to absorb a broad range of colors from the solar spectrum. Harvesting solar energy with twenty percent power conversion efficiency and a hundred times lower costs than present photovoltaic technology could be within reach. Solid-state lighting involving the use of semiconductor-nanocrystal-based light emitting diodes for general illumination is another rapidly developing technology with the potential to save immense quantities of energy. Nanostructured materials offer a number of opportunities for the development of enhanced power storage and conversion, and for the design of improved catalysts. Nanostructured catalysts can achieve high selectivity and turnover. For example, it is envisioned that the emerging tools of nanoscience will enable one-step conversion of cellulose or carbon dioxide into liquid fuels and economical photocatalytic conversion of water into hydrogen and oxygen. Fuel cell catalysts fabricated from nanoparticles of ruthenium-platinum have been shown to exhibit enhanced resistance to poisoning. Three-dimensional structuring of electrode materials can greatly enhance power storage in batteries and ultracapacitors, and provide advantages over existing technologies in terms of power losses and charge rates. Development and commercialization of these technologies would usher in entirely new energy storage systems that change the economics of solar and wind technologies, greatly contributing to energy independence and security.



Atomic-force microscope image of palladium nanoparticles electrodeposited on the surfaces of single-walled carbon nanotube, as part of a study on using these materials as mechanically flexible hydrogen sensors. Reproduced by permission from *Appl. Phys Lett.* © 2007, American Institute of Physics.

Coordination and Assessment Activities of the NNI

The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee leads the interagency coordination of the Federal Government's nanotechnology R&D enterprise. The NSET Subcommittee is under the National Science and Technology Council's (NSTC) Committee on Technology (CT). The participating agencies of the NNI execute the research, development, and funding functions of the NNI. External bodies periodically review the progress of the NNI and recommend strategies for further strengthening its activities. Figure 2 shows the various entities that play a role in NNI coordination and assessment activities and their relationships to each other. The roles of the various entities and their interactions are further described below.

Background

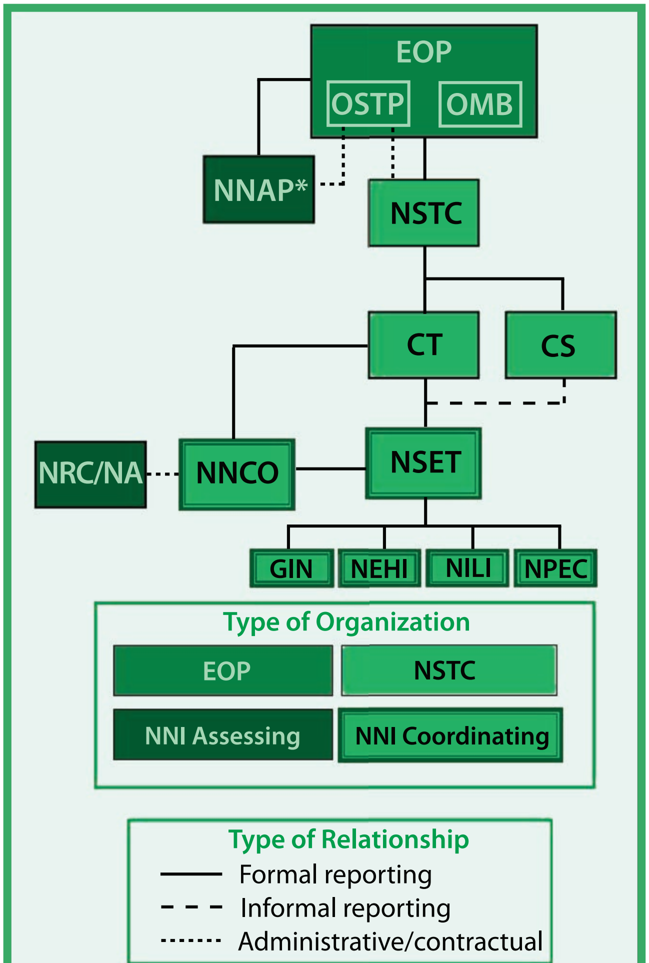
The beginnings of the NNI can be traced to September 1998, when the Interagency Working Group on Nanotechnology was formed. This working group sponsored workshops and studies to define the state of the art in nanoscale science and technology and to forecast future developments. Two years later, this effort was raised to the level of a Federal initiative. The NSET Subcommittee was then established under the NSTC's Committee on Technology to serve as the body responsible for interagency coordination. The National Nanotechnology Coordination Office (NNCO) was subsequently established as the point of contact on Federal nanotechnology R&D activities and to provide technical and administrative assistance to the NSET Subcommittee.

The importance of a coordinated Federal program for nanotechnology R&D was further recognized with the enactment of the 21st Century Nanotechnology Research and Development Act in December 2003 (hereafter, "the Act"). This legislation authorized appropriations for nanotechnology research, formalized many of the coordination structures that the NSTC had organized, and established additional mechanisms to ensure that the Government developed sound, informed nanotechnology R&D strategies and policies. This legislation also created the National Nanotechnology Advisory Panel (NNAP), called for a triennial review of the NNI by the National Research Council of the National Academies (NRC/NA), and established specific functions for the NNCO.

NSET Subcommittee

The NSET Subcommittee performs many of the coordination activities of the NNI, such as developing the NNI Strategic Plan, preparing the NNI supplement to the Presidential Budget, and sponsoring workshops that inform the Government's nanotechnology-related decision-making processes. Each agency participating in the NNI is represented on the NSET Subcommittee; a

Figure 2. Entities Involved in the Coordination and Assessment of the NNI



*Executive Order 13349 designates PCAST as the NNAP

(A glossary of abbreviations is provided in Appendix B.)

list is given at the front of this report. A Co-Chair from the Office of Science and Technology Policy (OSTP) and a Co-Chair from an NNI agency lead the NSET Subcommittee. It meets at least six times each year.

The member agencies of the NNI, working through the NSET Subcommittee, establish broad goals, identify priorities, and formulate plans for the NNI. This high-level framework, in turn, guides and informs the member agencies in developing their nanotechnology R&D implementation plans. The NSET Subcommittee also plans and sponsors interagency activities aimed at achieving the NNI goals. The subcommittee promotes a balanced investment across all of the agencies, to address the critical elements needed to support the development and utilization of nanotechnology. The subcommittee interacts with pertinent academic, industry, state and local government groups, and international organizations. The NSET Subcommittee also keeps the NSTC's Committee on Science (CS) informed of its activities.

Working Groups of the NSET Subcommittee

Four working groups currently exist under the NSET Subcommittee. These subgroups are focused on areas that the subcommittee recognizes will benefit from focused interagency attention and activity.

Global Issues in Nanotechnology Working Group

The NSET Subcommittee's Global Issues in Nanotechnology (GIN) Working Group coordinates international activities in nanotechnology, monitors foreign nanotechnology programs, and seeks to broaden international cooperation and communications with respect to nanotechnology R&D. The working group has representatives from all Federal agencies that have active nanotechnology R&D programs as well as from numerous agencies that have oversight roles in international affairs.

NNI agencies and representatives participate in many international activities, including bilateral and multilateral cooperative programs, monitoring of foreign nanotechnology R&D, and promotion of the trade and commercial interests of the United States. Cooperation and collaboration with other nations on nanoscale science and technology R&D, particularly in pre-competitive and non-competitive research areas, can further the progress of the NNI while helping our international partners achieve their own goals. The United States seeks to foster mutually beneficial relationships with other countries, in order to establish a framework for the safe, secure, and responsible use of nanotechnology worldwide.

In keeping with the NNI goal of supporting responsible development of nanotechnology, international cooperation is important to ensuring that health, environmental, safety, and security concerns surrounding the use of nanotechnology-enabled products are appropriately addressed by the global scientific community and relevant regulatory agencies. Effective communication among scientists, regulators, policy makers, consumers, industrial leaders, and other stakeholders also will be enhanced by cooperation with international partners. The development of a healthy global marketplace for nanotechnology products and ideas will require the establishment of consumer confidence, common approaches to nanotechnology environmental, health, and safety issues, efficient and effective regulatory schemes, and equitable trade practices for nanotechnology, not just in the United States, but worldwide.

Nanotechnology Environmental & Health Implications Working Group

Nanotechnology holds great potential. But in order to realize this potential fully, it is important to know how to handle and use engineered nanoscale materials safely in the lab, in manufacturing, in the workplace, and in consumer products, and to understand possible environmental, health, and safety impacts. NNI activities provide channels for the exchange of information and the formulation of research strategies that accelerate progress towards understanding the risks and benefits of nanotechnology and that lead to practices that protect human health and safety as well as the environment. The NSET Subcommittee's Nanotechnology Environmental and Health Implications (NEHI) Working Group coordinates many of the NNI activities in this area.

The NSET Subcommittee and NEHI Working Group provide leadership in establishing the national nanotechnology environmental, health, and safety research agenda and in communicating data and information related to environmental and health aspects of nanotechnology between NNI agencies and with the public. New tools and methods are required for the research that will enable risk analysis and assist in regulatory decision-making, and NNI activities support development of these tools and methods. All these activities require nanotechnology standards, including standard nomenclature and terminology, and the NNI works with consensus-based standards organizations to develop standards for nanotechnology. The outcome of this research, data collection, and tool and standards development is the information that provides the basis for the drafting of guidance in the safe handling and use of nanotechnology-derived materials and products by researchers, workers, and consumers.

The combined efforts of many sectors of the R&D community are required to address the environmental, health, and safety research priorities to strengthen the scientific foundation of risk assessments and risk management of nanotechnology-enabled products. The NNI agencies engage and interact with regional, state, and local groups, educational institutions, industry-supported groups, and non-governmental organizations. Interactions between the research community and the entities using the data collected in nanotechnology environmental, health, and safety research enhances the impact and value of NNI efforts and provides a collaborative approach.

Nanomanufacturing, Industry Liaison, & Innovation Working Group

Technology innovation is the key to realizing the NNI vision. This requires a close alliance among all the players in the innovation process, from researchers to industrial leaders, regulators, and investors. The NSET Subcommittee's Nanomanufacturing, Industry Liaison, and Innovation (NILI) Working Group coordinates many of the NNI activities in this area.

The NNI promotes U.S. leadership in the creation of new products and manufacturing processes derived from discovery at the nanoscale. The NNI creates mechanisms to facilitate nanotechnology innovation and to improve technology transfer to industry and promotes the exchange of information among Federal agencies, academia, and state, regional, and local organizations. Within the Federal Government, this effort includes interagency cooperation in the areas of standards, nomenclature, nanomanufacturing research, and use of programs that encourage innovation in small businesses. Industry liaison groups are a key tool in this undertaking. These are partnerships between the NNI and industry sectors. These liaison groups focus on a particular industry (e.g., electronics, chemicals, forest products). Formation of an industrial liaison group is open to any industrial sector. These groups review the status of relevant R&D, and they recommend new R&D directions and activities; work to identify best technology-transfer practices; and foster development of nanotechnology standards, terminology, nomenclature, and measurement and characterization methods.

Nanotechnology Public Engagement & Communications Working Group

The NNI recognizes that the perspectives of public and stakeholder groups are vital in the nanotechnology R&D enterprise and considers public engagement to be one of its key objectives. The NSET Subcommittee's Nanotechnology Public Engagement and Communications (NPEC) Working Group, in conjunction with the NNCO, coordinates many of the NNI activities in this area.

NPEC encourages, coordinates, and supports NNI member agencies and interagency efforts toward educating and engaging the public, policy makers, and stakeholder groups regarding nanotechnology, its applications and implications, and the work of the NNI. NPEC also facilitates the identification, prioritization, and implementation of activities involving public outreach, engagement, and communications on behalf of the NSET Subcommittee by promoting responsible communication of research results and topics of special interest; environmental, health, and safety issues; ethical, legal, and social implications issues; and public engagement.

To enable better communication among the NSET Subcommittee and its working groups, individual member agencies, and the NNCO, NPEC assists in the development of information and guidance for communications activities, and supports the development of best practices for outreach and engagement among governmental and non-governmental organizations, the public, and other stakeholders regarding the responsible development of nanotechnology.

National Nanotechnology Coordination Office

The National Nanotechnology Coordination Office (NNCO) provides technical and administrative support for the NSET Subcommittee, serves as a central point of contact for Federal nanotechnology R&D activities, and provides public outreach on behalf of the NNI.

The activities of the NNCO are numerous. The NNCO coordinates the preparation and publication of NNI interagency planning, budget, and assessment documents, such as the annual NNI supplement to the President's Budget. The NNCO organizes meetings of the NSET Subcommittee and its working groups. It also organizes NNI-sponsored workshops and, as appropriate, prepares and publishes reports of those workshops. These documents, along with nanotechnology-related news, educational resources, funding opportunities, and other information, are available at the NNI website, www.nano.gov. This website also provides information about recent developments in nanotechnology and NNI activities and serves as a resource for nanotechnology-related information. The NNCO coordinates development of information on the NNI and its activities for Congress when requested. The NNCO Director arranges for the triennial review of the NNI by the National Research Council of the National Academies. The NNCO will continue to organize public input and outreach activities; future examples may include web dialogues, citizens' panels, consensus conferences, and educational events.

Contributions from the NSET Subcommittee member agencies fund the NNCO. The White House Co-Chair of the NSTC Committee on Technology appoints the NNCO Director, in consultation with the Co-Chairs of the NSET Subcommittee. In accordance with the Act, the NNCO Director is detailed from a Federal agency to the NSTC as an agency representative and reports to the White House Co-Chair of the CT.

Executive Office of the President

Representatives from the Executive Office of the President (EOP) participate in NNI activities to ensure that implementation of the NNI is coordinated and consistent with Government-wide priorities. The primary points of interaction are the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB).

OSTP is responsible for advising the EOP on matters relating to science and technology and supports coordination of interagency science and technology activities. OSTP administers the NSTC, and the OSTP representative to the NSET Subcommittee is a Co-Chair of the subcommittee. This arrangement provides EOP-level input on and support for various NNI activities.

OMB is responsible for coordinating with the agency budget offices to establish the nanotechnology R&D budget for planning and tracking purposes. Each year, OMB collects budget information regarding the total Federal investment in nanotechnology R&D, as well as information about agency investments within each program component area.

Assessment

The Act calls for periodic assessment of the NNI through annual interagency reporting and review by external advisory bodies.

The Act calls for an annual interagency analysis of progress towards achieving the goals and priorities established for the NNI. This analysis is provided in the NNI supplement to the President's Budget, which also serves as the annual report called for in the Act. Specifically, progress towards achieving NNI goals and priorities is analyzed in terms of (1) coordination and cross-cutting activities, including activities of the NSET Subcommittee and (2) activities relating to the four NNI goals. Goal-related activities are: (a) NNI interagency activities, (b) NNI activities that take place within individual agencies, (c) NNI engagement with outside groups, and (d) nanotechnology-related activities external to the NNI, including international activities.

Review by outside advisory groups is vital to keeping NNI efforts focused and balanced, and the Act established two mechanism for such review. First, the Act called for the President to establish the National Nanotechnology Advisory Panel (NNAP) to advise the President and the NSTC on matters relating to the NNI. The Act specifically calls for the NNAP to assess the Federal nanotechnology R&D program at least once every two years. Executive Order 13349 designates the President's Council of Advisors on Science and Technology (PCAST) as the NNAP. The members of PCAST are senior representatives from industry and academic research institutions, with extensive experience in managing large science and technology organizations. In addition, PCAST identified a group of nanotechnology experts, which provided input and feedback on scientific and technological questions during the PCAST review. Second, the Act calls for the National Research Council of the National Academies (NRC/NA) to review the NNI every third year. The NRC/NA panel for the NNI reviews is comprised of a broad cross-section of technical experts with knowledge specifically related to nanotechnology. The NRC/NA provides independent science, technology, and health policy advice to the Government. It is the principal operating agency of the National Academies in providing services to the government, the public, and the scientific and engineering communities.

The first assessment by PCAST in its role as the NNAP was released in May 2005, and the first NRC/NA review was completed in November 2006. The perspectives of these two bodies, and their assessments, are complementary, and the NNI has benefited from the diverse inputs. The resulting recommendations have led to specific actions and focused attention in areas that were highlighted by both groups, including research on health and safety aspects of nanotechnology and expanded efforts to improve education and workforce preparation. Looking forward, reviews from both PCAST and the NRC/NA are expected in 2008; the latter will focus on assessing the NNI environmental, health, and safety research strategy. The NNI member agencies will implement the recommendation of these and subsequent reviews to further strengthen the initiative.

Appendix A. Workshops

The following is a list of workshops sponsored or endorsed by the Nanoscale Science, Engineering, and Technology Subcommittee between 2001–2007. These workshop were organized or supported by the National Nanotechnology Coordination Office or by agencies participating in the National Nanotechnology Initiative.

- Nanotechnology: Opportunities and Challenges (September 10, 2001).
  Report: http://www.wtec.org/nanoreports/FinalUCLAnanoRpt0302.pdf
- Nanomanufacturing and Processing (January 5–7, 2002).
  Report: http://www.nsf.gov/mps/dmr/nsfec_workshop_report.pdf
- Nanotechnology Innovation for Chemical, Biological, Radiological, and Explosive (CBRE): Detection and Protection (May 2–3, 2002).
  Report: http://www.wtec.org/nanoreports/cbre/
- From the Laboratory to New Commercial Frontiers (May 23, 2002).
  Report: http://www.wtec.org/nanoreports/ACF64.pdf
- Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function (September 30–October 1, 2002).
  Report: http://www.chemicalvision2020.org/nanomaterialsroadmap.html
- Nanoscale Science and Engineering for Agriculture and Food Systems (November 18–19, 2002).
  Report: http://www.csrees.usda.gov/nea/technology/in_focus/nanotech_if_workshop.html
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- Ethical Aspects of Nanotechnology (January 11–12, 2007).
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- Pollution Prevention through Nanotechnology Conference (September 25–26, 2007).

Appendix B. Glossary

The Act	The 21st Century Nanotechnology Research and Development Act (Public Law 108-153)
agencies	Departments, Agencies, Commissions, etc. of the Executive Branch of the United States Government
BIS	Bureau of Industry and Security (DOC)
CPSC	Consumer Product Safety Commission
CS	Committee on Science of the NSTC
CSREES	Cooperative State Research, Education, and Extension Service (USDA)
CT	Committee on Technology of the NSTC
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOEd	Department of Education
DOI	Department of the Interior
DOJ	Department of Justice
DOL	Department of Labor
DOS	Department of State
DOT	Department of Transportation
DOTreas	Department of the Treasury
EHS	Environmental, health, and safety
ELSI	Ethical, legal, and social implications
EOP	Executive Office of the President
EPA	Environmental Protection Agency
FDA	Food and Drug Administration (HHS)
FS	Forest Service (USDA)
GIN	Global Issues in Nanotechnology Working Group of the NSET Subcommittee
HHS	Department of Health and Human Services
IARPA	Intelligence Advanced Research Projects Activity
ITC	International Trade Commission
NASA	National Aeronautics and Space Administration
NCI	National Cancer Institute (HHS/NIH)
NCL	Nanotechnology Characterization Laboratory (HHS/NIH/NCI)
NEHI	Nanotechnology Environmental and Health Implications Working Group of the NSET Subcommittee

NIEHS	National Institute of Environmental Health Sciences (HHS/NIH)
NIH	National Institutes of Health (HHS)
NILI	Nanomanufacturing, Industry Liaison, and Innovation Working Group of the NSET Subcommittee
NIOSH	National Institute for Occupational Safety and Health (HHS/Centers for Disease Control and Prevention)
NIST	National Institute of Standards and Technology (DOC)
NNAP	National Nanotechnology Advisory Panel
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NPEC	Nanotechnology Public Engagement and Communications Working Group of the NSET Subcommittee
NRC	Nuclear Regulatory Commission
NRC/NA	National Research Council of the National Academies
NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC
NSF	National Science Foundation
NSRC	Nanoscale Science Research Center (funded by DOE)
NSTC	National Science and Technology Council
OMB	Office of Management and Budget (EOP)
OSTP	Office of Science and Technology Policy (EOP)
PCA	Program Component Area
PCAST	President's Council of Advisors on Science and Technology
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey (DOI)
USPTO	U.S. Patent and Trademark Office (DOC)

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National Science and Technology Council
Committee on Technology
Subcommittee on Nanoscale Science, Engineering, and Technology

National Nanotechnology Coordination Office
4201 Wilson Boulevard
Stafford II, Suite 405
Arlington, Virginia 22230

703-292-8626 phone
703-292-9312 fax

www.nano.gov