NATIONAL NANOTECHNOLOGY INITIATIVE

STRATEGIC PLAN

National Science and Technology Council

Committee on Technology

Subcommittee on Nanoscale Science, Engineering, and Technology

DRAFT FOR PUBLIC COMMENT

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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 committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at www.whitehouse.gov/administration/eop/ostp/nstc.

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The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee is the interagency body responsible for coordinating, planning, implementing, and reviewing the National Nanotechnology Initiative (NNI). It is a subcommittee of the Committee on Technology of the National Science and Technology Council. The National Nanotechnology Coordination Office (NNCO) provides technical and administrative support to the NSET Subcommittee and its working groups in the preparation of multiagency planning, budget, and assessment documents related to the NNI, including this strategy document. More information is available at www.nano.gov.

About this Document

This document is the strategic plan for the NNI. It describes the NNI vision and goals and the strategies by which these 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 Research and Development Act of 2003, and it also identifies specific objectives toward collectively achieving the NNI vision. This plan updates and replaces the NNI Strategic Plan of February 2014.

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Executive Summary

The National Nanotechnology Initiative (NNI), established in 2001, is now a collaboration of twenty Federal agencies and Cabinet-level departments with shared interests in nanotechnology research, development, and commercialization. These agencies recognize that the ability to understand and harness the novel phenomena that occur at the nanoscale is already leading to revolutionary new materials, devices, and structures. These advances promise to improve human health and quality of life, enhance the U.S. economy, boost job creation, and strengthen our national defense. Since the inception of the NNI, these agencies have invested more than $23 billion in support of cutting-edge research; world-class user facilities for characterization, modeling, and fabrication; and the responsible transfer of nanotechnology-based products from lab to market. As a result of these investments, nanotechnology has become ubiquitous in our daily lives and can be found in a wide variety of commercial products including healthcare products, cosmetics, consumer electronics, apparel, and automobiles. Nanotechnology is poised to revolutionize the way we diagnose and treat diseases such as cancer, help us improve our fitness, and reduce our energy consumption.

Under the 21st Century Nanotechnology Research and Development Act of 2003, NNI agencies are required to develop an updated NNI Strategic Plan every three years. This document represents a consensus among NNI agencies on the high-level goals and priorities of the initiative and on specific objectives to be pursued over at least the next three years. The plan provides the framework under which individual agencies conduct their own mission-specific nanotechnology programs, coordinate these activities with those of other NNI agencies, and collaborate.

Over the life of the NNI, nanotechnology has evolved from an area of fundamental research focused on understanding and exploiting the phenomena that occur at the nanoscale to what is now a broadly enabling technology. Recognizing this evolution, the focus of the NNI has broadened from investments in foundational (fundamental) research in nanomaterials and nanotechnology-enabled devices to include activities directed at how these novel materials and devices can be incorporated into nanotechnology-enabled systems. This update of the NNI Strategic Plan reflects that evolution and addresses how the NNI agencies will collaborate with each other and the broader nanotechnology community to expand the ecosystem that supports fundamental discovery, fosters innovation, and promotes the transfer of nanotechnology discoveries from lab to market.

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

Nanotechnology is inherently multidisciplinary, and NNI agencies have supported research at the frontiers and intersections of scientific disciplines such as biology, chemistry, materials science, and physics to enable new discoveries. Agencies will build on that legacy to foster research that exploits the convergence of nanotechnology, biotechnology, information technology, and cognitive science to lead to the next scientific breakthroughs and address key societal challenges. NNI agencies will also promote the integration of modeling and simulation together with data analytics across the research and development spectrum to accelerate nanotechnology discovery.

NNI agencies will continue to support a diverse and robust portfolio of Nanotechnology Signature Initiatives (NSIs) to provide additional focus and collaboration to accelerate technology development in areas of strategic national interest. In 2015, the White House Office of Science and Technology Policy (OSTP) announced the first Nanotechnology-Inspired Grand Challenge challenging the community to : *create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain*. Grand challenges such as this have ambitious but achievable goals that harness science, technology, and innovation to solve important national or global problems and have the potential to capture the public's imagination. NNI agencies will continue to explore grand challenges and other mechanisms to promote public–private collaborations that accelerate nanotechnology discovery, development, and deployment.

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

Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) funding has been instrumental in the transfer of nanotechnology products from lab to market. Building on this success, NNI agencies will explore additional mechanisms to foster commercialization, innovation, and entrepreneurship. Programs such as the NSF Innovation Corps (I-Corps), the NIH Translation of Nanotechnology in Cancer Consortium, and the Air Force Research Laboratory-supported Nano-Bio Manufacturing Consortium (NBMC) are excellent models for supporting innovation and commercialization. NNI agencies will continue to support activities such as these and to identify best practices that can be incorporated into new approaches to maximize the commercial benefit of NNI investments.

While sparking innovation and stimulating entrepreneurship is critical, sustaining success is also vital. NNI agencies together with the National Nanotechnology Coordination Office (NNCO) augment outreach to industry, technical societies, and trade organizations with more focused measures to identify and help address challenges faced by businesses working to commercialize nanotechnology. Among these challenges is the development of scalable, robust, and repeatable methods for the manufacture of nanomaterials and nanotechnology-enabled products (NEPs). NNI agencies will strengthen intersections with the National Network for Manufacturing Innovation (NNMI) and its Manufacturing Innovation Institutes to identify opportunities to address these and other nanotechnology-related manufacturing challenges.

Commercialization of U.S.-developed nanotechnology products requires active engagement with the international community in areas such as intellectual property, standards development, and the potential environmental, health, and safety (EHS) implications of engineered nanomaterials (ENMs) and NEPs. NNI agencies are active in and, in many cases, lead international collaborations in these and other areas. The agencies will continue these interactions and forge new partnerships to advance nanotechnology commercialization and other NNI goals.

Goal 3: Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology.

Success in nanotechnology research, development, and commercialization requires a skilled workforce—from the shop floor to the laboratory—and world-class physical and computational tools. NNI agencies will continue to promote the development of new experimental and computational tools to support advances in nanotechnology. A key accomplishment of the NNI has been the development of unique, high-value nanofabrication and characterization facilities that are open for use by researchers from industry, academia, and government. NNI agencies will pursue an "evergreen" approach to physical infrastructure that continually supports workhorse tools in addition to providing support for the development of new tools and techniques and for workforce training to maintain these facilities. This physical infrastructure must be complemented by a robust cyber infrastructure, including modeling and simulation tools, databases, and advanced data analytics. This cyber toolbox has been and will be increasingly critical to the understanding and development of nanotechnology.

The NNI also has a rich legacy in education and outreach through programs such as the NSF-sponsored Nanoscale Informal Science Education Network (NISE Net), a network of museums and other institutions that had more than 30 million people participating in its programs, events, and exhibitions from 2008 to 2015. Recently NNI agencies, in collaboration with NNCO, have significantly expanded outreach and student engagement in nanotechnology-related topics through activities such as contests and challenges and through the development of networks to encourage students and provide support for educators. NNI agencies will build on these mechanisms and explore other approaches to education and engagement that will inform students and the public about nanotechnology and will also inspire the next generation of scientists and engineers, including those from underrepresented groups.

Goal 4: Support responsible development of nanotechnology.

Responsible and sustainable development is critical throughout the entire nanotechnology enterprise to protect human health and the environment while realizing the societal and economic benefits of this broadly enabling technology. NNI agencies will continue to support collaborative fundamental research to refine our understanding of the EHS implications of ENMs and NEPs, as discussed in the 2011 NNI Environmental, Health, and Safety Research Strategy. NNI agencies have worked with industry to provide information and assistance to ensure safe handling of nanomaterials and the production of NEPs that are safe for consumers. The ethical, legal, and societal implications of nanotechnology continue to be important issues for the initiative.

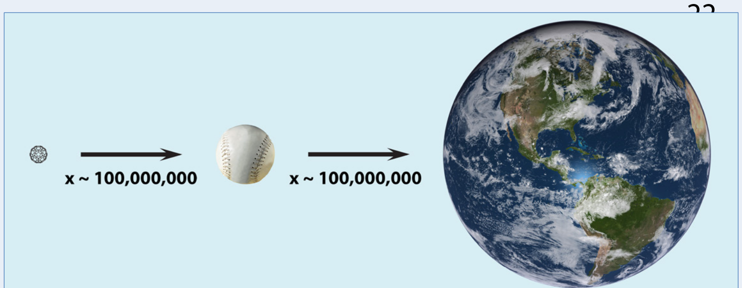
In 2016, the NNI initiated a series of webinars focused on promoting best safety practices in nanotechnology research, product manufacturing, and product disposal and recycling. NNI agencies will continue these activities and pursue other opportunities to collaborate with the nanotechnology community to share information and best practices. NNI agencies and NNCO also have been active in international collaborations, such as the U.S.–EU Communities of Research (CORs), to share information and coordinate activities; they will continue these efforts and look for new ways to promote global collaboration on the responsible development of nanotechnology.

The NNI

Introduction

Since 2001, Federal agencies and Cabinet-level departments have invested more than $23 billion in nanotechnology research, development, and commercialization. These investments, made under the auspices of the National Nanotechnology Initiative (NNI), have enabled groundbreaking discoveries that have revolutionized science; established world-class facilities for the characterization of nanoscale materials and their fabrication into nanoscale devices; educated tens of thousands of individuals from undergraduate students to postdoctoral researchers; and fostered the responsible incorporation of nanotechnology into commercial products. As a result, nanotechnology is becoming ubiquitous in our daily lives and has found its way into many commercial products, including cosmetics, apparel, consumer electronics, and automobiles. Nanotechnology-based diagnostics and therapeutics are poised to drastically improve the way we diagnose and treat diseases, such as cancer, and nanotechnology can help us improve our fitness and reduce our energy consumption. Looking toward the future, nanotechnology is moving from a fundamental research area to an enabling technology that can lead to new materials, devices, and systems that will profoundly impact our quality of life, economy, and national security. The strong collaborations built under the NNI will be critical in sustaining an ecosystem that invests in the next breakthroughs in nanoscale materials and devices but also promotes the effective and responsible transition of nanotechnology discoveries from lab to market. This strategic plan builds upon the collaborations and prior accomplishments of the NNI to develop and nurture that ecosystem and to move the NNI into its next phase.

What is nanotechnology?



If a buckminsterfullerene molecule (60 carbon atoms arranged in a sphere, with a diameter of 1.1 nanometers) were as big as a softball, a softball would be as big as the Earth.

Nanotechnology encompasses science, engineering, and technology at the nanoscale, which is about 1 to 100 nanometers. Just how small is that? A nanometer is one-billionth of a meter. For reference, a sheet of paper is about 100,000 nanometers thick. Nanoscale matter can behave differently than the same bulk material. For example, a material's melting point, color, strength, chemical reactivity, and more may change at the nanoscale. Nanotechnology is affecting all aspects of life through innovations that enable, for example, strong, lightweight materials for better fuel economy; targeted drug delivery for safer and more effective cancer treatments; clean accessible drinking water around the world; superfast computers with vast amounts of storage; self-cleaning surfaces; wearable health monitors; more efficient solar panels; safer food through packaging and monitoring; regrowth of skin, bone, and nerve cells for better medical outcomes; smart windows that lighten or darken to conserve energy; and nanotechnology-enabled concrete that dries more quickly and has sensors to detect stress or corrosion in roads, bridges, and buildings. By working at very small size scales, nanotechnology is improving our quality of life.

Table 1: Federal Departments and Agencies Participating in the NNI.

Department / Agency	Component agencies
11 Federal departments and independent agencies and commissions with nanotechnology R&D budgets	
Consumer Product Safety Commission (CPSC)†	
Department of Commerce (DOC)	Bureau of Industry and Security (BIS)‡ Economic Development Administration (EDA)‡ National Institute of Standards and Technology (NIST) U.S. Patent and Trademark Office (USPTO)‡
Deparmtnet of Defense (DOD)	
Department of Energy (DOE)	
Department of Health and Human Services (DHHS)	Food and Drug Administration (FDA) National Institutes of Health (NIH) National Institute for Occupational Safety and Health (NIOSH)
Department of Homeland Security (DHS)	
Department of Transportation (DOT)	Federal HIghway Administration (FHWA)
Environmental Protection Agency (EPA)	
National Aeronautics and Space Administration (NASA)	
National Science Foundation (NSF)	
U.S. Departmtent of Agriculture (USDA)	Agricultural Research Service (ARS) Forest Service (FS) National Institute of Food and Agricutlure (NIFA)
9 other participating departments and independent agencies and commissions	
Department of Education (DOEd)	
Department of the Interior (DOI)	U.S. Geological Survey (USGS)
Department of Justice (DOJ)	National Institute of Justice (NIJ)
Department of Labor (DOL)	Occupational Safety and Health Administration (OSHA)
Department of State (DOS)	
Department of the Treasury (DOTreas)	
Intelligence Community (IC)	
Nuclear Regulatory Commission (NRC)†	
U.S. International Trade Commission (USITC)†	

† Independent commission that is represented on NSET but is non-voting.
‡ No specific nanotechnology R&D budget.

Overview of the NNI

The National Nanotechnology Initiative, established in 2001, has grown to be a collaboration of twenty Federal departments and independent agencies with interests in nanotechnology research, development, and commercialization (see Table 1).[1] These agencies recognize that the ability to understand and harness the novel phenomena that occur at the nanoscale can lead to revolutionary new materials, devices, and structures. Furthermore, advances in nanotechnology can improve human health and quality of life, enhance our economy, boost job creation, and strengthen our national defense. Collectively the NNI agencies have a broad range of roles and responsibilities, from conducting and supporting fundamental and mission-focused research to developing and implementing regulations that provide for the safe and environmentally responsible development of nanotechnology and its incorporation into commercial products.

Funding support for the NNI comes directly from eleven of the participating agencies, rather than from a centralized NNI budget. The nanotechnology budgets of each of these agencies are reported in the annual NNI Supplement to the President's Budget, which also serves as the annual report for the NNI, summarizing investments by each agency and highlighting accomplishments and future plans. As an interagency research and development (R&D) effort, the NNI informs and influences Federal budget and planning processes through its individual participating agencies and through the National Science and Technology Council (NSTC).

The activities of the NNI are coordinated under the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC's Committee on Technology. NSET members work together to develop a comprehensive nanotechnology R&D program by establishing shared goals, priorities, and strategies that complement agency-specific missions and activities and provide opportunities for collaboration and leveraging of participating agencies' resources and investments. In addition, the NNI provides a central interface for stakeholders and interested members of the general public, including those from academia, industry, and regional/state organizations, as well as international counterparts. To these ends, the National Nanotechnology Coordination Office (NNCO) provides technical and administrative support to the NSET Subcommittee, serves as a central point of contact for Federal nanotechnology R&D activities, and performs public outreach on behalf of the NNI. Working groups established by the NSET Subcommittee serve to strengthen interagency coordination and collaboration in critical areas such as commercialization and the environmental, health, and safety aspects of nanotechnology (nanoEHS). In addition, coordinators are named for specific cross-cutting areas to serve as primary points of contact for these topics.

The vision of the 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 NNI expedites the discovery, development, and deployment of nanoscale science, engineering, 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 NNI agencies work collectively toward the following four goals:

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

[1] See Appendix A for a description of each agency's interest in the NNI.

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 a dynamic infrastructure and toolset to advance nanotechnology.

Goal 4: Support responsible development of nanotechnology.

As the NNI agencies work toward realizing the NNI vision, success will not be defined as a static endpoint. Rather, success will be measured by continual and substantive progress toward these four goals.

The NNI Strategic Plan

The National Nanotechnology Initiative Strategic Plan provides the framework that underpins the nanotechnology-related activities of the NNI agencies. Its aim is to ensure that advancements in nanotechnology and its applications continue in this vital R&D enterprise, while potential concerns about current and future applications are also addressed. The purpose of the strategic plan is to catalyze achievement in support of the goals and vision of the NNI, as outlined below, by providing guidance for agency leaders, program managers, and the research community regarding the planning and implementation of Federal nanotechnology R&D investments and activities.

The 21st Century Nanotechnology Research and Development Act of 2003 calls for the triennial update of the NNI Strategic Plan.[2] This strategic plan represents a consensus among NNI agencies on the high-level goals and priorities of the initiative and on specific objectives to be pursued over at least the next three years. It serves as an integrated, interagency strategy that informs the strategic plans of individual agencies (e.g., EPA's Nanomaterial Research Strategy,[3] FDA's Nanotechnology Regulatory Science Research Plan,[4] NASA's 2015 Nanotechnology Roadmap,[5] and the Strategic Plan for NIOSH Nanotechnology Research and Guidance[6]). Accordingly, this strategic plan provides the framework under which individual agencies can conduct their own mission-specific nanotechnology programs, and it promotes interagency collaboration and coordination.

This update of the NNI Strategic Plan is focused on creating an ecosystem that supports all aspects of the nanotechnology enterprise from fundamental discovery to commercial products. This plan emphasizes the use of various mechanisms for collaboration across the broader nanotechnology community to advance the goals of the NNI. These mechanisms include well-established structures such as the NNI Nanotechnology Signature Initiatives (NSIs), as well as newer approaches such as

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[2] 21st Century Nanotechnology Research and Development Act (15 U.S.C. §7501(c)(4), P.L. 108-153); www.gpo.gov/fdsys/pkg/PLAW-108publ153/html/PLAW-108publ153.htm).

[3] United States Environmental Protection Agency Office of Research and Development, *Nanomaterial Research Strategy* (EPA 620/K-09/011, U.S. Environmental Protection Agency, Washington, District of Columbia, 2009).

[4] United States Food and Drug Administration, *2013 Nanotechnology Regulatory Science Research Plan* (U.S. Food and Drug Administration, Washington, District of Columbia, 2013; www.fda.gov/ScienceResearch/SpecialTopics/Nanotechnology/ucm273325.htm).

[5] National Aeronautics and Space Administration, *NASA Technology Roadmaps, Technology Area 10: Nanotechnology* (National Aeronautics and Space Administration, Washington, District of Columbia, 2015; www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_10_nanotechnology_final.pdf).

[6] Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, *Protecting the Nanotechnology Workforce: NIOSH Nanotechnology Research and Guidance Strategic Plan* (National Institute for Occupational Safety and Health, Washington, District of Columbia, 2014; www.cdc.gov/niosh/docs/2014-106/).

Nanotechnology-Inspired Grand Challenges. This plan also relies upon opportunities to leverage complementary activities in existing Federal initiatives in healthcare,[7] information technology,[8] and advanced materials and manufacturing[9] to extend the reach and broaden the impact of the NNI. This update of the NNI Strategic Plan promotes new approaches to engaging the general public and inspiring the next generation of scientists and engineers, including those from underrepresented groups, through the use of contests and other challenges. This plan also seeks to build upon the highly regarded NNI collaborations on understanding the potential environmental, health, and safety (EHS) implications of nanotechnology and to use that understanding in developing science-based regulatory policies.

[7] For example, the Precision Medicine Initiative (www.whitehouse.gov/precision-medicine) and the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative (www.braininitiative.nih.gov/).
[8] For example, the National Strategic Computing Initiative (www.whitehouse.gov/sites/default/files/microsites/ostp/nsci_fact_sheet.pdf) and the Networking and Information Technology Research and Development Program (www.nitrd.gov/).
[9] For example, the Materials Genome Initiative (www.mgi.gov/), the National Network for Manufacturing Innovation (www.manufacturing.gov/nnmi/), and the NSTC Committee on Technology's Subcommittee on Advanced Manufacturing.

Goals and Objectives

The participating agencies pursue the NNI vision through four interdependent goals. These goals have remained consistent since they were first introduced in the 2004 NNI Strategic Plan and are all equally critical to the NNI's success. Based on extensive input from internal and external stakeholders, the NNI agencies have specified objectives in support of each goal as detailed below. Although not all member agencies are responsible for fulfilling all objectives, each objective is advanced by at least two agencies. The NNI agencies independently and collaboratively contribute to all four goals, and these activities are reported on an annual basis in the NNI Supplement to the President's Budget.

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

NNI agencies expand the limits of fundamental understanding of the phenomena that occur at the nanoscale and exploit those phenomena to develop new materials and devices whose performance exceeds that of conventional technologies. The overarching focus of Goal 1 is to advance nanoscience and nanoengineering through the implementation of the objectives described below. Progress in R&D will require the availability of a skilled workforce, infrastructure, and tools (Goal 3) and will produce the discoveries that will enable the responsible incorporation of nanotechnology into commercial products (Goals 2 and 4).

Goal 1 Objectives

1.1. Support R&D that extends the frontiers of nanotechnology and strengthens the intersections of scientific disciplines.

1.1.1. Extend the frontiers of nanotechnology with a diverse R&D portfolio that includes basic scientific research, foundational research, use-inspired research, applications research, and technology development.

1.1.2. Strengthen the intersections of scientific disciplines by supporting interdisciplinary research to facilitate convergence of knowledge, tools, and domains of nanotechnology with other areas in science and technology.

1.1.3. Sustain a strategic and complementary research portfolio incorporating intramural and extramural programs consisting of single-investigator efforts, multi-investigator and multidisciplinary research teams, and centers and networks for focused research.

1.1.4. Foster the development of comprehensive approaches to nanotechnology R&D that integrate simulation, modeling, and data analytics throughout all aspects of materials and device development, evaluation, and testing.

1.2. Identify and support nanoscale science and technology research enabled by breakthroughs in science, driven by national priorities, and informed by active engagement with stakeholders.

1.2.1. Engage with academia, industry, government, and the public to gather input and feedback on federally supported research.

1.2.2. Foster stakeholder collaborations with NNI agencies via means such as matching funds, challenge prizes, partnerships, and consortia.

1.2.3. Identify and facilitate opportunities for international collaboration.

1.3. Assess the performance of the U.S. nanotechnology R&D program.

1.3.1. Identify the common attributes of successful research programs and general best practices within the NNI agencies and within other domestic and international nanotechnology R&D programs.

1.3.2. Develop quantitative measures of performance in coordination with existing efforts to establish metrics for innovation.

1.3.3. Tailor, enhance, or augment traditional assessment strategies and employ them to assess the impact of NNI activities.

1.4. Advance a dynamic portfolio of Nanotechnology Signature Initiatives (NSIs) that are each supported by multiple NNI agencies and address significant national priorities.

1.4.1. Identify potential new NSIs with input from stakeholders.

1.4.2. Conduct and disseminate the outcomes of biennial assessments of each NSI to review progress, ensure relevance and need to continue, and identify future strategic areas of focus.

1.5. Utilize Nanotechnology-Inspired Grand Challenges to engage the broader community to solve problems of national and global importance.

1.5.1. Identify topics for potential grand challenges by engaging the broader community through mechanisms such as workshops, Requests For Information (RFIs), and webinars.

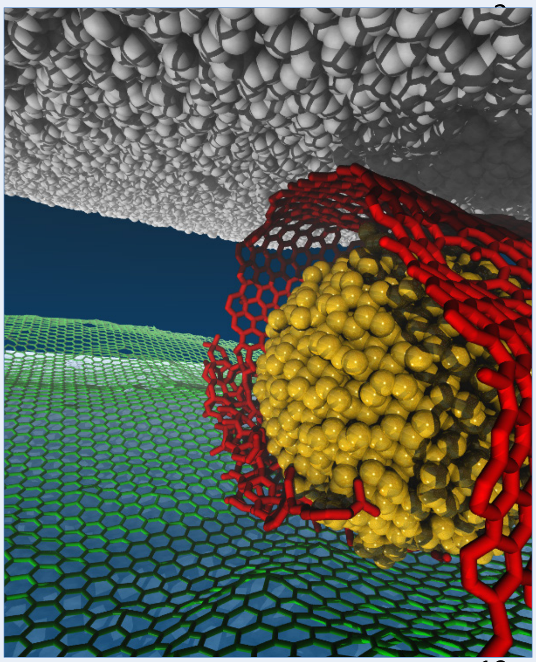
1.5.2. Develop approaches, including public–private partnerships and consortia, to plan and resolve grand challenges.

1.5.3. Conduct biennial assessments of the progress and impact of each grand challenge and report the results.

A unique, established strength of the nanotechnology enterprise lies in its interdisciplinary nature. A broad nanotechnology R&D portfolio invests at the frontiers and intersections of many fields including biology, chemistry, computer science, ecology, engineering, geology, materials science, medicine, physics, and the social sciences. Recently, NNI agencies have been exploring efforts focused on research at the convergence of nanotechnology, biotechnology, information technology, and cognitive sciences that leverage knowledge and approaches in each of these areas to solve problems of national and societal importance. As part of this broad nanotechnology R&D portfolio, NNI agencies will continue to explore convergence as a way of enhancing the impact that nanotechnology can have on scientific discovery and solving critical problems.

Activities targeted toward this goal span a broad continuum, from support for basic and fundamental research, to use-inspired and applications-focused research, to technology development. Research efforts of NNI agencies are a mixture of extramural research and research conducted in Government labs, each of which plays a unique and vital role in the discovery and innovation process. These efforts

Near Zero Friction from Nanoscale Lubricants



Visualized model of a superlubricity (low-friction) system (gold = nanodiamond particle; red = graphene nanoscroll; green = underlying graphene on blue silica; black/gray = diamond-like carbon surface). Image courtesy of the Center for Nanoscale Materials; image credit: J. Ingsley, Argonne National Laboratory.

Researchers at Argonne National Laboratory's Center for Nanoscale Materials, one of five DOE Nanoscale Science Research Centers (NSRCs), have attained superlubricity—the near absence of friction—using nanodiamonds wrapped in graphene flakes at the interface of diamond-like carbon and graphene on a silica substrate.[10] Friction hampers the movement of all mechanical parts in engines, motors, etc., in transportation, oil refineries, power plants, and other facilities, and it accounts for most of the energy lost in moving parts. This wear accelerates mechanical failures, ultimately causing machines to both break down sooner and cost more to run.

The Argonne research demonstrates that friction can be reduced and superlubricity can be achieved at the macroscale in a dry operating environment by the addition of nanodiamonds and graphene flakes between two surfaces, one made of graphene-coated silica and one made of diamond-like carbon. In this system, the coefficient of friction is just 0.004 (10–20 times lower than Teflon), and contact areas are reduced by more than 65%. Analysis of the wear debris revealed that the graphene flakes form nanoscroll-like features that wrap around the nanodiamonds. Computer simulations show that more and more graphene flakes scroll with time, gradually reducing the contact area between the nanoscrolls and the diamond-like carbon surface, which allows superlubricity to be attained. This discovery could enable significant cost savings by increasing machine life and reducing the amount of energy needed to run mechanical systems. In 2016 DOE awarded Argonne a Technology Commercialization Fund Award to develop the technology with the John Crane company.[11]

are executed through a balanced combination of grants to single investigators, collaborative research teams, and networks; research centers; and user facilities.

Modeling and simulation tools as well as data analytics can support and enhance all aspects of nanotechnology research, development, and commercialization. Computational modeling and simulation tools are becoming increasingly more efficient and accurate in predicting the behavior and performance of nanoscale materials and nanotechnology-enabled devices. These tools can reduce the time, effort, and cost required to develop robust synthesis and processing approaches to produce nanomaterials and nanomaterial-based products, improve nanomanufacturing methods, and focus testing and evaluation efforts on those tests that are the best representation of performance. Data

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[10] D. Berman, S.A. Deshmukh, S.K.R.S. Sankaranarayanan, A. Erdemir, A.V. Sumant, Macroscale superlubricity enabled by graphene nanoscroll formation. *Science* **348**, 1118–1122 (2015).
[11] energy.gov/technologytransitions/articles/doe-announces-16-million-54-projects-help-commercialize-promising

analytics tools can help process the large amounts of data generated from the testing and evaluation of nanoscale materials and nanotechnology-enabled devices and can identify trends that can be exploited to optimize the properties and performance of these materials and devices. NNI agencies will not only continue to support the development of improved simulation, modeling, and data analytics tools in support of nanotechnology research and development but will also encourage the development of integrated approaches that incorporate their use in all aspects of nanoscale material and device development, testing, and evaluation.

As the NNI moves toward its third decade, there is a greater emphasis not only on supporting fundamental research that will lead to the next discoveries in nanoscale materials and devices but also on developing nanotechnology-enabled systems. The NSIs provide one potential mechanism to facilitate this transition. In 2015, the five existing NSIs were reviewed to assess the progress that has been made against their research goals and objectives, to update these goals and objectives to ensure continued relevance, and to determine if there is still a need for the focus that NSIs provide in a given topical area. During that review process it was determined that a robust research ecosystem has been established to support nanotechnology-based solar energy R&D such that the focus of an NSI in this area was no longer required. Accordingly, the *Nanotechnology for Solar Energy Capture and Conversion* NSI was retired. In 2016, a new NSI, *Water Sustainability through Nanotechnology: Nanoscale Solutions for a Global-Scale Challenge*,[12] was launched to address the pressing technical challenges of ensuring water quality and supply, including increasing water availability, improving the efficiency of water delivery and use, and enabling the next generation of water monitoring systems. NNI agencies will continue to develop, implement, and routinely review a robust portfolio of NSIs to address national priorities.

Collaborations and partnerships are a key aspect of the NNI and of the U.S. innovation ecosystem. These interactions include academic, industrial, and international collaborations in areas of mutual interest and benefit, where partnering will accelerate and/or improve research outcomes. Public–private partnerships and other novel approaches to managing and implementing research should be pursued that engage the broader community in advancing the knowledge base and in developing solutions to pressing national and global problems. Along these lines, the NNI has turned to the use of Nanotechnology-Inspired Grand Challenges, ambitious but achievable goals that harness nanoscience, nanotechnology, and innovation to solve important national or global problems and have the potential to capture the public's imagination. Based upon input from NNI agencies and the public, the first such grand challenge was announced in 2015 calling on the scientific community to work together to "*create a computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and process information with the efficiency of the human brain.*"[13] NNI agencies, industry, universities, and private foundations have expressed an interest in addressing this challenge and are working to produce transformational computing capabilities that will be essential for turning the rising deluge of data into useful information when and where it is needed. NNI agencies will work closely with the scientific community to identify topics for additional grand challenges and to develop plans to address them. Nanotechnology is an enabling element of many other national initiatives beyond the

[12] www.nano.gov/NSIWater
[13] www.nano.gov/FutureComputing

NNI, including the Brain Research through Advancing Innovative Neurotechnologies (BRAIN)[14] and National Microbiome[15] Initiatives. NNI agencies will continue to support these and other important national initiatives and will explore ways to contribute to the development of new initiatives.

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

Nanotechnology is rapidly becoming ubiquitous in a variety of products that improve our daily lives—from cosmetics and sunscreens, to healthcare, to consumer electronics, and to automobile tires and components. However, more work is needed to fully realize the benefits that nanotechnology can have for our national security, economic well-being, creation of jobs, and quality of life. The focus of this goal is to establish and expand the ecosystem and the resources to foster nanotechnology innovation and the responsible transfer of nanotechnology-enabled products (NEPs) from lab to market.

Successful commercialization of any new technology depends upon a number of factors. Robust, cost-effective manufacturing methods are needed to reliably make products that take full advantage of the novel properties of their nanoscale constituents. Investment strategies are needed to reduce risk and shepherd the most promising technologies from lab to market. Maximizing the benefits of NEPs to the U.S. economy requires efforts to remove barriers to global commercialization, as well as understanding the potential markets for those products.

The NNI fosters technology transfer by facilitating interactions with key industry sectors and providing access to resources available at NNI agencies, e.g., results of funded nanotechnology R&D, access to user facilities and government collaborators, and aiding in the establishment of a business environment conducive to the responsible development of NEPs. Partners in this endeavor include international, regional, State, and local organizations that promote nanotechnology development and commercialization as well as professional societies, trade associations, and other nongovernmental organizations.

Goal 2 Objectives

2.1. Assist the nanotechnology-based business community in understanding the Federal Government's R&D funding and regulatory environment.

2.1.1. Disseminate information on where the Federal Government can directly assist in the transfer and commercialization of nanotechnology-enabled products.

2.1.2. Disseminate information about resources available to support commercialization of nanotechnology-based products.

2.2. Increase focus on nanotechnology-based commercialization and related support for public–private partnerships.

2.2.1. Sustain successful initiatives and expand the number of public–private partnerships.

2.2.2. Collect and disseminate information on best practices to advance commercialization of U.S.-derived nanotechnologies.

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[14] P. S. Weiss, President Obama announces the BRAIN Initiative. *ACS Nano* **7**(4), 2873–2874 (2013).
[15] P. S. Weiss, Launching the Microbiome Initiative. *ACS Nano* **10**(6), 5589–5590 (2016).

2.2.3. Foster development of robust, scalable nanomanufacturing methods with sufficient precision to facilitate commercialization.

2.3. Promote broader accessibility and utilization of user facilities, cooperative research centers, and regional initiatives to accelerate the transfer of nanoscale science from lab to market.

2.3.1. Provide flexible and timely access to tools and processes, expertise, and training critical to the transition from discovery to prototype development.

2.3.2. Build broader awareness of resources available at federally funded user facilities to support the transfer of nanoscale science from lab to market.

2.4. Engage in international activities integral to the development and responsible commercialization of nanotechnology-enabled products and processes.

2.4.1. Participate and, where appropriate, lead in the development of international standards for nanotechnology.

2.4.2. Establish, sustain, or join international collaborations and cooperative activities to further nanotechnology-related commercialization, innovation, and trade.

2.4.3. Support forums in which U.S. and international stakeholders can exchange technical information and discuss issues relevant to enabling commercialization.

Transitioning NEPs from lab to market continues to be a priority for the NNI. NNI agencies utilize traditional mechanisms to support technology transfer such as the Small Business Innovation Research (SBIR) and Small Business Technology Transfer Research (STTR) programs.[16] In addition, NNI agencies promote technology transfer and entrepreneurship through activities such as the NSF Innovation Corps (I-Corps) program,[17] the NIH Translation of Nanotechnology in Cancer consortium[18], and the Nano-Bio Manufacturing Consortium (NBMC) supported by the Air Force Research Laboratory.[19] Identifying best practices from each of these programs that lead to successful commercialization and employing them in other programs will maximize the benefits of NNI investments in commercialization. NNI agencies will continue to collaborate and share information and to work with industry and academia to foster innovation and commercialization.

NNI agencies recognize the important role of collaboration between the Federal Government, academia, and industry in facilitating the commercialization of federally funded nanotechnology discoveries. Over the life of the initiative, NNI agencies have interacted with key industry sectors to better understand their technology needs and to address these needs through public–private partnerships and other collaboration mechanisms. The NNI will continue these interactions through focused workshops, town hall meetings, webinars, and collaborations with professional societies and trade groups.

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[16] www.sbir.gov/
[17] www.nsf.gov/news/special_reports/i-corps/index.jsp
[18] nano.cancer.gov/collaborate/collaborating/nanotechnology.asp
[19] www.nbmc.org/

NNI agencies are also pursuing ways to leverage activities and resources in other Federal initiatives and programs to accelerate the commercialization of NEPs. The National Network for Manufacturing Innovation (NNMI),[20] initiated in 2012, is a partnership between government, industry, and academia to collaborate and co-invest to nurture manufacturing innovation and accelerate commercialization. The nine institutes established to date are excellent resources to support commercialization of NEPs because most of the institutes have capabilities and expertise in nanomanufacturing. NNI agencies are currently engaged with each of these institutes and will explore ways to collaborate with them to accelerate commercialization and to foster innovations in nanomanufacturing.

Nanotechnology Startup Challenge in Cancer (NSC^2)

The startup team behind AuTACA, a start-up from Wake Forest School of Medicine, NSC^2 Winner Innovation Excellence Award for NIH Invention #5.

In October 2015, the National Cancer Institute (NCI) partnered with the Center for Advancing Innovation[21] (CAI) in collaboration with Medimmune to launch the Nanotechnology Startup Challenge in Cancer[22] (NSC^2). NSC^2 is accelerating commercialization of nanotechnology inventions intended for cancer applications by recruiting young entrepreneurs and students to launch start-up companies based on these inventions. Staff from the NIH and CAI identified eight promising nanotechnology inventions from scientists in participating NIH institutes—NCI, the National Institute of Biomedical Imaging and Bioengineering (NIBIB), and the National Heart, Lung, and Blood Institute (NHLBI). These inventions formed the core of NSC^2 technologies, but teams were also invited to bring in external technologies to compete.

Teams entered the challenge by submitting information on their chosen invention, as well as the expertise and background of team members. In April 2016, 28 teams comprised of 274 scientists, entrepreneurs, and legal and business experts were accepted into the challenge, including four teams with "third-party" inventions originating outside NIH. As part of CAI's required accelerator training, competing teams received coaching in business development from CAI and education from outside experts from the biotechnology industry, venture capital community, foundations, and government in crucial areas including research and development planning, regulatory strategy, intellectual property, and financial modeling.

On July 26, 2016, the ten winners and finalists of the NSC^2 were announced, chosen by expert judges based on their business plans, financial models, and live pitches. These teams each advanced to the final stage of the challenge, Start-up. The teams are now launching their companies, with mentoring on business management, staffing, technology licensing, and raising seed money from investors. The challenge has provided a new path to commercializing cancer nanotechnology and provides a model for engaging industry in effective technology transfer.

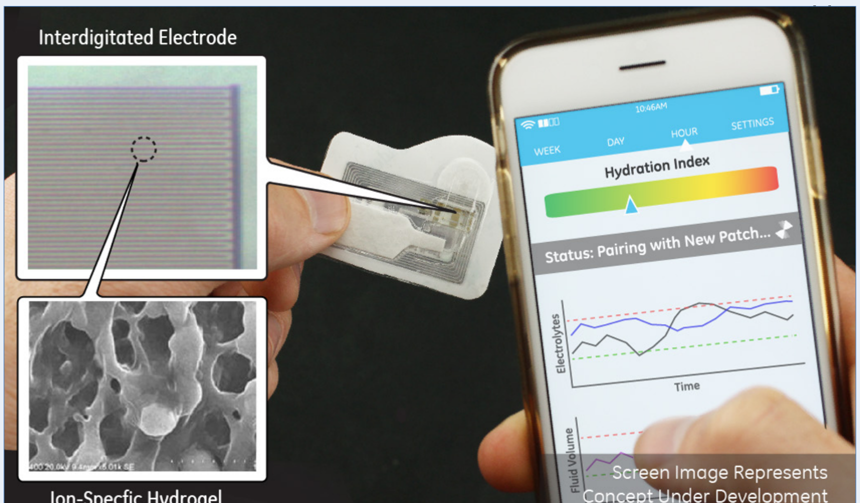
[20] www.manufacturing.gov/nnmi/
[21] www.thecenterforadvancinginnovation.org/
[22] www.nscsquared.org/

Public–Private Partnerships: Nano-Bio Manufacturing Consortium (NBMC)

The Nano-Bio Manufacturing Consortium (NBMC) is a public–private partnership between the Air Force Research Laboratory, industry, and academia with the objective of creating an industrial ecosystem of suppliers, integrators, and end-users to develop a common platform utilizing nanomaterials, bio-macromolecules, and flexible hybrid electronics to enable human performance monitoring for both defense and commercial products, as well as other nano-bio-enabled technologies.

The immediate goal is to create an industrial commons that cooperatively develops pervasive technology by jointly addressing critical path challenges surrounding material supply, qualification, processing, integration, and requirements that are responsive to end-use scenarios. The introduction of open architecture concepts focuses the commons on accelerating the risk reduction of key component technology, interoperability of design tools, consideration of manufacturability early in R&D, and development of robust supply chain relationships.

Established in 2013 through a cooperative agreement with FlexTech Alliance, the NBMC is executing more than $10 million in R&D over three years through 11 collaborative projects, fully cost-shared (at least 50%) with industrial and academic partners.



Wireless biomarker microfluidic sensor patch for measurement of electrolytes in sweat and evaluation of hydration status using ion-specific nanomaterials deposited on highly sensitive interdigitated electrodes (NBMC-funded project led by GE and including UES, Inc.; Air Force Research Laboratory; American Semiconductor; University of Massachusetts Amherst; University of Connecticut; University of Arizona; and Dublin City University). Image credit: GE

Demonstrations to date include development of subsystems and integration into conformal "skin-like" devices that attach to the body to selectively detect biometric information and biomarkers that correlate with stress, fatigue, and cognitive ability.

NNI agencies are also exploring ways that the Federal Government can help shepherd promising technologies to commercialization. One way is by supporting and growing a market for mission-critical technologies until the commercial market reaches a sustainable level. Investments by DOD under the Defense Production Act Title 3 Program[23] have enabled, for example, the development of a production-scale capability to manufacture carbon nanotube sheets and yarns. These materials have been utilized to replace the metallic conductors in data cables to produce cables that are 30–70% lighter than conventional cables and significantly more durable. These ultralightweight data cables are finding both military and commercial applications in satellites and aircraft. NASA has built upon this capability and is working with industry to improve the mechanical properties of these yarns, utilize them as

[23] www.dpatitle3.com/dpa_db/

reinforcements in ultralightweight composites, and demonstrate their suitability for future NASA missions. NNI agencies will continue to explore mechanisms such as these to collaborate with industry and facilitate commercialization.

A key component of fostering the successful transfer of NEPs from lab to market is creating awareness of and access to Federal resources that support commercialization, including funding opportunities (e.g., SBIR and STTR programs), user facilities, and nanoEHS research. Identifying these resources and how to access them can be a challenge for any business, but it is particularly true for small- and medium-sized businesses that may not have the personnel and resources necessary to gather this information and make the right contacts. NNCO and the NSET Subcommittee have addressed this need through outreach and active engagement with industry, including one-on-one interactions, webinars, workshops, and other events that provide for communication and collaboration, and through outreach activities under the Nanotechnology Innovation and Commercialization Ecosystem (NICE) Working Group.[24] In 2015, NNCO established a webinar series focused on highlighting the successes and challenges of nanotechnology-based businesses.[25] The webinars are intended to identify best practices that could be adopted by other businesses and problems that the Federal Government could help address. NNI agencies and NNCO will continue these activities and will look for new opportunities to share information.

Since the EHS aspects of engineered nanomaterials (ENMs) are an essential factor in the commercialization of NEPs, NNI agencies have worked with industry to provide advice and guidance on ENMs in all phases of a product's lifecycle. For example, NIOSH has worked extensively with industry on the safe handling of ENMs in the workplace by providing on-site safety assessments (including monitoring) and support, and in the publication of Intelligence Bulletins.[26] These and other nanoEHS collaborations are discussed further in the section on Goal 4.

Significant public and private investments in nanotechnology R&D worldwide have led to the commercialization of an ever-expanding array of NEPs across a variety of industry sectors. At the international level, vibrant and dynamic exchange of information on topics such as market needs, intellectual property rights, and regulation is accompanying the rapid pace of global innovation in nanotechnology and the associated knowledge gains. With supply chains distributed across multiple countries, NNI agencies will continue to engage early and often in international forums that support responsible commercialization and best practices. These forums include organizations that develop international standards, government-to-government collaborations, and other activities that bring together stakeholders from the United States and around the world.

Many NNI agencies are already active in and lead important international activities. Agencies will maintain and strengthen this strategic engagement while balancing budget constraints and mission objectives. NNI agencies will also explore means for leveraging public–private partnerships to maximize the impact of their participation and strengthen ties with the U.S. private sector. NNI agencies' engagements span a wide range of issues, including the development of consensus standards,

[24] See www.nano.gov/NICE. This working group was previously the Nanomanufacturing, Industry Liaison, and Innovation (NILI) Working Group. The name was changed when the working group was rechartered in May 2015.
[25] www.nano.gov/SMEwebinars2016
[26] www.cdc.gov/niosh/pubs/cib_date_desc_nopubnumbers.html

specifications, protocols, exchange of scientific and technical information, and identification of market trends. By participating in a variety of forums and partnerships, NNI agencies will proactively address nanotechnology-related intellectual property rights as well as potential nanoEHS, consumer, and societal issues—all of which enable innovation, commercialization, trade, and U.S. leadership in strategic and transformative technologies.

Advancing the Commercialization of Cellulosic Nanomaterials Applications

Photos of pears that are uncoated vs. pears coated with nanocellulose-based barrier coating at ambient condition (20±2°C and 30±2% relative humidity) for three weeks. Photo courtesy of Oregon State University.

Cellulosic nanomaterials derived from trees are abundant, renewable, and sustainable, and have exceptional properties. Cellulosic nanocrystals, for example, couple high strength with light weight and also exhibit useful electrical and optical properties. USDA Forest Service is advancing the commercialization of cellulosic nanomaterials in multiple end-use applications by employing a strategy that is focused on filling knowledge gaps, overcoming technical barriers, and working through government-university-industry partnerships. Because there are hundreds of potential proprietary applications for cellulosic nanomaterials, the Forest Service has entered into both informal and formal (e.g., the Public–Private Partnership for Nanotechnology, P^{3}Nano) partnerships to pool resources, provide early adopters and end-use researchers with access to kilogram to ton quantities of three basic types of cellulosic nanomaterials, and concentrate USDA intramural R&D and technology transfer efforts on overcoming technical and economic hurdles that benefit multiple end-use applications. These efforts include:

- Developing the science and technology to disperse cellulosic nanomaterials into matrices of other materials.
- Forming stress-free films and coatings.
- Applying Surface modifications.
- Characterizing/measuring the physical properties of cellulosic nanomaterials.
- Drying, dewatering, and dispersing cellulose nanomaterials.
- Forming high-strength aerogels.
- Developing compatibilizers for cellulosic nanomaterial-reinforced polymer composites.

Example applications being developed through partnerships include use of cellulosic nanomaterials in barrier coatings for fruit, concrete and precast concrete, aerogel foams for insulation and sound deadening, and reinforced paper products.

Goal 3: Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology.

The successful development of nanotechnology, from basic research through commercialization, requires a strong foundation and continuous improvements in the human, physical, and cyber infrastructure. Substantial investments, strengthened by interagency cooperation and collaboration through the NNI, are needed to develop the talent and facilities necessary to achieve the other NNI goals of advancing a world-class R&D program (Goal 1), fostering the transfer of new technologies into products for commercial and public benefit (Goal 2), and supporting responsible development of nanotechnology (Goal 4).

Goal 3 Objectives

3.1. Expand outreach and informal education programs in order to inform the public about the opportunities and impacts of nanotechnology.

3.1.1. Develop and publish materials appropriate for informing the public at large and educational materials for students at all levels.

3.1.2 Utilize social media, contests, and other novel approaches to inform and inspire the public, in particular students, about nanotechnology.

3.2. Establish and sustain programs that assist in developing and maintaining a skilled nanotechnology workforce.

3.2.1. Develop, publish, and disseminate materials for educating and training the workforce, at all levels, from vocational to professional.

3.2.2. Continue to provide opportunities for practical training experience for students in federally supported nanotechnology facilities.

3.2.3. Encourage education about the areas of convergence between nanotechnology and other related scientific disciplines, such as biotechnology, information technology, and cognitive science.

3.3. Provide, facilitate the sharing of, and sustain the physical and cyber R&D infrastructure, notably user facilities and cooperative research centers.

3.3.1. Establish regular mechanisms to determine the current and future infrastructure needs of users and stakeholders of these facilities and centers.

3.3.2. Develop, operate, and sustain state-of-the-art tools, infrastructure, and user facilities, including ongoing investment, staffing, and upgrades.

3.4. Promote the storage and sharing of data, and the development and use of informatics tools for nanotechnology R&D.

3.4.1. Encourage informatics literacy in the nanotechnology workforce.

3.4.2. Support the development of integrated, accessible modeling and informatics tools in all aspects of nanotechnology research, development, and commercialization.

3.4.3. Support the development of databases, as well as machine-readable formats and data standards to enable greater interoperability.

Over the first fifteen years of the NNI, considerable progress has been made with respect to the infrastructure that supports nanotechnology research and development. This infrastructure includes educational resources and workforce programs, national networks of user facilities, and a cyber infrastructure with databases, models, and simulations. But infrastructure needs, of course, are a moving target, and it is important to leverage and build upon the existing resources as the requirements of the nanotechnology community evolve and expand.

While nanotechnology is rapidly finding its way into a wide variety of consumer products, much of the public remains unaware of this emerging technology. The NSF-supported Nanoscale Informal Science Education Network (NISE Net) made significant strides in public outreach and established a strong community of interest. The resources developed by NISE Net and other efforts have been made readily accessible in a searchable database.[27] In addition to the resources developed by agency grantees, NNCO and the NNI agencies have collaborated with public and private entities to develop educational videos, animations, and contests.[28] Efforts like these need to expand, and other means, such as increased use of social media, should be explored to engage a broader public audience in a two-way dialogue. The NNI agencies and NNCO will continue to look for opportunities to reach students and the general public where they get information (such as television, virtual communities, etc.) and to collaborate with appropriate organizations to inform and inspire the public about nanotechnology.

The novel properties of nanoscale materials can excite students to learn more about nanotechnology and about science, technology, engineering, and mathematics (STEM) fields more broadly. Furthermore, the inherent interdisciplinary nature of nanotechnology helps prepare students to meet future workforce needs. Beyond the informal education and outreach activities discussed above, nanotechnology resources and programs have been developed for all stages of education. Some states, such as Virginia, have even incorporated nanotechnology concepts

Nanoscale Informal Science Education Network (NISE Net)

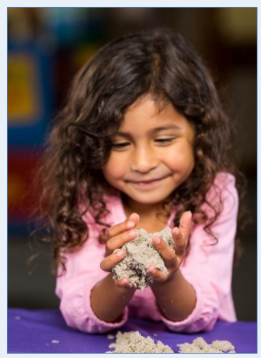


Photo credit: Gary Hodges, Sciencenter

Reaching more than 30 million people from 2008 through 2015, the NSF-funded Nanoscale Informal Science Education Network (NISE Net) introduced nanotechnology and how it will impact our society to people all across the country. As a national community of researchers and informal science educators dedicated to fostering public awareness, engagement, and understanding of nanoscale science, engineering, and technology, NISE Net has created activities, programs, and exhibits for public audiences that have been implemented in more than 500 institutions, including science museums, schools, science festivals, and more. Resources developed under this activity continue to be available and used broadly. As the program period came to a close in 2015, the community has transitioned to the National Informal STEM Education Network. NISE Net is building on the strong community and knowledge foundation established under the initial program and expanding into new topic areas, including synthetic biology and other emerging technologies.

[27] nanohub.org/publications/118
[28] www.nano.gov/multimedia-and-contests

Generation Nano: Small Science, Superheroes Contest

Image Credit: Amina Khan, NSF

NSF and NNI collaborated in 2015 to launch the first "Generation Nano: Small Science, Superheroes" contest. This competition is designed to excite students who may not already be engaged with science, technology, engineering, and math (STEM) topics to learn more about nanotechnology. Generation Nano inspires students to imagine how nanotechnology can save the day and asks students to design nanotechnology-enabled gear for an original superhero. Students submit a brief technical write-up explaining the technology behind their gear and either a short comic or video featuring their hero using their nanotechnology-enabled gear. For the first year, submissions came from 116 students representing 14 different states. NSF brought the three finalists to the 2016 USA Science and Engineering Festival to present their comics and the science behind them to visitors. During the three-day Festival #GenNano had a potential social media reach of nearly 16 million followers. The legendary comic book creator Stan Lee helped to promote the contest through his social media channels, including a Vine video that has been looped more than 30,000 times. Based on the success of the first year, NSF has decided to repeat the competition with a second launch scheduled for fall 2016.

Panel from the winning comic by Eric Liu, Thomas Jefferson High School for Science and Technology.

into their K–12 education standards. Resources, from lesson plans to text books and complete courses, have been developed. A searchable database has been established to promote easy access to these resources, particularly for teachers,[29] and a teachers network is beginning to coalesce. Through the use of webinars and discussion threads, teachers in the network are able to share best practices for incorporating nanoscale topics in K–12 classrooms. NNCO and the NNI agencies will continue to support teachers through Research Experience for Teachers (RET) programs,[30] workshops, engagement at science teacher conferences, and promotion of resources for teaching nanotechnology.

[29] nanohub.org/publications/118
[30] www.nsf.gov/funding/pgm_summ.jsp?pims_id=505170

With the assistance of NNI agency-supported centers and programs, colleges and universities are now offering undergraduate minors and majors, technician training, and postgraduate programs in nanoscale science and engineering. A strong network of degree programs and certificate-based technician training programs—such as those provided by the Nanotechnology Applications and Career Knowledge (NACK) Network and the Nano-Link Center for Nanotechnology Education[31]—have been established through NSF's National Advanced Technological Education (ATE) Program. The success of these programs depends on strong collaboration between educators and industry to ensure the incorporation of the specific skills required for local workforces. NNI agencies will continue to support efforts to develop the nanotechnology technician workforce, including interactions with national laboratories and NNI-funded user facilities.

University educational programs in nanotechnology are administered within traditional departments or through newly formed centers, departments, schools, or colleges. Nanoscience and nanotechnology principles impact all science, technology, and engineering disciplines and are embedded throughout traditional programs, even where nanotechnology-specific degrees or programs don't exist. NNI agencies and NNCO will continue to support efforts to develop and share best practices and resources for faculty interested in incorporating nanotechnology concepts in their courses. NNI agencies will also continue to provide and promote opportunities for students to engage in research and other practical training experiences at universities and national laboratories through programs such as the Research Experiences for Undergraduates (REU)[32] and the Summer Undergraduate Research Fellowship (SURF).[33] In 2016, college students across the country established a network aimed at raising awareness of cutting-edge research,[34] including the convergence of nanotechnology with biotechnology, information technology, and cognitive science. NNCO will facilitate the expansion of this student-led network and to promote opportunities for student research and internships.

The nanotechnology enterprise requires support for a widely accessible state-of-the-art physical infrastructure. As nanotechnology rapidly advances, shared-use facilities must maintain existing tools and continuously refresh their equipment to meet the evolving needs of users from industry, academia, and government for synthesis, processing, fabrication, characterization, modeling, and analysis of nanomaterials and nanosystems. In many cases, single researchers or institutions find it difficult to justify funding the acquisition of and support for all necessary tools. Therefore, user facilities critically enable research and development and accelerate commercialization by co-locating a broad suite of nanotechnology tools, maintaining and replacing these tools to keep them at the leading edge, and providing expert staff to ensure the most productive use of the tools. The facilities also support the development of advanced nanoscale fabrication methods and measurement tools. Finally, shared facilities are a vital resource for training nanotechnology researchers and for creating a community of shared ideas by mixing researchers from different disciplines and sectors. NNI user facilities include the NSF National Nanotechnology Coordinated Infrastructure (NNCI), DOE Nanoscale Science Research Centers (NSRCs), NIST Center for Nanoscale Science and Technology (CNST), and National Cancer Institute (NCI) Nanotechnology Characterization Laboratory (NCL). An emphasis on the physical infrastructure to support nanotechnology research and development will continue to be a key priority for the NNI.

[31] See www.nano4me.org/ and www.nano-link.org/.
[32] www.nsf.gov/funding/pgm_summ.jsp?pims_id=5517&from=fund
[33] www.nist.gov/surf/
[34] www.nano.gov/node/1506

U.S. Army Research Laboratory (ARL) Open Campus Initiative

The Rodman Materials Research Laboratory, Aberdeen Proving Ground, Maryland. The Rodman Building is home to the U.S. Army Research Laboratory's structural materials research, and has extensive materials characterization and synthesis facilities for metals, ceramics, polymers, glasses, and composites. By utilizing the Open Campus framework, visiting scientists can work side-by-side with ARL scientists and engineers in ARL facilities such as the Rodman Laboratory. Find out more about Open Campus and other ARL facilities across the nation at www.arl.army.mil/opencampus/.

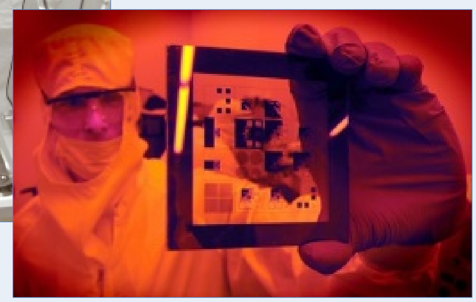
The U.S. Army Research Laboratory (ARL) Open Campus initiative directly impacts advancement in nanoscience and technology by building a framework to accelerate discovery, innovation, and transition. Started in 2014, Open Campus is a new business model to pursue leading-edge basic and applied research in a truly collaborative fashion by enabling the continuous flow of people and ideas between government, academia, and the private sector. The model accelerates progress toward NNI goals by increasing public–private partnerships, growing Army education and outreach programs, leveraging Army resources (e.g., equipment, facilities, and subject matter experts), and facilitating seamless involvement of all partners. Recently, Open Campus expanded ARL's physical presence in the national and International community by exploiting a model of regional research and development hubs. These collaborative innovation hubs bring new resources to solving Army problems and provide access to large pools of experts. As an extension of Open Campus, ARL opened a remote collaboration site in southern California in 2016—ARL West—with additional sites in the Southwest and Central United States set to open in late 2016 or early 2017. ARL West taps into the fast-growing technology expertise and capabilities in the Los Angeles area and is focused on research into how humans generate and interact with data to make decisions more effectively and efficiently. ARL West also allows access to regional excellence in nanotechnology. ARL South will focus its hub on materials and manufacturing including electronic devices and structural components. Regional strengths include exploiting nanostructured materials as feedstocks for additive manufacturing. ARL Central will focus on filling technology gaps and protection goals in high-strain-rate environments. Success in creating materials for the high-strain-rate environment is reliant on understanding and exploiting the nanoscale.

The Army's Strategic Material Research Open Campus initiatives strive to enable efficient and focused collaboration opportunities, including nanoscience, technology, and commercialization, through regional and national initiatives. Additional collaborative efforts directly impacting NNI goals are new centers. Established and near-term planned centers are: Center for Research in Extreme Batteries—kicked off in 2015; Additive Manufacturing Science Center—kicked off in 2015; Semiconductor Research Nanofab Center—in progress; and Center for Semiconductor Materials and Device Modeling—in progress. In the aggregate, the Open Campus initiative will be an accelerator of the NNI vision.

National User Facility Network

Under the NNI, several participating agencies have built or supported the development of user facilities to create an extensive and unparalleled resource for outside users. These user facilities are geographically diverse and provide state-of-the-art tools—both physical and computational—to create, characterize, and understand nanomaterials and nanotechnology-enabled components and devices. The technical staff at these centers are available to consult with users on topics ranging from experimental design and troubleshooting to tool selection and training.

The physical user facilities described below collectively serve more than 11,000 researchers a year, and nanoHUB.org hosts more than 345,000 users a year. These resources provide the infrastructure and expertise to fuel a vibrant nanotechnology research ecosystem.



Photos from several NNCI sites. Clockwise from top right: A researcher prepares to enter the Cornell NanoScale Science and Technology Facility (Photo Credit: Cornell University Marketing); a researcher examines a photomask at the Chapel Hill Analytical and Nanofabrication Laboratory (Photo Credit: Dan Sears, the University of North Carolina at Chapel Hill); and Professor David Dickensheets, left, and student Erwin Dunbar work with silicon wafers at Montana State University in Bozeman. Photo Credit: Montana State University.

- **National Nanotechnology Coordinated Infrastructure (NNCI):** NSF launched the NNCI in 2015, providing a total of $81 million over five years to support 16 sites and a coordinating office. The NNCI is the successor to the National Nanotechnology Infrastructure Network, which ran from 2004 to 2014.
- **Nanoscale Science Research Centers (NSRCs):** The NSRC Program operates a system of five coordinated centers strategically located at DOE national laboratories across the United States. Each scientifically distinct center contains laboratories for synthesis, nanofabrication, characterization, one-of-a-kind signature instruments, and theory/modeling/simulation expertise. NSRCs are co-located with major x-ray, neutron, and high-performance computing facilities to enable users to conduct comprehensive high-impact nanoscience research.
- **NIST Center for Nanoscale Science and Technology (CNST)**: Within DOC, the NIST CNST provides rapid access to the tools needed to make and measure nanostructures. These tools are provided to anyone who needs them, both inside and outside NIST, with a particular emphasis on helping industry.
- **Nanotechnology Characterization Laboratory (NCL):** Working in concert with NIST and FDA, the National Cancer Institute (NCI) established the NCL to perform preclinical efficacy and toxicity testing of nanoparticles. The NCL serves as a national resource and knowledge base for all cancer researchers to facilitate the regulatory review of nanotechnologies intended for cancer therapies and diagnostics.
- **Network for Computational Nanotechnology (NCN):** The NSF-funded NCN provides simulation services and educational material through nanoHUB.org, which hosts a rapidly growing collection of simulation programs for nanoscale phenomena that run in the cloud and are accessed through a web browser.

For more information on the NNI user facility network, see www.nano.gov/userfacilities.

In addition to the human and physical infrastructure, the NNI agencies have established foundational cyberinfrastructure for nanotechnology research and development. For example, the NSF-funded Network for Computational Nanotechnology (NCN)[35] has developed models and simulation tools to predict behavior at the device, circuit, and system level for nanoelectronics, nanoelectromechanics, and nanobiological systems, and serves as a virtual laboratory for the nanotechnology community with online simulation and education. This cyber infrastructure is critical for the storage and sharing of data and the development and use of informatics tools. The emphasis on sharing data, models, and simulations will accelerate research breakthroughs and the development of nanotechnology, but open sharing of research outputs is a cultural transition for many scientists and engineers. For this reason, many of the NNI efforts in this area have been embedded in the broader nanotechnology community and will expand in the coming years. Examples of community-focused informatics efforts include the U.S.–EU Communities of Research (CORs)[36] and the Nanotechnology Knowledge Infrastructure (NKI) Signature Initiative.[37] The NNI agencies will continue to support the cyber infrastructure required to advance nanotechnology and to collaborate with academia, industry, journals, and nongovernmental organizations as appropriate.

Goal 4: Support responsible development of nanotechnology.

Responsible development of nanotechnology is required throughout the entire enterprise to protect the environment and human health while realizing the societal and economic benefits of nanotechnology. Responsible development underpins all of the other goals, including fundamental research (Goal 1); evaluation and handling of nanomaterials throughout the product lifecycle, from research and development through commercialization to end-of-life considerations (Goal 2); and the safety infrastructure from laboratory safety protocols to student training and worker safety (Goal 3). Efforts to ensure responsible development of nanotechnology are inherently multidisciplinary and require coordination among multistakeholder national and international teams.

Goal 4 Objectives

4.1. Support the creation of a comprehensive knowledge base for evaluation of the potential risks and benefits of nanotechnology to the environment and to human health and safety.

4.1.1. Identify and update relevant knowledge gaps and prioritize needs through active stakeholder engagement, including with industry, government, and nongovernmental organizations.

4.1.2. Adopt or develop and validate measurement tools and decision-making models to enable hazard and exposure quantification for human and environmental risk assessment and management.

4.1.3. Engage in international efforts, including those aimed at generating best practices and consensus standards.

[35] nanoHUB.org
[36] us-eu.org/communities-of-research/
[37] www.nano.gov/NSINKI

4.2. Create and employ means for timely dissemination, evaluation, and incorporation of relevant environmental, health, and safety (EHS) knowledge and best practices.

4.2.1. Explore new avenues to engage with a broad group of stakeholders, to communicate EHS research progress, and to share technical information.

4.2.2 Pursue mechanisms to disseminate information about the state of understanding with respect to EHS aspects of nanotechnology.

4.2.3. Participate in coordinated international efforts focused on sharing data, guidance, and best practices for environmental and human risk assessment and management.

4.3. Develop the national capacity to identify, define, and responsibly address concepts and challenges specific to the ethical, legal, and societal implications (ELSI) of nanotechnology.

4.3.1. Promote awareness and education of ELSI among relevant stakeholders, including manufacturers, regulators, nongovernmental organizations, workers, and the public.

4.3.2. Foster deliberative interactions, such as public forums, among relevant stakeholders concerning national and global ELSI.

4.4. Incorporate sustainability in the responsible development of nanotechnology.

4.4.1. Encourage the development of engineered nanomaterials that are safer and more sustainable alternatives to materials—nanoscale and otherwise—that are now in use.

4.4.2. Promote the design and development of safe and environmentally benign manufacturing and end-of-life processes for engineered nanomaterials and nanotechnology-enabled products.

In support of Goal 4, the NNI published, with input from stakeholders, a nanoEHS research strategy in 2011.[38] This document was developed with a broad, multi-agency perspective. It details specific research needs in six interrelated and synergistic nanoEHS core research areas: (1) a nanomaterial measurement infrastructure that provides accurate and reproducible data coupled with (2) predictive modeling and informatics to quantitatively assess (3) human exposure, (4) human health, and (5) the environment essential for science-based (6) risk assessment and risk management of ENMs and NEPs.

The NNI agencies, individually and collaboratively, support efforts that address the needs identified in the nanoEHS research strategy. In 2014, the NNI released a progress review[39] to provide examples of ongoing, completed, and anticipated nanoEHS research and to illustrate the breadth of activities in all six core research areas. As detailed in the progress review, extensive collaboration and coordination among the NNI agencies has led to the creation of a wealth of knowledge that supports the evaluation of potential risks of nanotechnology. For example, comprehensive measurement techniques and modeling tools have been developed that consider the full life cycles of ENMs in various media, exposure assessment data have been collected, and resources have been developed to inform

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[38] Nanoscale Science, Engineering, and Technology Subcommittee of the Committee on Technology, *National Nanotechnology Initiative 2011 Environmental, Health, and Safety Research Strategy* (National Science and Technology Council, Washington, District of Columbia, 2011; www.nano.gov/2011EHSStrategy).

[39] Nanoscale Science, Engineering, and Technology Subcommittee of the Committee on Technology, *Progress Review on the Coordinated Implementation of the National Nanotechnology Initiative 2011 Environmental, Health, and Safety Research Strategy* (National Science and Technology Council, Washington, District of Columbia, 2014; www.nano.gov/2014EHSProgressReview).

workplace exposure control strategies for key classes of ENMs. Modes of interaction between ENMs and physiological and environmental systems have contributed to improved assessment of transport and transformations of ENMs in various environmental media and biological systems. A life cycle perspective on nanomaterial risk assessment and management has been widely adopted.

The NNI agencies will continue to work together and with domestic and international collaborators to leverage investments, identify gaps, prioritize needs, develop analytical risk assessment and management tools, and support the expansion of knowledge in nanoEHS. Identification of gaps and prioritization of needs for nanoEHS knowledge should be accomplished through an analysis of the state of the science and active stakeholder engagement. There is a clear need to develop broadly available and validated data and applicable measurement tools, including models and standards, that enable quantification of hazard and exposure, characterization of risks, and selection of risk management strategies. The NNI will continue to work to ensure that the nanoEHS knowledge base encompasses the full life cycle of ENMs and NEPs—ENM production, NEP manufacture and consumer use, and ENM and NEP end-of-life (disposal or recycling)—through the use of formal methods and tools.

International Collaboration to Understand Behavior of Nanomaterials in the Environment

The CEINT Mesocosm Facility is home to 30 complex simulated wetland ecosystems, enabling a wide array of uniquely realistic investigations into the mechanisms that govern nanomaterial transport, transformation, ecological interactions, bio-uptake, and biological interactions. Photo courtesy of CEINT.

As engineered nanomaterials (ENMs) are incorporated into a growing number of products, it is important to understand if and how they may be released across the product life cycle, and to understand how the released form interacts with ecosystems and organisms. The Center for the Environmental Implications of NanoTechnology (CEINT), headquartered at Duke University and funded by NSF and EPA, investigates the potential risks associated with ENMs, while nurturing fundamental discovery of nanoparticle interactions in nature, which may be the basis for future advances in agriculture, nanomedicine, environmental protection, and materials science. CEINT research examines the release of new nanomaterials from consumer products over time, as well as the impact of emerging nanomaterials made from multiple nanoscale elements and structures.

Enabled by increased capability for data sharing and evaluation, CEINT is the central hub of an international effort examining nanotechnology implications for living systems and the environment. The Center's vision is that this international effort *will become a template for future efforts to evaluate the potential environmental risks of emerging technologies in general.* CEINT is integrating the collective findings from these efforts to build predictive models for ENM behavior and risk forecasting. To that end, CEINT is leading an effort that engages partners in the European NanoSafety Cluster, the Nanomaterial Registry, and nanoHUB to create the NanoInformatics Knowledge Commons, a first-generation data repository of nanoparticle properties, effects, and protocols and associated analytical tools.

Guidance for Responsible Development of Nanotechnology

Partnerships with the private sector are a key to NIOSH success. Photos courtesy of NIOSH.

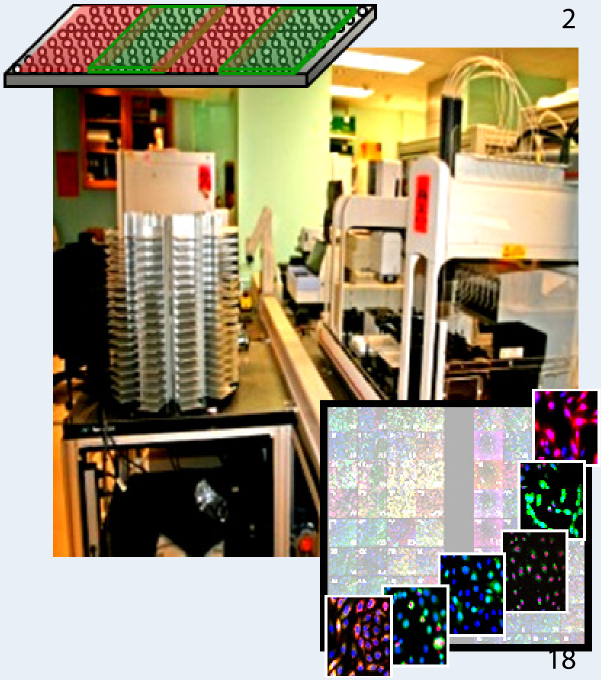
To derive true benefit from nanotechnology, it must be developed and deployed in a way that protects the health and well-being of workers. The first challenge that must be met is that of protecting the health and well-being of workers who are manufacturing and applying new engineered nanomaterials for the creation of new and improved products and applications that will benefit society. NIOSH, as an active member of the NNI, has realized great success in developing partnerships with the private sector to develop and disseminate good risk management guidance based on direct interaction with companies who manufacture, formulate, or use nanomaterials. NIOSH has already conducted more than 100 site visits and works with nanomanufacturing facilities to evaluate potential worker hazards and develop strategies to mitigate risk.

A key output of NIOSH research is the formulation of guidance for the safe handling and processing of nanomaterials. Much of the knowledge gained and used by NIOSH is a direct result of direct interaction with private sector partners. NIOSH has developed guidance materials that include recommended exposure limits; risk assessments; exposure measurement strategies and techniques; process emission controls focused on eliminating worker exposures; and recommendations for personal protective equipment.

As knowledge is created to support the responsible development of nanotechnology, the NNI agencies are employing a variety of means to disseminate and incorporate this information into practice. These efforts include webinars, guidance documents, progress reviews, and fact sheets. The NNI agencies will continue to actively share nanoEHS findings and to promote the development and dissemination of information on the state of the science in these areas.

One of the strengths of the NNI is the strong communication and collaboration among agencies with vastly different roles and missions. This collaboration, enabled by the NSET Nanotechnology Environmental and Health Implications (NEHI) Working Group, ensures that nanoEHS research activities are informed by the collective needs of the NNI agencies. The knowledge gained using measurement tools—protocols, standards, instruments, methods, models, and validated data—supports science-based risk assessment and management. NNI agency efforts will continue to promote the development and validation of measurement tools and decision-making models, including emerging methods and tools that support decision analysis where data are incomplete. The NNI agencies will continue to play a strong participatory and, where appropriate, leading role in international activities to develop consensus standards and in other international activities.

High-Throughput Screening and Predictive Toxicological Modeling



Cellular high-throughout screening platform in the UC CEIN Laboratory at UCLA.

The University of California Center for Environmental Implications of Nanotechnology (UC CEIN), funded by NSF and EPA, has been preparing the nanoEHS community for the utility of high-throughput screening methods and predictive toxicology for evaluating engineered nanomaterials. By assembling nanomaterial libraries that represent a wide range of nanomaterial categories, UC CEIN has established a reference grid for more than 300 nanomaterials that can be hierarchically ranked through the use of mechanism-based adverse outcome pathways in cells, bacteria, and various environmental life forms. The testing also reflects the link between material physicochemical properties and triggering of molecular injury that, in whole-animal testing, reflects the possibility of adverse health outcomes. This platform now allows tiered risk assessment of industrial nanomaterials by *in vitro* testing (tier 1) and sparing animal testing with shorter (tier 2) or longer term (tier 3) protocols for assisting regulatory decision making based on exposure potential. The aim of tiered testing is to progressively shift to tier 1 assessment as more confidence is gained with the system, including limiting the volume of testing by grouping and read-across. The screening also provides structure–activity analysis that can be used for safer design of nanomaterials.

This platform has enabled UC CEIN to develop predictive toxicological profiling and a comprehensive database of industrially important materials (e.g., silver, copper, silica, transition metal oxides, rare earth oxides, catalyst nanomaterials, III-V semiconductors, single and multiwall carbon nanotubes, graphene, composite materials, powders, and nanotherapeutics) as a resource to profile and rank new materials, which could also be used for categorization and read-across. The UC CEIN approach, data repository, and computational tools are available to assist nanomaterial or new chemical characterization and data collection for premanufacturing notices to EPA, predictive toxicological modeling to limit the use of more expensive animal tests, regulatory decision analysis, and safer design based on quantitative structure–activity relationships. The tiered approach can also be used as a screening tool during the R&D design stage. The Center's comprehensive infrastructure has been used to launch multistakeholder discussions between academia, industry, and regulatory partners. Outputs include the development of joint white papers describing the utility of high-throughput screening for nanotechnology,[40] including use for material categorization and a tiered decision analysis approach that can replace expensive animal testing, such as 90-day inhalation studies.[41]

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[40] A. E. Nel, *et al.,* A multi-stakeholder perspective on the use of alternative test strategies for nanomaterial safety assessment. *ACS Nano.* **7**, 6422–6433 (2013).
[41] H. Godwin, *et al.*, Nanomaterial categorization for assessing risk potential to facilitate regulatory decision-making. *ACS Nano.* **9**, 3409–3417 (2015).

The NSF-funded Centers for Nanotechnology in Society[42] have developed considerable capacity to address the ethical, legal, and societal implications of nanotechnology and raised national awareness of these issues. With this strong foundation, ELSI considerations are now embedded throughout NNI activities including, for example, focused efforts within the National Nanotechnology Coordinated Infrastructure.[43] The NNI agencies and NNCO will continue to foster interactions and discussions in national and global forums.

Responsible development of nanotechnology includes incorporating principles of sustainability. Sustainability applies to the evaluation of existing nanomaterials across their life cycle, the integration of sustainability concepts into the design of new materials, and sustainable development in general. NNI activities will continue to promote integration of sustainability in the design, development, and manufacture of ENMs and NEPs.

Additionally, the potential for nanotechnology to improve societal, economic, and environmental sustainability needs to be addressed for improvement of societal well-being. Some of the beneficial applications that nanotechnology could provide in support of societal sustainability are ENMs for more efficient generation and use of energy, water purification, production of food and bio-based industrial and commercial products, and remediation of environmental contaminants. Recognizing the particular promise of nanotechnology to address the technical challenges related to water quality and quantity, the NNI launched the Water Nanotechnology Signature Initiative in 2016.[44]

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[42] www.cns.ucsb.edu/ and cns.asu.edu/
[43] www.nnci.net/
[44] www.nano.gov/NSIWater

The NNI Collaboration Ecosystem

One of the significant strengths of the NNI is the collaborative ecosystem that has been established and that continues to evolve with the needs of the community as nanoscale science and engineering matures. The NNI agencies have adopted a number of mechanisms to not only share information but also to ensure that resources are leveraged to the greatest extent possible to more quickly advance the four goals of the NNI. The interagency planning and coordination of the NNI takes place through the White House National Science and Technology Council (NSTC) Committee on Technology's Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and its working groups and coordinators. In order to accelerate nanotechnology development in topical areas of national importance, the Nanotechnology Signature Initiatives (NSIs) were formed to enhance coordination and collaboration among the participating agencies and to engage with the public. Grand challenges were adopted in 2016 as a mechanism to bring together the NNI collaboration ecosystem, including the Federal Government, industry, and academia, to pursue ambitious but achievable goals. Much of the research and development activity of the NNI takes place outside of the Federal agencies in the form of grants and contracts to universities and industry. To better connect these efforts, several community-building and engagement activities are being employed, ranging from webinars and workshops to contests and the development of networks. The nanotechnology knowledge developed under the NNI has broad application to many other Federal initiatives. Strong collaborations have been developed with these initiatives, and NNI agencies will pursue additional partnerships with these and future efforts.

The Structure of the NNI

The NSTC is the Cabinet-level body that serves as the principal means within the Executive Branch for the prioritization and coordination of the Federal research and development enterprise; it is made up of five primary committees. Under the NSTC Committee on Technology, the NSET Subcommittee is responsible for the coordination, planning, implementation, and review of the NNI. Each agency participating in the NNI is represented on the NSET Subcommittee, which typically meets monthly to discuss ongoing activities and future plans. The NSET Subcommittee develops the NNI Strategic Plan, prepares the annual NNI Supplement to the President's Budget, and sponsors public workshops, webinars, and other interagency activities. There are currently two working groups chartered under the NSET Subcommittee: the Nanotechnology Environmental and Health Implications (NEHI) Working Group and the Nanotechnology Innovation and Commercialization Ecosystem (NICE) Working Group. These working groups provide focused interagency attention in their respective areas and collectively plan relevant activities. The NNI also has designated coordinators in cross-cutting topical areas to track developments, lead in organizing activities, report to the NSET Subcommittee, and serve as central points of contact. There are currently four coordinators, focused on standards development; nanoEHS research; global issues; and education and public engagement.

The National Nanotechnology Coordination Office (NNCO) serves as the central point of contact for the NNI and provides technical and administrative support to the NSET Subcommittee and its working groups and coordinators. The NNCO maintains the NNI website, www.nano.gov, and performs public outreach and engagement on behalf of the NNI.

Nanotechnology Research and Development Community

The NNI community extends beyond the Federal Government and includes the grantees, students, companies, technical and professional societies, and others engaged in nanotechnology research and development. This vibrant community exists as a result of the efforts of the NNI agencies over the past sixteen years. With the expansion of scientific knowledge in nanotechnology, formal and informal collaborations have developed among researchers across a diverse range of fields and countries. These interactions and collaborations have been and continue to be facilitated by agency activities including public–private partnerships, research centers, and networks. In addition to providing fabrication, characterization, and testing capabilities, the physical infrastructure also provides a place for researchers, industry, and ideas to mix, further expanding the community. This community has broken down the traditional disciplinary boundaries and laid the foundation for interdisciplinary discovery, which is increasingly vital to research as fields converge.

Program Component Areas

Program Component Areas (PCAs) provide an organizational framework for categorizing the investments of the NNI agencies as required by the 21st Century Nanotechnology Research and Development Act. The investments and major changes related to each PCA are reported in the annual NNI Supplement to the President's Budget.[45] The PCAs in this 2016 NNI Strategic Plan are similar to those in the 2014 NNI Strategic Plan,[46] with the inclusion of the newly established grand challenge mechanism in PCA 1: Nanotechnology Signature Initiatives and Grand Challenges. The current PCAs are:

1. Nanotechnology Signature Initiatives and Grand Challenges
2. Foundational Research
3. Nanotechnology-Enabled Applications, Devices, and Systems
4. Research Infrastructure and Instrumentation
5. Environment, Health, and Safety

Nanotechnology Signature Initiatives

Recognizing the need to accelerate nanotechnology development in key areas of national importance, the NNI agencies and the White House Office of Science and Technology Policy (OSTP) developed NSIs as a mechanism for enhanced interagency coordination and focused investment. The NSIs provide a spotlight on these critical areas and define the shared vision of the participating agencies. Inherently interdisciplinary, these R&D efforts benefit greatly from coordinated planning and collaboration. By leveraging the expertise, capabilities, and resources of appropriate Federal agencies, the NSIs accelerate research and development and overcome challenges specific to their respective technology areas. The agency participants in the signature initiatives actively collaborate to plan and conduct activities to advance the goals of the NSIs. Depending on the needs of the NSI, these activities may include release of Requests for Information (RFIs), workshops and webinars, symposia and town hall meetings embedded in the technical programing of conferences, and the development of resource portals on the

[45] The NNI Supplement to the President's 2017 Budget is available at www.nano.gov/2017BudgetSupplement.
[46] Nanoscale Science, Engineering, and Technology Subcommittee of the Committee on Technology, *2014 National Nanotechnology Initiative Strategic Plan* (National Science and Technology Council, Washington, District of Columbia, 2014; www.nano.gov/2014StrategicPlan).

The Launch of a New Nanotechnology Signature Initiative (NSI): Water Sustainability through Nanotechnology

The NNI's portfolio of Nanotechnology Signature Initiatives (NSIs) is intended to be dynamic and is designed to change as technical and societal priorities evolve. As such, the *Water Sustainability through Nanotechnology: Nanoscale Solutions for a Global-Scale Challenge* NSI was launched in March 2016 to take advantage of the unique properties of engineered nanomaterials that may generate significant breakthroughs in addressing our Nation's water challenges. The water NSI is designed to aid in the development of technological solutions that can alleviate current stresses on the water supply and provide methods to sustainably utilize water resources in the future. The three specific thrusts of the water NSI are to:

The NSF-funded Nanosystems Engineering Research Center on Nanotechnology Enabled Water Treatment (NEWT) will help provide clean water in a reliable and affordable fashion. NEWT is developing highly compact, mobile, and modular water treatment systems that will be easy to deploy, capable of tapping unconventional water sources, and will enable access to clean water and wastewater reuse almost anywhere in the world. Image credit: NEWT/Rice University.

1. Increase water availability using nanotechnology.
2. Improve the efficiency of water delivery and use with nanotechnology.
3. Enable next-generation water monitoring systems with nanotechnology.

This activity will leverage existing and emerging efforts of six Federal agencies—DOC/NIST, DOE, EPA, NASA, NSF, USDA/NIFA—to create the necessary technical breakthroughs. These efforts include DOE's Water-Energy Tech Team; the Innovations at the Food-Energy-Water Nexus activity at NSF and USDA/NIFA; and EPA's 2014 Water Technology Innovation Blueprint, Promoting Technology Innovation for Clean and Safe Water. Where appropriate, the water NSI will also interface with other interagency Federal activities such as the NNI's Sensors NSI and the Open Water Data Initiative to build and share cross-community expertise and to collaboratively address key challenges that span multiple groups.

NNI website nano.gov. In some cases, development of public–private partnerships may also be an appropriate mechanism to advance the areas spotlighted by NSIs.

The portfolio of NSIs is intended to be dynamic. As first introduced in the 2014 NNI Strategic Plan and described in Objective 1.4, each NSI is reviewed biennially to determine the value of its continuation and to update plans to ensure continued relevance. Based on this annual evaluation, one of the original NSIs, Solar Energy Collection and Conversion, was retired in 2015. It was determined that this NSI had produced a well-established and sustainable community such that the additional focus afforded by a signature initiative was no longer required. The NSET Subcommittee continues to examine other potential topics in nanoscale science and technology that may benefit from similar close coordination. New NSIs are selected based on alignment with national scientific, economic, and environmental priorities; potential impact on the advancement of nanoscale science and technology; and the need for enhanced interagency coordination and collaboration (for example, areas that cannot be adequately addressed by a single agency). In March of 2016, a new signature initiative, Water Sustainability through

Nanotechnology, was established. Additional information about the NSIs, including white papers, is available at www.nano.gov/signatureinitiatives. The current signature initiatives are:

- Sustainable Nanomanufacturing: Creating the Industries of the Future
- Nanoelectronics for 2020 and Beyond
- Nanotechnology Knowledge Infrastructure: Enabling National Leadership in Sustainable Design
- Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment
- Water Sustainability through Nanotechnology: Nanoscale Solutions for a Global-Scale Challenge

Nanotechnology-Inspired Grand Challenges

Grand challenges are a mechanism to engage the community beyond the Federal Government to help catalyze breakthroughs needed to solve key national and global problems. A Nanotechnology-Inspired Grand Challenge is defined as an ambitious but achievable goal that harnesses nanoscience, nanotechnology, and innovation to solve important national or global problems and that has the potential to capture the public's imagination. In its October 2014 assessment of the NNI, the President's Council of Advisors on Science and Technology (PCAST) recommended that agencies engage research, development, and industrial stakeholders in the identification and selection of grand challenges to focus and amplify the impact of Federal nanotechnology activities. Nanotechnology-Inspired Grand Challenges address complex R&D tasks that require the research, development, and commercialization communities to come together with the Federal Government to work toward solutions. To kick-start the process, the NSET Subcommittee held a retreat in mid-2015 to identify potential topic areas; it then released an RFI seeking suggestions from the public for potential Nanotechnology-Inspired Grand Challenges.[47] After considering more than 100 responses, the first Nanotechnology-Inspired Grand Challenge was announced in October 2015, which challenged the community to "*create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.*" This Grand Challenge for Future Computing is a rallying cry not only to the NNI and the broader nanotechnology community, but also to those involved in two other national initiatives: the National Strategic Computing Initiative and the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative. More information about this grand challenge, including statements of support from a wide variety of organizations and a Federal white paper describing the interagency vision for the emerging and innovative solutions needed to realize the challenge goals, can be found at www.nano.gov/grandchallenges. This 2016 NNI Strategic Plan introduces Objective 1.5 for the NNI agencies to explore other complex technical topics that may be advanced by the grand challenge mechanism.

[47] www.federalregister.gov/articles/2015/06/17/2015-14914/nanotechnology-inspired-grand-challenges-for-the-next-decade

A Nanotechnology-Inspired Grand Challenge for Future Computing

This challenge will look beyond conventional computing based on the Von Neumann architecture.

In October 2014, the President's Council of Advisors on Science and Technology (PCAST) recommended that the NNI engage with the public to identify and select grand challenges in order to focus and amplify the impact of Federal nanotechnology activities. Working with the NNI agencies, the White House Office of Science and Technology Policy (OSTP) then issued a Request For Information (RFI) on June 15, 2015, seeking suggestions from the public for Nanotechnology-Inspired Grand Challenges. After considering more than 100 responses from R&D experts and industrial stakeholders, OSTP announced the first grand challenge on October 20, 2015:

Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.

This Nanotechnology-Inspired Grand Challenge is relevant to two other U.S. initiatives: the National Strategic Computing Initiative and the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative. Five NNI agencies—DOD, DOE, IC, DOC/NIST, and NSF—have programs that support research in pursuit of this challenge, and support for this effort outside the Government is also strong. A wide range of private sector and non-Federal groups have released statements in support of this grand challenge. The NNI agencies listed above released a white paper on July 29, 2016, that presents a collective vision of the emerging and innovative solutions needed to realize the challenge goals. By coordinating and collaborating across multiple levels of government, industry, academia, and nonprofit organizations, the nanotechnology and computer science communities can look beyond the decades-old approach to computing based on the von Neumann architecture and chart a new path that will continue the rapid pace of innovation beyond the next decade.

A human can do tasks in ways that a conventional computer cannot, with a fault-tolerant, adaptive brain that uses less energy than it takes to power an incandescent light bulb. By combining innovations in nanotechnology, computer science, and neuroscience, radically new approaches to creating both hardware and software can be developed, enabling computers capable of efficiently interpreting images and speech, proactively spotting patterns and anomalies in data, learning from data as it is received, and solving unfamiliar problems using what has been learned.

Contests and Community Networks

The NNI extends beyond the twenty Federal agencies and departments involved in the initiative and includes the thousands of university professors, students, and industrial scientists and engineers who benefit from numerous grants and contracts by NNI agencies to academia and industry. These researchers, however, often do not feel connected to or engaged with the NNI, and opportunities to share knowledge or leverage resources may not be fully realized. Despite the fact that nanotechnology is becoming ubiquitous in everyday consumer products, the public remains largely unaware of nanotechnology–what it is and its benefits and risks. To address these issues, the NNI agencies have launched a number of efforts to engage the public and build the broader NNI community. With support from NNCO, these agencies will continue efforts such as image and video contests for students that highlight student research and help build broader awareness of the NNI activities. Another mechanism to support public awareness and education is the development of nanotechnology-focused community networks for students and teachers. NNCO will continue to facilitate these networks to enable the sharing of resources and best practices through activities such as regular teleconferences, webinars, and the establishment of web-based resource portals. NNCO and the NNI agencies will also work together and with others to develop content, such as brochures, videos, and animations, and to look for venues where nanotechnology content can be included to engage and educate the broader public.

Communities of Research

Communities of interest can be powerful mechanisms to build and sustain relationships among people with common or synergistic research goals. The NNI is collaborating with the European Union (EU) to facilitate the U.S.–EU Communities of Research (CORs),[48] which serve as a platform for American and European researchers to share information and collaborate, primarily on nanoEHS issues. Established in 2012, these CORs have collaborated on activities such as joint papers,[49] webinars, and workshops, as well as an interactive "nanoEHS scrimmage" to spark collaborations and new ideas.[50] Topic areas evolve with the interests and needs of the broader community, but are currently focused on the following:

- Characterization
- Databases & Computational Modeling for NanoEHS
- EcoToxicity
- Human Toxicity
- Exposure through Product Life
- Risk Assessment
- Risk Management & Control

The U.S.–EU CORs enable the leveraging of knowledge across national boundaries and provide the mechanism for enhanced communication to help the research community address issues such as the current state of knowledge in important areas. The NNI will look for opportunities to employ this mechanism in other collaborative areas (geographical and/or topical), as appropriate.

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[48] us-eu.org
[49] Selck, H., *et al.*, Nanomaterials in the aquatic environment: A European Union–United States perspective on the status of ecotoxicity testing, research priorities, and challenges ahead. *Environ. Toxicol. Chem.*, **35**, 1055–1067 (2016).
[50] nanoehs.enanomapper.net/

Concluding Remarks

The National Nanotechnology Initiative has been highly successful in its efforts to advance nanotechnology research, development, and the responsible transfer of nanotechnology-based products from the lab to market. Investments by NNI agencies, collectively more than $23 billion over the life of the NNI, have supported groundbreaking, multidisciplinary research that has expanded the boundaries of scientific understanding of phenomena that occur at the nanoscale and how these phenomena can be exploited to produce new materials and devices with properties and performances exceeding those of conventional systems. In addition, NNI investments have created a network of state-of-the-art user facilities for characterization, modeling, and fabrication that support a broad range of activities from fundamental research to the development of commercial products. NNI agencies have also supported fundamental research to understand the potential risks of ENMs and NEPs and have used this understanding to develop science-based regulations to protect human health and the environment and to ensure the full benefits of nanotechnology to society. Funding from NNI agencies has helped inform the public and stakeholders about nanotechnology and its benefits and risks, develop a highly skilled workforce supporting nanotechnology research and commercialization, and educate and inspire the next generation of scientists, engineers, and entrepreneurs.

The NNI is at a crossroads. Nanotechnology has evolved from an area of fundamental research to an enabling technology. Recognizing this evolution, the NNI has expanded its focus from support for fundamental research on nanomaterials and devices to include new efforts focused on utilizing these materials and devices to develop nanotechnology-enabled systems. The next phase of the NNI will require a robust ecosystem that supports fundamental discovery, fosters innovation, and promotes the transfer of nanotechnology discoveries from lab to market, along with continued efforts to ensure the safety of NEPs across their entire life cycle. This strategic plan reflects the collective vision of NNI agencies on how they will collaborate with each other and the broader nanotechnology community to expand this ecosystem.

Appendix A. Agency Interests in the NNI

The NSET Subcommittee was established in July 2000 as part of the NSTC Committee on Technology to facilitate interagency collaboration on nanoscale R&D and to provide a framework for setting Federal R&D budget priorities related to nanotechnology. Moreover, the NSET Subcommittee provides a platform for communication, collaboration, and coordination that promotes the engagement of all participating agencies, including those with an interest but no targeted funding in nanotechnology. In the following sections, the agencies describe their individual interests in nanotechnology R&D and the NNI, as they collectively contribute to the welfare of the Nation and to their respective agency missions and responsibilities.[51]

Consumer Product Safety Commission (CPSC)

CPSC, in cooperation with Federal partners, analyzes the use and safety of nanotechnology in consumer products. In order to meet identified data needs, the CPSC staff has met with and collaborates with staff at a number of Federal agencies in areas of mutual interest where collaboration would be beneficial and support the respective missions of each agency. More consumer products are using compounds or materials that have been produced using nanotechnologies that directly manipulate matter at the atomic level and produce materials that could not have been produced in the past.

Nanomaterials with the same chemical composition as larger-scale materials may demonstrate different physical and chemical properties and may behave differently in the environment and the human body. CPSC has developed an internal nanotechnology team composed of various technical experts (e.g., engineers, toxicologists, and economists) to advise the Commission on the safe use of nanotechnology in consumer products. As part of the NNI, the CPSC nanotechnology team participates in the interagency collection and analysis of data and in the development of reports that focus on the potential EHS issues associated with the use of nanotechnology.

Department of Commerce (DOC)

DOC participates in the NNI to promote job creation, economic growth, sustainable development, and improved standards of living for all Americans by working in partnership with businesses, universities, communities, and our Nation's workers. The Department touches the daily lives of the American people in many ways, with a wide range of responsibilities where nanotechnology is important, including trade, economic development, technology, innovation, entrepreneurship and business development, environmental stewardship, and statistical research and analysis. The Bureau of Industry and Security (BIS), Economic Development Administration (EDA), National Institute of Standards and Technology (NIST), and U.S. Patent and Trademark Office (USPTO) are active participants in the NSET Subcommittee. Their engagement informs the department- and Federal Government-wide coordination of nanotechnology-related trade and economic policies, R&D, standards activities, and protection of intellectual property.

[51] The latest information on the nanotechnology activities of NNI agencies is available at www.nano.gov.

Bureau of Industry and Security (BIS)

The interagency coordination provided by the NNI enables BIS to stay apprised of new nanotechnology advancements that may present national security challenges and that may provide opportunities for companies in the national defense industrial base. Further, the NNI creates mechanisms (e.g., through regular meetings of the NSET Subcommittee) for BIS to share information about national security needs and challenges with other Federal agencies. BIS may also exercise its statutory data collection authority, as needed, in support of the NNI vision. Together, these exchanges support the BIS mission to advance U.S. national security, foreign policy, and economic objectives by ensuring an effective export control and treaty compliance system and promoting continued U.S. strategic technology leadership.

Economic Development Administration (EDA)

The mission of EDA is to lead the Federal economic development agenda by promoting innovation and competitiveness, preparing American regions for growth and success in the worldwide economy. Economic development results in a sustained increase in prosperity and quality of life through innovation, lowered transaction costs, and the utilization of capabilities toward the responsible production and diffusion of goods and services. The vision and four goals of the NNI Strategic Plan align strongly with EDA's mission and leading-edge economic development policy. The NSET Subcommittee provides a venue for EDA to understand the current state of nanotechnology development and to collaborate across the Federal Government to increase the rate and efficiency of nanotechnology commercialization efforts that originate in and near our Nation's research laboratories. EDA's support for commercialization includes funding for innovation centers, coordination with universities and Federal labs, collaborative funding opportunities with other Federal agencies, and technical assistance and capacity building for regional innovation ecosystems that support entrepreneurs. Further, EDA funding priorities include support for innovation in nanotechnology-relevant sectors such as advanced and additive manufacturing, energy, green growth, and others.

National Institute of Standards and Technology (NIST)

Advancing nanoscale measurement science, standards, and technology is an important component of NIST's mission to promote U.S. innovation and industrial competitiveness. From leading cutting-edge research, to providing world-class user facilities, to coordinating the development of standards that promote trade, NIST's nanotechnology program directly impacts priorities important to the Nation's economy and well-being. The NNI-related research conducted in NIST's laboratories and user facilities develops measurements, standards, and data crucial to a wide range of industries and Federal agencies, from the development of new measurement and fabrication methods necessary for advanced manufacturing to the development of the reference materials and data necessary to accurately measure key nanomaterial properties needed for the responsible development and use of nanotechnology. NIST further supports the U.S. nanotechnology enterprise through its two user facilities, the NIST Center for Neutron Research (NCNR) and the Center for Nanoscale Science and Technology (CNST). The NCNR provides access to a broad range of world-class neutron scattering tools for characterizing the atomic- and nanometer-scale structure and dynamics of materials. As the Department of Commerce's nanotechnology user facility, the CNST enables innovation by providing rapid access to the tools needed to make and measure nanostructures, with a particular emphasis on helping industry.

The NNI has enabled NIST to prioritize and coordinate nanotechnology research in numerous areas, most notably in nanoelectronics, nanomanufacturing, and energy, as well as nanoEHS. NIST is working closely with other NNI agencies in planning and implementing the NSIs. Through activities of the NSET Subcommittee's Nanotechnology Environmental and Health Implications (NEHI) Working Group, NIST receives input from a broad range of stakeholders on the critical measurement science and measurement tools—protocols, standards, instruments, methods, models, and validated data—required for risk assessment and management of ENMs and NEPs. This input is essential to the development and implementation of NIST's programmatic efforts.

NIST staff members participate widely, and lead, in nanotechnology-related standards development and international cooperation activities. NIST staff expertise helps ensure the technical quality and efficacy of the resulting international standards and enables rapid technology transfer from NIST to the stakeholder community. NIST experts participate and provide leadership in multilateral activities such as the Organisation for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials, the International Organization for Standardization (ISO) Technical Committee 229, the International Electrotechnical Commission Technical Committee 113, and ASTM International Committee E56. Interagency coordination and information sharing related to these activities is facilitated through the NSET Subcommittee and the NNI's Coordinators for Global Issues and for Standards Development.

U.S. Patent and Trademark Office (USPTO)

The strength and vitality of the U.S. economy depends directly on effective mechanisms that protect new ideas and investments in innovation and creativity. USPTO is at the cutting edge of the Nation's technological progress and achievement as the Federal agency responsible for granting patents, registering trademarks, and providing intellectual property policy advice and guidance to the Executive Branch. Through its participation in the NNI and work with other agencies in the NSET Subcommittee, USPTO has made several improvements to its processes to keep pace with the rapid advances being made in this area. Notably, USPTO adopted the NNI definition of nanotechnology in its development of the first detailed, patent-related nanotechnology classification hierarchy of any major intellectual property office in the world. USPTO also has used the networking and information-sharing opportunities presented by participation in the NNI to establish nanotechnology-related training opportunities for patent examiners. USPTO has significantly contributed to the NNI by providing advice on patent and other intellectual-property-related matters as well as contributing a variety of nanotechnology-related patent data, which have been used as benchmarks to analyze nanotechnology development and to perform trend analysis of nanotechnology patenting activity in the United States and globally.

Department of Defense (DOD)

DOD leadership considers nanotechnology to have high and growing potential to contribute to the warfighting capabilities of the Nation. Because of the broad and interdisciplinary nature of nanotechnology, DOD leadership views it as an enabling technology area that should receive the highest level of Department attention and coordination. The vision of the Assistant Secretary of Defense for Research and Engineering includes nano science and engineering as one of six high-interest basic science areas, along with synthetic biology, quantum information science, cognitive neuroscience, human behavior modeling, and novel engineered materials. The definition, potential, and challenges of nanotechnology are described by DOD in the following terms: The science of materials on the atomic scale makes possible new classes of electronics and sensors, chemical catalysts, high-strength materials, and energetic materials. Challenges include developing new ENMs, functionalizing them when necessary, developing scalable processes for manufacturing, and incorporating them into devices. DOD also invests in nanotechnology for advanced energetic materials, photocatalytic coatings, active microelectronic devices, structural fibers, strength- and toughness-enhancing additives, advanced processing, and a wide array of other promising applications. The DOD nanotechnology efforts are based on coordinated planning and federated execution among the military departments and agencies (e.g., the Defense Advanced Research Projects Agency [DARPA] and the Defense Threat Reduction Agency [DTRA]). Although DOD does not establish funding targets for nanotechnology specifically, its support for nanotechnology-related R&D has remained robust through the competitive success of nanotechnology-related efforts in core research planning, technology development solicitations, and other programs, such as Small Business Innovation Research (SBIR), the Multidisciplinary University Research Initiative (MURI), and the Vannevar Bush Faculty Fellowship Program.[52]

DOD was among the initial participating agencies in the NNI and the NSET Subcommittee and considers the Initiative and its formal coordination forums to have been valuable as a means to facilitate technology planning, coordination, and communication among the Federal agencies. The meetings and workshops hosted or facilitated by the NSET Subcommittee and NNI participants help to identify and define options and opportunities that materially contribute to DOD planning activities and program formulation. The transparency that is enabled by the NNI is viewed as symmetrically beneficial to DOD, the other agencies, and the many private-sector stakeholders in the broad arena of nanoscience, nanotechnology, and nanotechnology-enabled applications.

Department of Education (DOEd)

DOEd is committed to supporting and improving science, technology, engineering, and mathematics (STEM) education for students from preschool to graduate school. DOEd also seeks to improve access to quality STEM education for all students, particularly students from groups that have historically been underserved in the STEM fields, including students in low-income communities, students of color, females, students with special educational needs, and students living in rural communities. In addition, DOEd supports STEM educators through a variety of programs and initiatives. DOEd's STEM Office can be supportive of interagency working groups by participating in regular subcommittee meetings. The NNI provides a conduit to help DOEd appreciate the specific STEM requirements for proficiency in nanotechnology by connecting them with experts at NSF, DOL, and other Federal agencies. In return, DOEd can provide valuable information to the NNI agencies on nanotechnology-relevant student requirements and teacher training.

Department of Energy (DOE)

DOE views nanoscience and nanotechnology as having a vitally important role to play in solving the energy and climate-change challenges faced by the Nation. This broad and diverse field of R&D will likely

[52] Formerly the National Security Science and Engineering Faculty Fellowship Program. www.acq.osd.mil/rd/basic_research/program_info/vbff.html

have a dramatic impact on future technologies for solar energy collection and conversion, energy storage, alternative fuels, and energy efficiency, to name just a few. DOE has participated in the NNI since its inception and maintains a strong commitment to the Initiative, which has served as an effective and valuable way of spotlighting needs and targeting resources in this critical area of science and technology. The NNI continues to provide a focus for overall investment in physical sciences, a crucial locus for interagency communication and collaboration, and an impetus for coordinated planning. The research and infrastructure successes spurred by the NNI have made the United States a world leader in this area, with significant national benefit.

The majority of DOE NNI investments are made by the Office of Science (SC), with an emphasis on fundamental phenomena and processes. Examples of such research supported include the following: nanostructured materials for electron and ion transport in next-generation batteries and fuel cells; nanoscale quantum materials for future energy technologies; fundamental understanding of nanoscale defects that will enable predictive design of materials with superior mechanical properties and radiation resistance; elucidation of the elementary steps of light absorption, charge separation, and charge transport in nanostructured materials and chemical systems for improved solar energy conversion; atomically precise materials for molecular electrocatalysts that efficiently convert electrical energy into chemical bonds in fuels; and enhanced computational capabilities for the simulation of chemical and geochemical processes at the molecular and nanoscales. Additional NNI investments come from the Office of Energy Efficiency and Renewable Energy (EERE) and from the Advanced Research Project Agency–Energy (ARPA-E) in areas such as ENMs and nanotechnology-enabled devices. These funds support nanotechnology R&D at universities, national laboratories, nonprofit research institutes, and companies of all sizes.

In addition, DOE supports major research facilities, a category in which the DOE investment is significantly larger than that of other agencies, due primarily to the operation of five Nanoscale Science Research Centers (NSRCs) located at DOE laboratories. The NSRCs operate as user facilities, with access based on submission of proposals that are reviewed by independent evaluation boards and provided at no cost for nonproprietary work. The NSRCs support synthesis, processing, fabrication, and analysis at the nanoscale and are designed to be state-of-the-art user centers for interdisciplinary nanoscale research, serving as an integral part of DOE's comprehensive nanoscience program that encompasses new science, new tools, and new computing capabilities.

Department of Health and Human Services (DHHS)

DHHS participates in the NNI as part of its mission to protect the health of all Americans and provide essential human services. The Food and Drug Administration (FDA), National Institute for Occupational Safety and Health (NIOSH), and National Institutes of Health (NIH) contribute to the NSET Subcommittee to address a range of priorities relevant to the NNI. DHHS also contributes to the NNI EHS efforts that support and promote responsible development of nanotechnology through a variety of mechanisms, most notably the NEHI Working Group of the NSET Subcommittee.

Food and Drug Administration (FDA)

The use of nanotechnology can lead to novel therapies, early detection of disease, and better health outcomes for patients, but can also alter the safety, effectiveness, performance, and/or quality of FDA-regulated products. For this reason, FDA is interested in additional scientific information and tools to help better detect and predict potential effects of such changes on both human and nonhuman animal health.

FDA investments help address questions related to the safety, effectiveness, quality, and/or regulatory status of products that contain ENMs or otherwise involve the use of nanotechnology; develop models for safety and efficacy assessment; and study the behavior of nanomaterials in biological systems and their effects on both human and nonhuman animal health. These investments support FDA's mission to protect and promote public health and help support the responsible development of nanotechnology.

FDA has developed a regulatory science program in nanotechnology to foster the responsible development of FDA-regulated products that may contain ENMs or otherwise involve the application of nanotechnology. The FDA program establishes tools, standardized methods, and data to assist in regulatory decision-making while providing in-house scientific expertise and capacity that is responsive to nanotechnology-related FDA-regulated products.

The Office of the Commissioner, in partnership with the FDA Nanotechnology Task Force (NTF), facilitates communication and cooperation across the agency on nanotechnology regulatory science research, both within FDA and with national and international stakeholders. The NTF provides the overall coordination of FDA's nanotechnology regulatory science research efforts in the following programmatic investment areas: (1) scientific staff development and professional training; (2) laboratory infrastructure and product-testing capacity; (3) collaborative and interdisciplinary regulatory science research on characterization, detection, identification, quantitation of nanomaterial structure–activity relationships that influence the safety and efficacy of nanomaterials in FDA-regulated products; and (4) consensus standards development.

As needed and appropriate, FDA continues to foster and develop collaborative relationships with other Federal agencies through participation in the NNI, through the NSET Subcommittee and the NEHI Working Group, as well as with regulatory agencies, healthcare professionals, industry, academics, consumers, and other stakeholders. Most recently, NTF has increased its international engagement through:

- Participation in the U.S.–EU Communities of Research (CORs).
- Participation in the International Pharmaceutical Regulators Forum Nanomedicines Working Group.
- Organization of the "Global Summit on Regulatory Science: Nanotechnology Standards and Applications" scheduled for September 2016,
- Continued participation in ISO and ASTM International activities in standards development, along with other stakeholders.

The goal of these activities is to strengthen global regulatory research collaboration and coordination to advance nanotechnology for the benefit of human and animal health and to develop novel characterization/measurement tools, reference materials, and consensus standards to aid commercialization and responsible development of FDA-regulated products. These collaborations allow information to be exchanged efficiently and serve to identify research needs related to the use of ENMs.

Although FDA activities are relevant to all four NNI goals, FDA efforts are primarily focused on Goals 3 and 4, to develop a skilled workforce, infrastructure, and toolset and to support responsible development of nanotechnology.

National Institute for Occupational Safety and Health (NIOSH)

NIOSH is responsible for conducting research and providing guidance to protect the health and safety of people at work. Workers are generally the first people in society to be exposed to the hazards of an emerging technology, and nanotechnology is no exception. The workplaces where ENMs and NEPs are developed, investigated, manufactured, used, and disposed of are quite varied and span all economic sectors. NIOSH conducts focused research on hazard identification, exposure assessment, risk characterization, and risk management to protect the health and safety of workers. The results of this research allow NIOSH to develop effective recommendations and to promote responsible development of the technology. In addition to investigating the potential implications of nanotechnology, NIOSH is also evaluating how nanotechnology can be applied to address occupational safety and health issues. In order to meet the need for a unified approach to this complex research challenge, the NIOSH Nanotechnology Research Center (NTRC) was chartered to manage NIOSH's investment in nanotechnology and to coordinate a multidisciplinary research program across the Institute. In addition to providing internal coordination of the NIOSH research program, the NTRC serves as an interface point for NNI participating agencies, for private sector organizations manufacturing or formulating nanomaterials, and for other agencies and research institutes nationally and internationally.

NIOSH toxicology studies continue to provide better understanding of the ways in which some types of ENMs may enter the body and interact with the body's organ systems. The scope of these research efforts has expanded beyond the few nanoparticle types evaluated at the start of the NIOSH nanotechnology research program. A key component of this effort is to understand the characteristics, properties, and material modes of action relevant for predicting potential health risks. The toxicology studies have served as a starting point to identify the priority materials for further risk assessment, exposure evaluations, and development of risk management practices.

NIOSH field investigators continue to work with a growing number of private sector companies to assess potential occupational exposure to ENMs, including a focused effort on carbon nanotubes. However, more data are needed on the full extent and magnitude of workers' exposures to broad categories of ENMs in workplaces that manufacture or use ENMs, nanostructures, and nanodevices. NIOSH field investigators continue to expand the scope of assessment and the number and type of facilities that can be assessed.

Controlling worker exposure to ENMs is one of the first steps in a risk-based approach to responsible development of nanotechnology. NIOSH will increase its effort with private sector partners to evaluate the extent of adherence to risk management guidance, with an initial focus on evaluating the effectiveness of engineering control measures. Additional field research is needed to address questions raised about possible human health risks in exposed nanotechnology workers and to develop guidance for medical screening and prospective epidemiologic studies. Starting in late 2016, NIOSH will work collaboratively with private- and public-sector partners to evaluate the effectiveness of risk management practices developed for nanomaterials that are now appropriate when those materials are used in advanced manufacturing processes. Risk management practices applied to advanced/additive manufacturing processes using nanoscale metal materials will be evaluated.

NIOSH will continue to work with NNI agencies and a broad range of national and international private and public partners to develop research-based information and guidance to protect workers involved with ENMs. The results being produced by NIOSH will continue to serve as the foundation for meeting the critical NNI research needs related to human hazard and exposure assessment, exposure mitigation, risk assessment techniques, risk management practices, and human medical surveillance and epidemiology. NIOSH has developed formal collaborations with the National Toxicology Program (National Institute of Environmental Health Sciences, NIEHS), CPSC, DOD, and OSHA. It has also developed productive informal interactions with other agencies, including EPA, NIST, DOE, and FDA. NIOSH will continue to develop partnerships in the public–private arena, such as its collaboration with the State University of New York (SUNY) Polytechnic Institute's Colleges of Nanoscale Science and Engineering to launch the Nano Health and Safety Consortium.

National Institutes of Health (NIH)

NIH is the primary Federal agency for conducting and supporting biomedical and behavioral research. The NIH mission is to seek fundamental knowledge about the nature and behavior of living systems and the application of that knowledge to enhance health, lengthen life, and reduce illness and disability. NIH recognizes that advances in nanoscience and nanotechnology have the potential to make valuable contributions to biology, medicine, and related disciplines, which in turn could contribute to a new era in healthcare. The Federal agencies' R&D investments, for example, have resulted in advanced materials, tools, and nanotechnology-enabled instrumentation that can be used to study and understand biological processes in health and disease. NIH-supported R&D efforts, in particular, are bringing about new paradigms in the detection, diagnosis, and treatment of common and rare diseases, resulting in new classes of nanotherapeutics and diagnostic biomarkers, tests, and devices.

NIH has participated in the NNI since 2001. The NNI serves as a framework within which NIH can work collaboratively with other agencies to address some of the most perplexing challenges in the development and application of nanotechnologies for biomedical applications. Through the interagency planning, coordination, and communication efforts, scientists are addressing key challenges by:

- Understanding the manner in which nanoscale building blocks and processes integrate and assemble into larger systems and how these processes can be precisely controlled to achieve predictable outcomes.
- Learning how to design ENMs that can seamlessly and functionally integrate with tissues of the body to perform biological functions.
- Developing "top-down" and "bottom-up" engineering approaches to control properties that allow the identification, characterization, and quantification of biological molecules, chemicals, and structures involved in early-stage changes or progression in a disease state.
- Engineering complex, theranostic-based nanoparticles and nanodevices to target therapies and diagnose the progress of treatments.
- Adopting new materials, nanotechnology-enabled tools, and analytical instruments from diverse fields to support medical research.

NIH continues to support the NNI by stimulating R&D in nanoscience and nanotechnology through both intramural and extramural funding activities in all five Program Component Areas, with major financial investments in foundational research (PCA 2) and nanotechnology-enabled applications, devices, and systems (PCA 3). For more information on specific topics funded by NIH, please visit the NIH Research Portfolio Online Reporting Tool at www.report.nih.gov. NIH plays a substantive role in developing scientific understanding of how to design ENMs for safe use in manufacturing and for use in medical treatments. The National Cancer Institute (NCI), for example, established the Nanotechnology Characterization Laboratory (NCL), which has developed a comprehensive assay portfolio for the assessment of the safety of nanoparticles in *in vivo* applications, and NIEHS and the National Toxicology Program have focused on assessing properties relevant to the chronic exposure of workers to ENMs. NIH also supports large center grants, program grants, and small businesses whose technologies or products are licensed or currently undergoing Phase I–III clinical trials.

Department of Homeland Security (DHS)

DHS interests in nanoscience are primarily focused on the application of nanoscale materials and devices that provide enhancements in component technology performance for homeland security applications. The applications for the efforts described below are in threat detection for enhanced security for aviation, mass transit, and first responders:

- *Materials toolbox:* These efforts are focused on the development of materials systems that allow systematic control of chemical and structural features from molecular scales (functional groups) through nano- and microscales. The ability to precisely tune material properties is critical for successful development of improved active sensor surfaces and analyte collection substrates as well as for development of novel sensing structures and arrays.
- *Advanced preconcentrators:* The DHS Science and Technology Directorate is interested in the development of high-performance nanoscale preconcentrators for use in next-generation detection systems.
- *Advanced sensing platforms:* Work on the development of nanoscale sensing platforms continues with industry partners. The emphasis of these efforts is on development of manufacturing techniques for low-cost sensor platforms and wearable sensing technologies.

Department of the Interior (DOI) / U.S. Geological Survey (USGS)

USGS, serving as the primary science organization within DOI, has seven mission areas, including environmental health. The science supporting the environmental health mission area focuses on the environment–health interface. Research characterizes processes that affect interactions among the physical environment, the living environment, and people, as well as the factors that affect ecological and human exposure to disease agents and the resulting toxicological or infectious diseases. The mission of USGS in environmental health science is to contribute scientific information to environmental, natural resource, agricultural, and public health managers, who use that information to support sound decision making. The five main goals are:

- Identify, prioritize, and detect contaminants and pathogens of emerging concern.
- Reduce the impact of contaminants on the environment, fish and wildlife, and people.

- Reduce the impact of pathogens on the environment, fish and wildlife, domesticated animals, and people.
- Discover the complex interactions between, and combined effects of, exposure to contaminants and pathogens.
- Prepare for and respond to environmental impacts and related health threats of natural and anthropogenic disasters.

The intended outcome of this science is prevention and reduction of adverse impacts to the quality of the environment, the health of our living resources, and human health. Communicating with, and receiving input from, partners and stakeholders regarding their science needs is essential. USGS engages all stakeholders to ensure that its efforts are focused on the highest priority environmental health issues, and that products are provided in the most timely and usable form to all those who can use them. USGS must reach out to the scientific community, internally and externally, to ensure that efforts are integrated with and take full advantage of the activities of others.

Department of Justice (DOJ) / National Institute of Justice (NIJ)

The NIJ investment in nanotechnology furthers DOJ's mission through the sponsorship of research that provides objective, independent, evidence-based knowledge and tools to meet the challenges of crime and justice, particularly at the state and local levels. New projects are awarded on a competitive basis; therefore, total investment may change each fiscal year. However, NIJ continues to view nanotechnology as an integral component of its R&D portfolio as applicable to criminal justice needs.

Department of Labor (DOL) / Occupational Safety and Health Administration (OSHA)

OSHA plays an integral role in nanotechnology by protecting the Nation's workforce. OSHA accomplishes its mission by collaborating and sharing information with other Federal agencies through NNI activities and NSET Subcommittee meetings. As part of this effort, OSHA's goal is to educate employers on their responsibility to protect workers and to educate workers on safe practices in handling ENMs. OSHA is developing guidance and educational materials promoting worker safety and health that will be shared with the public directly and through the NNI.

Department of State (DOS)

DOS participates in the NNI to identify and promote multilateral and bilateral scientific activities that support U.S. foreign policy objectives, protect national security interests, advance economic interests, and foster environmental protection. DOS assists NNI agencies in establishing partnerships with counterpart institutions abroad by holding regular joint committee meetings with representatives from more than fifty countries. These meetings are governed by binding science and technology agreements that facilitate exchange of scientific results, provide for protection and allocation of intellectual property rights and benefit sharing, facilitate access for researchers, address taxation issues, and respond to the complex set of issues associated with economic development, domestic security, and regional stability. DOS engages in multilateral international organizations that support the responsible development of nanotechnology, including the OECD Committee for Scientific and Technological Policy and its subsidiary Working Party on Biotechnology, Nanotechnology, and Converging Technologies; the Strategic Approach to International Chemicals Management; and ISO.

Department of Transportation (DOT) / Federal Highway Administration (FHWA)

FHWA sees great promise in the application of nanotechnology to help solve long-term transportation research needs in support of DOT's strategic goals: Safety, State of Good Repair, Economic Competitiveness, Quality of Life in Communities, and Environmental Sustainability. By strategically investing in focused research areas and leveraging investments in nanoscale technology by other NNI partners and Federal agencies, industry, and academia, FHWA aims to accelerate the capability to provide safer, more efficient, longer-lasting highway transportation systems. FHWA's Exploratory Advanced Research Program is investing in nanoscale research to address key highway research issues in infrastructure, safety, operations, and the environment. Nanotechnology promises breakthroughs in multiple areas, offering a potential for synergy and benefits across many traditional highway research focus areas.

The development of innovative materials and coatings can deliver significant improvements in durability, performance, and resiliency of highway and transportation infrastructure components. Nanoscale engineering of traditional transportation infrastructure materials (e.g., steel, concrete, asphalt, and other cementitious materials, as well as recycled forms of these materials) offers great promise.

In the near- to mid-term, FHWA sees promise in new methods for nanoscale characterization of complex heterogeneous materials that can support multiscale modeling and increased understanding of material interactions throughout the lifecycle of pavements and materials, resulting in the broad impact of a decrease in the use of increasingly scarce virgin materials and the energy required to construct and maintain the highway system.

In the longer term, nanoscale science may allow for pavements and structures with embedded sensors and active controls that provide for multiple functions and increased resilience, such as pavements that change texture or increase porosity when wet, pavements with dynamic lane markings meeting the needs of traffic conditions, or materials that change tension in response to wind or water forces or traffic loading.

FHWA's long-term strategy is to continue targeted investment in select areas while building an appreciation for highway research needs with NNI agencies and the broader nanoscale research community in order to augment longstanding partnerships and make significant progress toward improving the Nation's highway and transportation systems.

Department of the Treasury (DOTreas)

DOTreas works through the NSET Subcommittee to help the NNI achieve its vision congruent with that of DOTreas: to serve the American people and strengthen national security by managing the Federal Government's finances effectively; to promote economic growth and stability; and to ensure the safety, soundness, and security of U.S. and international financial systems. DOTreas monitors those aspects of developing nanotechnology that could most effectively assist the execution of its role as the steward of the U.S. economic and financial systems and as an influential participant in the global economy. DOTreas seeks to assess and utilize nanotechnology in the discharge of its responsibilities, including advising the President on economic and financial issues, encouraging sustainable economic growth, and fostering improved governance in financial institutions. It seeks to harness those aspects of nanotechnology R&D that will allow it to better operate and maintain systems that are critical to the Nation's financial infrastructure, such as the production of coin and currency. Interactions with the NSET Subcommittee help DOTreas as it endeavors to capture developments in nanoscale science and engineering that are changing the parameters of its domestic and international operations, particularly those impacting its critical national security-related activities in implementing economic sanctions against foreign threats to the United States, identifying and targeting the financial support networks of national security threats, improving the safeguards of U.S. financial systems, and creating new economic and job opportunities to promote economic growth and stability at home and abroad.

Environmental Protection Agency (EPA)

EPA's interest in the NNI is to collaborate to better understand the implications and emerging applications of ENMs to help protect human health and the environment. Innovations in chemical and material design are rapidly changing the landscape of industrial and consumer products as novel materials such as ENMs are incorporated to enhance product performance. Scientifically supported approaches are required to efficiently screen for and evaluate potential impacts of ENMs to human health and the environment. EPA conducts applied research to develop, collate, mine, and apply information on ENMs to support risk-based decisions on sustainable manufacture and use.

In this research, a life cycle perspective is applied and available information synthesized to consider potential for impacts associated with manufacture, use, and disposal of products containing ENMs. Results of this research will provide the methods and tools to enable EPA to efficiently evaluate emission, transformation, potential exposure, and impacts of ENMs across the material/product life cycle. The long-term impact will be to accelerate the pace at which the safety of existing nanomaterials is assessed and to inform the sustainable design and development of emerging materials and products.

To help nanotechnology create maximum societal benefits and to minimize its potential environmental impacts, EPA collaborates with Federal partners within the NSET Subcommittee, and with international organizations such as OECD, to bridge research gaps, address critical issues such as regulatory needs and test guidelines, and communicate information about nanotechnology to all interested stakeholders.

National Aeronautics and Space Administration (NASA)

The three prime drivers for NASA's aerospace R&D activities are to (1) reduce vehicle weight, (2) enhance performance, and (3) improve safety, durability, and reliability. Nanotechnology is a tool to address each of these drivers. Nanotechnology research at NASA is focused in four areas: engineered materials and structures; energy generation, storage, and distribution; electronics, sensors, and devices; and propulsion. This research is conducted through a combination of in-house activities at NASA research and flight centers, competitively funded research with universities and industry, and collaborations with other agencies, universities, and industry. Through the University Research Centers Program, NASA has also funded nanotechnology research at minority-serving institutions, including the Center for Advanced Nanoscale Materials at the University of Puerto Rico and the High Performance Polymers and Composites Center at Clark Atlanta University. A major emphasis of NASA's nanotechnology R&D is on transitioning nanotechnology discoveries into mission applications.

NASA has participated in the NNI since its inception and is committed to partnering with other participating agencies to identify key technical challenges in nanotechnology R&D, focus resources to address these challenges, and accelerate the development of nanotechnology breakthroughs and their translation into commercial products.

National Science Foundation (NSF)

NSF supports fundamental nanoscale science and engineering in and across all disciplines. It supports formal and informal nanotechnology education and physical research infrastructure in academic institutions. It also advances nanotechnology innovation through a variety of translational research programs and by partnering with industry, states, and other agencies.

The NSF nanotechnology investment in 2016 supported more than 5,000 active projects, more than 30 research centers, and several infrastructure networks for device development, computation, and education. It impacted more than 10,000 students and teachers. Approximately 150 small businesses have been funded to perform research and product development in nanotechnology through the SBIR and Small Business Technology Transfer (STTR) programs. NSF's nanotechnology research is supported primarily through grants to individuals, teams, and centers at U.S. academic institutions. The efforts in team and center projects have been particularly fruitful because nanoscale research and education are inherently interdisciplinary pursuits, often combining elements of materials science, engineering, chemistry, computer science, physics, and biology.

Fundamental changes envisioned through nanotechnology require a long-term R&D vision. NSF sponsored the first initiative dedicated to nanoparticles in 1991 and the 1997–1999 Partnership in Nanotechnology program, and it produced the 1999 interagency report *Nanotechnology Research Directions: Vision for Nanotechnology in the Next Decade*,[53] which was adopted as an official National Science and Technology Council (NSTC) document in 2000. NSF pushes the frontiers of science and technology innovations through continual interaction with the nanotechnology community, new programs, and ongoing evaluation of current investments. The NSF-led study *Nanotechnology Research Directions for Societal Needs in 2020* was released in 2010.[54] With input from academic, industry, and government experts from more than 35 countries, the report addresses the progress and impact of nanotechnology since 2000 as well as the vision and research directions for nanotechnology in the next ten years. Further, convergence of nanotechnology with other technologies and areas of application have been analyzed in the NSF-led 2013 report developed in collaboration with NIH, EPA, DOD, NASA, and USDA, *Convergence of Knowledge, Technology, and Society*.[55]

NSF supports the NSIs through core programs and new solicitations. NSF has a dedicated program for nanomanufacturing and has program solicitations each year to support new concepts for high-rate synthesis and processing of nanostructures, nanobiotechnology methods, and methods to fabricate devices, assemble them into systems, and then further assemble them into larger-scale structures of relevance to industry. EHS implications of nanotechnology, including development of predictive toxicity of nanomaterials and rigorous experiments to develop models for nanomaterial exposures in the environment, will be investigated in three dedicated multidisciplinary centers and in more than 60 other smaller groups.

[53] www.nano.gov/node/948
[54] www.wtec.org/nano2
[55] www.wtec.org/NBIC2

NSF also has a focus on addressing education and societal dimensions of nanotechnology. Education-related activities include development of materials for schools, curricula for nanoscience and engineering, new teaching tools, undergraduate programs, technical training, and public outreach programs.

Nuclear Regulatory Commission (NRC)

The mission of NRC is to license and regulate the Nation's civilian use of byproduct, source, and special nuclear materials in order to protect public health and safety, promote the common defense and security, and protect the environment. NRC's scope of responsibility includes regulation of commercial nuclear power plants; research, test, and training reactors; nuclear fuel cycle facilities; medical, academic, and industrial uses of radioactive materials; and transport, storage, and disposal of radioactive materials and waste. In addition, NRC licenses the import and export of radioactive materials and works to enhance nuclear safety and security throughout the world.

As a regulatory agency, NRC does not typically sponsor fundamental research or product development. Rather, NRC is focused in part on confirmatory research to verify the safe application of new technologies in the civilian nuclear industry. Currently the agency's focus with respect to nanotechnology is to monitor developments that might be applied within the nuclear industry to help NRC carry out its oversight role.

U.S. Department of Agriculture (USDA)

Nanotechnology has the potential to impact all areas that USDA provides leadership on: food, agriculture, natural resources, rural development, nutrition, the environment, and related issues. The Agricultural Research Service (ARS), Forest Service (FS), and National Institute of Food and Agriculture (NIFA) participate in the NSET Subcommittee to promote coordinated research, development, commercialization, education, and outreach on nanoscale science, engineering, and technology in support of a variety of applications, including cellulosic and other nano- and biomaterials, agricultural production, and human nutrition, as well as food safety and food quality. USDA also contributes to NNI EHS efforts toward responsible development and deployment of nanotechnology.

Agricultural Research Service (ARS)

ARS is USDA's chief in-house scientific research agency. ARS research leverages science and technology, including ENMs and NEPs, to enable substantial improvements in long-term agricultural production, in food safety and quality, and in human nutrition. Examples of this research include the development of nanorod-based biosensors to rapidly, accurately, and selectively identify Salmonella; the incorporation of nanoemulsions, nanoparticles, and microfibrils into edible films to develop food products with improved barrier and mechanical properties, greater nutritional value, and improved taste; and the use of nano-cantilevers to detect toxin molecules with high sensitivity.

Forest Service (FS)

Nanotechnology has enormous promise to bring about fundamental changes in and significant benefit from our Nation's use of renewable resources. For example, cellulose nanomaterials derived from trees: (1) are renewable and sustainable; (2) are produced in trees via photosynthesis from solar energy, atmospheric carbon dioxide, and water; (3) store carbon; and (4) the material itself is carbon neutral. Cellulosic nanocrystals, for example, are predicted to have strength properties comparable to Kevlar, have piezoelectric properties comparable to quartz, and can be manipulated to produce photonic structures. The USDA FS, in collaboration with a public–private partnership named P^3Nano (the Public–Private Partnership for Nanotechnology), has been partnering with industry and academic institutions to conduct research in industry-driven topics. Current global research directions in cellulose nanomaterials indicate that this material could be used for a variety of new and improved product applications, including lighter and stronger paper and paperboard products; stronger cement materials; barrier coatings; body armor; lightweight automobile and airplane composite panels; electronics; biomedical applications; rheology modifiers; and replacement of petrochemicals in plastics and composites. Several commercial products containing cellulose nanomaterials are already on the market. Examples include rheology modifiers in gel ink for ballpoint pens, deodorants in adult diapers, additives in personal care products, and growth media for biomedical research. The U.S. forest products industry, the major player in cellulose nanomaterials, has actively engaged with NNI agencies and programs via its industry technology alliance—the Agenda 2020—and via co-organizing workshops.

Through participation in the NNI and representation on the NSET Subcommittee, FS is partnering with other Federal entities (e.g., NIST, DOE, DOD, NIOSH), industry, and academia to develop the precompetitive science and technology critical to the economic and sustainable production and use of new high-value, nanotechnology-enabled forest-based products. Participation in the NNI and the NSET Subcommittee has helped create a favorable environment for increased FS investment in nanotechnology R&D. FS nanotechnology research has contributed broadly to the NNI Program Component Areas with primary emphasis on PCA 1 (Nanotechnology Signature Initiatives/Sustainable Nanomanufacturing), PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems), and PCA 4 (Research Infrastructure and Instrumentation), with possible future investments in PCA 5 (Environment, Health, and Safety).

National Institute of Food and Agriculture (NIFA)

Established by the 2008 Farm Bill, NIFA is USDA's primary extramural research, education, and extension agency. NIFA's mission is to invest in and advance agricultural research, education, and extension to solve societal challenges. NIFA's current priority areas are: (1) global food security; (2) climate change; (3) sustainable bioeconomy; (4) childhood obesity; (5) food safety; and (6) water. Nanoscale science, engineering, and technology have demonstrated their relevance and great potential to enable revolutionary improvements in agriculture and food systems, including plant production and products; animal health, production, and products; food safety and quality; nutrition, health, and wellness; renewable bioenergy and bio-based products; natural resources and the environment; agriculture systems and technology; and agricultural economics and rural communities.

NIFA's predecessor agency (Cooperative State Research, Education, and Extension Service, or CSREES) was among the early participating agencies in the NSET Subcommittee, joining in 2002, and that agency (later, NIFA) has actively participated in and contributed to NNI activities ever since. The NNI provides a solid platform on which NIFA can effectively explore broad opportunities in nanoscience and nanotechnology to address critical societal challenges facing agriculture and food systems through coordination, collaboration, and leveraging resources with other Federal agencies. Scientific discoveries and technological breakthroughs inspire agricultural and food scientists to seek novel solutions. The extensive infrastructure networks developed by the NNI agencies enhance the productivity and expand the capability of agricultural and food science R&D in academia and industry. NIFA actively contributes to and benefits significantly from its participation in the NNI activities to identify research gaps and opportunities through workshops and discussions, to support public engagement and communication, to facilitate public–private partnerships in close collaboration with industry, and to participate in and promote international information exchanges and cooperation. NIFA also supports multiagency joint research efforts of common interest and importance as appropriate to its mission, goals, and objectives. The agency's nanotechnology programs have broadly contributed to the NNI, with primary emphasis on Nanotechnology Signature Initiatives (PCA 1); Foundational Research (PCA 2); Nanotechnology-Enabled Applications, Devices, and Systems (PCA 3); and Environment, Health, and Safety (PCA 5). NIFA's SBIR program also supports innovative nanotechnology R&D throughout its broad topic areas.

U.S. International Trade Commission (USITC)

The USITC representative attends NSET Subcommittee and working group meetings to keep the Commission abreast of current trends and issues related to nanotechnology that may have the potential to impact international trade. Upon request, the USITC representative may provide technical support to the NSET Subcommittee.

Appendix B. Stakeholder Workshop Summary

The *2016 NNI Strategic Planning Stakeholder Workshop* was held on May 19–20, 2016, in Washington, DC. The goal of this workshop was to obtain input from stakeholders regarding the vision for the next phase of the National Nanotechnology Initiative. Topics covered included future technical directions, implementation mechanisms, education and outreach activities, and approaches for promoting commercialization. The conversations during the workshop directly informed the development of this document, and the strategic planning group devoted several meetings to discussing the themes that emerged during the workshop. For example, inspired by workshop discussions on topics such as data analytics and modeling, the strategic planning group added several nanoinformatics-relevant objectives and sub-objectives to the plan.

The workshop was attended by approximately 80 participants from a variety of backgrounds, including government, academia, industry, and nongovernmental organizations. In addition, the live webcast was accessed 286 times during the event. The workshop was two full days, with a half day devoted to each of the four NNI goals. The discussions for each goal spanned introductory plenary sessions with presentations and discussion panels, as well as breakout sessions in which the groups addressed questions provided by the workshop organizers. More information about the workshop, including links to the agenda, presentation slides, and videos of the plenary presentations, is available at www.nano.gov/2016StakeholderWorkshop.

The following sections reflect a summary of workshop discussions and participant comments and do not necessarily represent the Federal Government's perspective.

Cross-Cutting Themes

Several themes were repeatedly emphasized throughout the workshop, highlighting the importance of these topics across the four NNI goals. The recurrent themes fell into two broad categories: (1) topics that reflect the maturation and evolution of nanotechnology R&D; and (2) structural observations and recommendations.

The Maturation and Evolution of Nanotechnology R&D

Sixteen years after the advent of the NNI, basic research is building on the foundation of knowledge that has been developed to date and is becoming more complex, as evidenced by the emergence of research in areas such as precision medicine and precision materials. Further, nanotechnology is increasingly moving from the lab to the market. This transition was reflected in the workshop conversations, which were heavily focused on nanotechnology-enabled systems, as well as the translation of research into applications. One of the dominant themes at the workshop was nanomanufacturing. Participants argued that greater focus on manufacturing science is needed to take full advantage of nanotechnology discoveries. On the fundamental research side, there is a need to develop scalable, robust, and repeatable processes that retain the material's initial properties. On the applied side, key challenges are yield, throughput, and cost. One approach to addressing these nanomanufacturing issues would be to strengthen links between the NNI and the National Network for Manufacturing Innovation (NNMI). With respect to infrastructure, awareness of nanomanufacturing facilities is surprisingly low, and there is a need to concisely capture and share information on manufacturing opportunities and resources, as well as shared physical and virtual infrastructure.

Data and informatics are also topics that have grown in visibility and relevance in recent years. Computing speeds have increased orders of magnitude since the inception of the NNI, and many research problems are now data-limited, where they previously were computing-limited. As such, theory is beginning to drive more experiments. Future increases in computing speeds will present tremendous opportunities for predictive, precision materials development across all scales and will fundamentally change the way that science and product development are carried out. The experiment, theory, and simulation loop can be strengthened to support this change, and new computational tools and data management strategies are needed. As plenary speaker Paul Weiss put it, scientists and engineers should "think smart data instead of big data." On the topic of modeling and simulation, workshop participants argued that the field is currently too fractured and that model validation and standards are still needed. Many questions related to data storage, sharing, dissemination, and use are not unique to nanotechnology, while other issues, such as ontology development, are nanotechnology-specific. There is a need for comprehensive, publicly available data resources, and these resources could be developed based on existing resources in other scientific and technological domains. Sharing and analyzing data is essential, and the attendees suggested that the Federal Government can support this trend by enforcing data security and sharing requirements. The biggest challenges with data sharing are cultural reluctance to share coupled with the existence of few incentives to share. As journals begin to require data submission with published papers, there will be a very large amount of nanomaterial data collected, which could be in diverse formats and that will need to be curated by a trusted curator. The issue of format diversity needs to be addressed as soon as possible because postmortem or legacy data is almost impossible to curate. Finally, data reproducibility is still a significant challenge.

Collaborating for Success

Nanotechnology has been a fundamentally important and key enabling technology for many other Federal initiatives, and is closely related to several other initiatives. Intersections between the NNI and the Materials Genome Initiative (MGI), the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative, the Precision Medicine Initiative, the National Strategic Computing Initiative, and the Microbiome Initiative were all mentioned during the workshop. For example, many of the NNI's nanoinformatics interests are related to MGI activities. Throughout the workshop, attendees repeatedly emphasized that it will continue to be important for the NNI to interface with these other initiatives.

On a similar note, the need for scientists, engineers, and technology developers to collaborate broadly across institutions, disciplines, sectors, and countries was also a frequent topic. These collaborations can be encouraged by building stronger relationships among disparate communities. For example, there is a natural connection among the scientists who generate nanoEHS knowledge under Goal 4 and the businesses and workers who produce NEPs under Goal 2; nanoEHS knowledge can be integrated in the product design so that new products are safe. It would be particularly beneficial to strengthen the connections between the nanoEHS community and small businesses. There is also an opportunity for the nanoEHS community to cross-pollinate with the biomedical community and to share information related to the safety of nanoparticle systems. In support of technology development, the need to foster and reinforce connections among academia, national labs, industry, and manufacturers was mentioned in multiple sessions. These relationships could be supported through mechanisms such as precompetitive consortia. International collaborations are also an essential component of the nanotechnology ecosystem, particularly in the nanoEHS arena. Finally, research on transdisciplinary topics and converging technologies will be increasingly important.

Participants extensively discussed possible metrics and indicators to assess the impact of the NNI. Keeping in mind that the technology development timeline is generally on the scale of multiple decades, nanotechnology is still in an early phase of development. Nevertheless, a big challenge is identifying which materials, processes, and products contain nanotechnology or are nanotechnology-enabled. One suggestion was to work with trade associations or to undertake social media analysis to gather more information on this question. Further complicating the development of metrics is the fact that it is also difficult to identify exactly how much the nanotechnology-enabled component or process contributes to a product's overall value. Participants in several breakout sessions advocated for measuring success broadly, noting that there are multiple ways to gauge impact. For example, beyond publication numbers, research productivity could be measured by data Digital Object Identifiers (DOIs), patents, products made, tools developed, lives saved, etc. There are many new and nontraditional metrics that were not around five years ago.

Goal-Specific Themes

In addition to the topics that cut across multiple goals, important goal-specific themes also emerged during the workshop discussions. For example, during a discussion of biomedical sciences under Goal 1, plenary speaker Michelle Bradbury argued that it is beneficial to spend time carefully developing the drug or assay before testing it in biological systems; yet, it is difficult to publish this early development work. A paradigm shift is needed because strong early development work is essential for successful translation. It is also key to validate in humans phenomena and trends that are seen in animals. There is a notable knowledge gap between preclinical studies and validation work in clinical trials. For both the physical and biomedical sciences, attendees emphasized the importance of international collaborations to leverage complimentary expertise and synergistic funding. Finally, participants were enthusiastic about the Nanotechnology-Inspired Grand Challenge mechanism in general, and the future computing topic for the first grand challenge in particular.

For Goal 2, plenary speaker Marcie Black suggested that the Federal Government can encourage nanotechnology startups with accessible and cost-effective physical facilities, favorable domestic and international intellectual property policies, and grants. Participants noted that the technical staff at small companies can spend a significant portion of their time working on paperwork for grants and that the Federal Government works on a different timescale than small companies; it was suggested that the process for awarding and managing grants to small companies could be streamlined. Similarly, a big challenge for biomedical companies is funding advanced development, particularly when the company is starting to think about the path to FDA approval and licensing at the same time. Funding mechanisms are needed that don't dampen the process. Workshop attendees noted that companies may face nanotechnology-specific challenges on their way to commercialization, including insurance and standards. Again, nanomanufacturing was a major topic of conversation at the workshop, and in response to this emphasis, it has been incorporated throughout the 2016 Strategic Plan.

Conversations in multiple sessions touched on issues of workforce development and education, which fall under Goal 3. Participants argued that the scientific workforce should be creative, analytical, and entrepreneurial, and be able to communicate clearly and work across disciplines. The NNI has been a catalyst for and sustainer of interdisciplinary research, and some workshop attendees noted that the NNI has been "the ultimate melting pot" for science and engineering, equipping students with essential collaboration and communication skills. Ph.D.-level students are being well trained, but plenary speaker Oliver Brand contended that better continuing education and community college training is needed. Similarly, attendees in the workforce and training breakout session suggested that training programs need to be more targeted to industry's workforce needs. On the topic of education, participants in several workshop sessions discussed the need to collect and disseminate best practices and resources for teachers. It was noted that a teacher-friendly nanotechnology education resource portal was added to nanoHUB.org in early 2016 to address this need.[56] Attendees in several breakout sessions suggested that user facilities could engage teachers and students through internships, lab tours, and virtual experiments. Participants also advocated for novel K–12 education methods such as game-based learning and social media.

Speakers and attendees repeatedly highlighted the need for an "evergreen" physical infrastructure that includes developing new tools, maintaining older workhorse tools, and enabling a workforce to manage the tools. Participants in multiple breakout sessions felt that the United States lags in tool development, despite previously being a leader, and attendees advocated for more support for tool development. Specific needs include multimodal tools, device fabrication (rather than component fabrication) capabilities, and field-deployable instruments for nanoEHS studies. As nanotechnology continues to mature and to move into the marketplace, participants argued that user facilities can do more to support translation, scale-up, and manufacturing. For example, there is an opportunity to strengthen ties to the NNMI, facilitate rapid prototyping, and support manufacturing (e.g., roll-to-roll). User facilities also provide a natural venue for community-forming activities across disciplines and sectors. Finally, many potential users may not be aware of what facilities and resources are available; mechanisms to increase awareness and guide users to the available resources would be beneficial.

Similar to the discussions around fundamental research, the workshop conversations related to Goal 4 reflected a community that is building on the nanoEHS knowledge developed over the 16 years of the NNI to conduct more complex and realistic studies. Plenary speaker Gregory Lowry noted that the acute effects of ENMs are well studied and relatively limited, but that chronic and accumulated effects may need more attention. As such, the entire field is moving more toward "realism" in research studies by looking at, for example, relevant exposure scenarios and chronic exposures, but new tools are needed to support this transition. Participants suggested that standardized methods are needed across toxicity and exposure studies and to characterize ENMs. These standardized methods are particularly important for studies in complex matrices such as soils, tissues, and complex aerosol mixtures.

There is a growing belief that exposure and hazard are inseparable. The exposure route influences the nanomaterial's potential hazard, and in some cases, the hazard can influence the exposure. Thus, system properties and processes cannot be ignored. However, more information is needed about what happens to ENMs during consumer use. On the environmental side, scientists understand enough about the

[56] nanohub.org/publications/118

processes and materials to model their behavior, but the models still need to be validated. The community-renewed focus on exposure science and calls for state-of-the science reports further underscore the maturation of nanotechnology since the inception of the NNI.

With respect to trends over the next five to ten years, participants at several breakout sessions mentioned that categorization of nanomaterials in risk groups will be increasingly important. The conversation around risk assessment will also continue to grow more sophisticated. Instead of evaluating whether an ENM is "safe," scientists and policymakers are beginning to evaluate whether a particular material is safer than its alternatives. Scientists are also starting to look at ways to optimize the benefit-to-risk ratio by maintaining material functionality and minimizing adverse impacts. Finally, the workshop conversation moved beyond simply developing and collecting nanoEHS knowledge toward the use of this knowledge to produce safer and sustainable nanomaterials and technologies. Participants throughout the workshop emphasized the importance of communicating and disseminating what is already known, particularly to state and local governments, product manufacturers, and consumers.

Appendix C. Abbreviations and Acronyms

ARL	Army Research Laboratory (DOD)
ARPA-E	Advanced Research Projects Agency-Energy (DOE)
ARS	Agricultural Research Service (USDA)
ATE	Advanced Technological Education (NSF)
BIS	Bureau of Industry and Security (DOC)
BRAIN	Brain Research through Advancing Innovative Neurotechnologies
CAI	Center for Advancing Innovation
CEINT	Center for the Environmental Implications of NanoTechnology
CNST	Center for Nanoscale Science and Technology (DOC/NIST)
COR	Community of Research
CPSC	Consumer Product Safety Commission
DARPA	Defense Advanced Research Projects Agency (DOD)
DHHS	Department of Health and Human Services
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
DOIs	Digital Object Identifiers
DOJ	Department of Justice
DOL	Department of Labor
DOS	Department of State
DOT	Department of Transportation
DOTreas	Department of the Treasury
DTRA	Defense Threat Reduction Agency (DOD)
EDA	Economic Development Administration (DOC)
EERE	Office of Energy Efficiency & Renewable Energy (DOE)
EHS	environment(al), health, and safety
ELSI	ethical, legal, and societal implications
ENM	engineered nanomaterial
EPA	Environmental Protection Agency
EU	European Union
FDA	Food and Drug Administration (DHHS)
FHWA	Federal Highway Administration (DOT)
FS	Forest Service (USDA)
I-Corps	Innovation Corps (NSF)
IC	Intelligence Community
ISO	International Organization for Standardization
MGI	Materials Genome Initiative
MURI	Multidisciplinary University Research Initiative
NACK Network	Nanotechnology Applications and Career Knowledge Network
nanoEHS	nanotechnology-related environment(al), health, and safety
NASA	National Aeronautics and Space Administration
NBMC	Nano-Bio Manufacturing Consortium
NCI	National Cancer Institute
NCL	Nanotechnology Characterization Laboratory

NCN	Network for Computational Nanotechnology
NCNR	NIST Center for Neutron Research (DOC/NIST)
NEHI	Nanotechnology Environmental and Health Implications Working Group (NSET)
NEP	nanotechnology-enabled product
NEWT	Nanosystems Engineering Research Center on Nanotechnology Enabled Water Treatment
NHLBI	National Heart, Lung, and Blood Institute (DHHS/NIH)
NIBIB	National Institute of Biomedical Imaging and Bioengineering (DHHS/NIH)
NICE	Nanotechnology Innovation and Commercialization Ecosystem Working Group (NSET)
NIEHS	National Institute of Environmental Health Sciences (DHHS/NIH)
NIFA	National Institute of Food and Agriculture (USDA)
NIH	National Institutes of Health (DHHS)
NIJ	National Institute of Justice (DOJ)
NIOSH	National Institute of Occupational Safety and Health (DHHS)
NISE Network	Nanoscale Informal Science Education Network 2008 to 2015 (NSF); National Informal STEM Education Network (NSF) 2016 ff.
NIST	National Institute of Standards and Technology (DOC)
NKI	Nanotechnology Knowledge Infrastructure (NSI)
NNCI	National Nanotechnology Coordinated Infrastructure
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NNMI	National Network for Manufacturing Innovation
NRC	Nuclear Regulatory Commission
NSC^2	Nanotechnology Startup Challenge in Cancer
NSET	Nanoscale Science, Engineering, and Technology Subcommittee (NSTC Committee on Technology)
NSF	National Science Foundation
NSI	Nanotechnology Signature Initiative
NSRC	Nanoscale Science Research Centers (DOE)
NSTC	National Science and Technology Council
NTF	Nanotechnology Task Force (FDA)
NTRC	Nanotechnology Research Center (NIOSH)
OECD	Organisation for Economic Co-operation and Development
OSHA	Occupational Safety and Health Administration (DOL)
OSTP	Office of Science and Technology Policy (Executive Office of the President)
PCA	Program Component Area
PCAST	President's Council of Advisors on Science and Technology
RFI	Request For Information
R&D	research and development
RET	Research Experiences for Teachers
REU	Research Experiences for Undergraduates
SBIR	Small Business Innovation Research
SC	Office of Science (DOE)
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer Research
SUNY	State University of New York
SURF	Summer Undergraduate Research Fellowship
UC CEIN	University of California Center for Environmental Implications of Nanotechnology
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey (DOI)
USITC	U.S. International Trade Commission
USPTO	U.S. Patent and Trademark Office (DOC)