Triennial Review of the National Nanotechnology Initiative

DETAILS

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National Materials and Manufacturing Board

Division of Engineering and Physical Sciences

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Preface

The National Nanotechnology Initiative (NNI) is a multi-agency effort to advance nanoscale science, engineering, and technology and to capture the associated economic and societal benefits. The NNI comprises the collective activities and programs among the 27 participating federal agencies,[1] which are coordinated through the efforts of the interagency Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council and the National Nanotechnology Coordination Office (NNCO).

In accordance with the provisions of the 21st Century Nanotechnology Research and Development Act (Section 5 of Public Law 108-153), the NNCO asked the National Research Council[2] (NRC) to conduct a triennial review of the NNI. In particular, the NRC was asked to assess (1) mechanisms to advance focused areas of nanotechnology toward advanced development and commercialization and (2) the physical and human infrastructure needs for successful realization in the United States of the benefits of nanotechnology development. In response to this request, the NRC formed an ad hoc committee of experts in nanotechnology research, innovation, education, and facilities.

This report represents the consensus of the Committee on Triennial Review of the National Nanotechnology Initiative, which met five times between June and December 2015. The committee benefited enormously from meeting with representatives from government, industry, and academia. In particular, the committee thanks the following for contributing their time and expertise:

Larry Bell, Museum of Science-Boston,
Robert Celotta, National Institute of Standards and Technology,
Teresa Clement, Raytheon Missile Systems.
Khershed Cooper, National Science Foundation,
Lance Criscuolo, Zyvex Technologies,
Dorothy Farrell, National Institutes of Health,
Lisa Friedersdorf, National Nanotechnology Coordination Office,
Frank Gayle, National Institute of Standards and Technology.
Piotr Grodzinski, National Cancer Institute,
Nancy Healy, Georgia Institute of Technology,
Lori Henderson, Nanoscale Science, Engineering, and Technology Subcommittee,
Daniel Herr, Nanomanufacturing Innovation Consortium,
Mark Hoover, National Institute for Occupational Safety and Health,
Catherine Hunt, The Dow Chemical Company,
Frank Jaworski, Raytheon Vision Systems,
Alex Liddle, National Institute of Standards and Technology,
George Maracas, Department of Energy,
Scott McNeil, National Institutes of Health,
Michael McQuade, United Technologies Corporation,

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[1] See Appendix C for the actual participating agencies.

[2] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historical context identifying programs prior to July 1.

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Daphne Schmidt, Math Science Innovation Center,
Russell Shilling, Department of Education,
Lew Sloter, Department of Defense,
Mark Tuominen, University of Massachusetts,
Richard Vaia, Wright-Patterson Air Force Base,
Lloyd Whitman, White House Office of Science and Technology Policy, and
Stanley Williams, Hewlett Packard Labs.

Information from and discussions with these individuals were essential to the Academies' work.

On behalf of the committee, we express our deep appreciation to Academies staff, in particular James Lancaster, acting director of the National Materials and Manufacturing Board (NMMB), and Erik Svedberg, study director of this report, who provided insight, guidance, and support throughout the study and preparation of the report.

Finally, as co-chairs of the committee, we thank the other committee members who worked diligently and gave generously of their time.

Celia I. Merzbacher, *Chair*
James S. Murday, *Vice Chair*
Committee on Triennial Review of the National
Nanotechnology Initiative

Acknowledgment of Reviewers

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Dawn A. Bonnell, University of Pennsylvania,
William F. Brinkman, Princeton University,
Samuel H. Fuller, Analog Devices, Inc.,
Bertrand I. Halperin, Harvard University,
Steven M. Larson, Memorial Sloan-Kettering Cancer Center,
Edwin P. Przybylowicz, Eastman Kodak Company,
David J. Srolovitz, University of Pennsylvania
Sally Tinkle, Science and Technology Policy Institute
Pryia Vashishta, University of Southern California

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of the report was overseen by Michael R. Ladisch, Purdue University, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of the report rests entirely with the authoring committee and the institution.

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Summary

Nanoscale science, engineering, and technology, often referred to simply as "nanotechnology," is the understanding, characterization, and control of matter at the scale of nanometers, the dimension of atoms and molecules. Advances in nanotechnology promise new materials and structures that are the basis of solutions, for example, for improving human health, optimizing available energy and water resources, supporting a vibrant economy, raising the standard of living, and increasing national security.

The National Nanotechnology Initiative (NNI) is a coordinated, multiagency effort with the mission to expedite the discovery, development, and deployment of nanoscale science and technology to serve the public good. Established in 2001, the NNI comprises the collective activities and investments of 27 participating agencies with diverse missions and presently a total annual investment of ~$1.5 billion. These activities are coordinated through the efforts of the interagency Nanoscale Science, Engineering, and Technology Subcommittee and with the support of the National Nanotechnology Coordination Office (NNCO).

Thanks in large part to the NNI, fundamental science and engineering related to nanotechnology has advanced rapidly. Understanding materials and processes at the nanoscale has the imminent potential to enable innovation in areas that are of commercial interest and of national priority.

This report is the triennial review of the NNI called for by the 21st Century Nanotechnology Research and Development Act of 2003 (P.L. 108-153). The ad hoc Committee on Triennial Review of the National Nanotechnology Initiative convened by the National Research Council[1] was guided by the following statement of task.

> A. Examine and comment on the mechanisms in use by the National Nanotechnology Initiative (NNI) to advance focused areas of nanotechnology towards advanced development and commercialization, along with the approaches taken to determine those focus areas and to implement the NNI's Signature Initiatives. If warranted, recommend possible improvements.
> B. Examine and comment on the physical and human infrastructure needs for successful realization in the United States of the benefits of nanotechnology development. Consider research and development, product design, commercialization, and manufacturing needed both to advance nanoscience and engineering and to grow those portions of the American economy that are spurred by advances in nanotechnologies. If warranted, recommend possible improvements.

Following an overview of the NNI (Chapter 1), this report addresses part A of the statement of task, that is, NNI mechanisms to advance focused areas of nanotechnology toward advanced development and commercialization, with particular attention to advancing nanomanufacturing (Chapters 2 and 3). The report goes on to address part B of the statement of task, evaluating and recommending improvements in the physical and human infrastructure (Chapters 4 and 5) to support not only nanotechnology research but also private sector innovation. The following sections summarize the report and highlight the key findings

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historical context identifying programs prior to July 1.

and recommendations that the committee believes can significantly improve and guide the NNI going forward.

FOCUSING THE NATIONAL NANOTECHNOLOGY INITIATIVE

In order to better assess NNI efforts to advance focused areas of nanotechnology toward development and commercialization, the committee considered the process of innovation more broadly. Technology-based innovation is the process of converting the results of basic science and engineering research into practical applications for commercial and/or public benefit. It is the outcome of a complex set of interconnected technological activities that (1) involve an ecosystem of participants and institutions from the public and private sectors and (2) require expertise in various areas and disciplines.

Technological activities that culminate in innovation range from basic and applied research to product design and development, to scaled-up manufacturing. Innovation can be an evolutionary improvement to existing products or revolutionary advancements that enable entirely new products and even new industries. Whether evolutionary or revolutionary, there are many paths that innovation can follow; it can result from the "push" of new ideas emerging from research toward development and application, or from the "pull" of new solutions to industry-defined needs and challenges.

The federal government is the primary sponsor of basic research, whereas the private sector invests more heavily in product development and manufacturing. Federal agencies have established a number of programs aimed at pushing the ideas resulting from basic and applied research to a stage where traditional private sector investment is available. These programs, while not specifically aimed at nanotechnology, can—and in some cases already do—support the commercialization of NNI-funded research.

The NNI currently employs two mechanisms to focus on areas of national importance. Nanotechnology Signature Initiatives (NSI's) are multiagency initiatives designed to focus a spotlight on technology areas that may be more rapidly advanced through enhanced interagency coordination and collaboration. There five current NSIs are in nanomanufacturing, nanoelectronics, nanotechnology knowledge infrastructure, sensors, and sustainable water. In 2016, the NSI on solar energy was retired. Goals for each NSI are outlined in a white paper[2], but without more detailed plans and adequate resources, progress will lag.

A second, new mechanism the NNI is using to focus on areas of importance is Nanotechnology-Inspired Grand Challenges. These are ambitious but achievable goals that will harness nanotechnology to solve national or global problems and that have the potential to capture the public's imagination. The first such Grand Challenge, announced in 2015, is the Grand Challenge for Future Computing, which envisions "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[3]." As the title suggests, the Nanotechnology-Inspired Grand Challenges will depend on advances in areas beyond nanotechnology. Therefore, the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee members will not have the entire expertise, programmatic influence or control, and resources to support the full breadth of research that is needed to achieve the grand challenges.

Conversely, the success of other initiatives, such as the Department of Energy's SunShot program on solar energy, the White House Innovation Strategy to Build a Sustainable Water Future, the White

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[2] Nanoscale Science, Engineering, and Technology Committee on Technology, 2010, *Nanotechnology for Solar Energy Collection and Conversion*, http://www.nano.gov/sites/default/files/pub_resource/nnisiginitsolarenergyfinaljuly2010.pdf.

[3] Office of Science and Technology Policy, 2015, *A Nanotechnology-Inspired Grand Challenge for Future Computing*, https://www.whitehouse.gov/blog/2015/10/15/nanotechnology-inspired-grand-challenge-future-computing.

House Precision Medicine Initiative, the White House Materials Genome Initiative, and the White House Manufacturing Initiative's Manufacturing Innovation Institutes, depend on continued progress in nanotechnology, even though the managers leading those initiatives may not have deep knowledge in the nanoscale. The NNI participating agencies have the capability to support the nanotechnology-related aspects of these initiatives that are relevant to the agencies' respective missions.

> **Finding:** The NNI is investing in technology areas that are critical to the goals of other federal initiatives, and vice versa. The various initiative leaders and managers both inside and outside of the NNI may not have the entire expertise or programmatic influence or control to efficiently achieve their respective initiative goals. (Chapter 2)
>
> **Recommendation: The Nanoscale Science, Engineering, and Technology Subcommittee should strengthen engagement with the leadership of other high-priority initiatives in order to determine critical nano-enabled technological dependencies. The subcommittee then should focus NNI efforts to address those dependencies.** (Chapter 2)

In addition to the mechanisms in use today, innovation incentive prizes are a means for focusing efforts on solving targeted problems. This approach complements the traditional process of awarding funding. Existing nongovernmental organizations that manage innovation prizes have established methodologies for developing and managing such competitions.

A focus area related to advanced development and commercialization of nanotechnology that warrants special attention is nanomanufacturing. Research on the manufacture of nanoscale materials, devices, and structures is key to realizing the benefits of nano-enabled technologies.

Nanomanufacturing also is an area that is integrally related to other high-profile initiatives focused on advanced manufacturing, in particular the Manufacturing Innovation Institutes (MIIs) and the National Institute of Standards and Technology (NIST) Advanced Manufacturing Technology Consortia (AMTech) program. MIIs are public-private partnerships with substantial federal funding that focus on a particular area of advanced manufacturing, developing new processes and educating skilled workers. MIIs bridge the funding gap between fundamental research and commercialization. The AMTech program supports existing or new consortia to develop roadmaps for research and development in areas of advanced manufacturing in addition to those that are the subject of MIIs. Connections between the NNI and advanced manufacturing programs such as the MII program and AMTech can accelerate progress toward the goals of those programs.

> **Finding:** In many cases, progress or success in the MIIs and in implementation of the roadmaps developed under the AMTech program will require advances in nanomanufacturing. (Chapter 3)
>
> **Recommendation: NNI-participating agencies should explicitly support the early-stage (technology readiness level 1-3) nanomanufacturing research needed to enable the roadmaps and goals of current advanced manufacturing programs, in particular the existing Manufacturing Innovation Institutes.** (Chapter 3)
>
> **Recommendation: The Nanoscale Science, Engineering and Technology Subcommittee should form a nanomanufacturing working group to identify nanoscale research needs of advanced manufacturing, coordinate efforts between the NNI and the federal programs focused on advanced manufacture, and foster greater investment by those programs in nano-enabled technologies.** (Chapter 3)

PHYSICAL INFRASTRUCTURE FOR NANOTECHNOLOGY

The NNI agencies have built a substantial publically accessible infrastructure for nanoscale research and development, such as the NIST Center for Nanoscale Science and Technology (CNST). This infrastructure comprises both physical and computational tools, including characterization and fabrication facilities, as well as online simulation and education resources. The existence and quality of these infrastructure resources are key factors in reducing barriers to discovery and technological innovation, and in developing and retaining the nation's science and engineering talent pool. The agencies managing these resources need to plan for renewal of instrumentation and equipment in future years.

> **Finding:** There is a clear lack of identified funds for the development of new leading-edge instrumentation or recapitalization of commercial tools at NNI-sponsored user facilities, with the exception of CNST. As a result, there is a real risk of obsolescence of the physical and computation infrastructure available to the nanoscience and technology research enterprise and a corresponding decrease in the user value. (Chapter 4)
>
> **Recommendation: The National Science Foundation and the Department of Energy should identify funding mechanisms for acquiring and maintaining state-of-the-art equipment and computational resources to sustain leading-edge capabilities at their nanoscale science and engineering user facilities.** (Chapter 4)

The growth in basic research and development at the intersection of nanotechnology and biology requires infrastructure with specialized capabilities for the synthesis and characterization of complex and hybrid materials and structures. The ability to reliably manufacture such complex nanomaterials at scale poses novel challenges. As increasing numbers of nanomaterials and nanotechnologies are developed for medical and other applications that involve contact with the body or the environment, there also will be a need to establish standards and guidelines for assessing and managing risks to the environment, health and safety.

The National Cancer Institute's Nanotechnology Characterization Laboratory (NCL), with support from NIST and the Food and Drug Administration (FDA), has developed tiered analyses and provides data that help both developers and the FDA in the assessment of the safety of nanoparticles for cancer therapeutics and diagnostics. This demonstrated approach could be expanded to address nanomaterials for other medical applications. NCL also could be expanded or replicated to develop standard analyses and provide information at an early stage of development of nanomaterials in general, for assessment of potential risks to humans and the environment. Such tools and methods would greatly improve risk assessment capabilities of both developers and regulatory agencies, ultimately expediting responsible commercialization.

Along these lines, the FDA's National Center for Toxicological Research (NCTR) in Jefferson, Arkansas, is the site of a new nanotechnology core facility. The facility serves the needs of NCTR by supporting nanotechnology toxicity studies, developing analytical tools to quantify nanomaterials in complex matrices, and developing procedures for characterizing nanomaterials in FDA-regulated products. Unlike the NCL, however, these facilities are not accessible to commercial developers. In addition, the 2017 NNI budget includes Consumer Product Safety Commission funding for a new nanotechnology center at the National Institute of Environmental Health Sciences to conduct research in exposure and risk assessment of engineered nanomaterials in consumer products. Access by commercial developers to this center has not been established.

> **Finding:** The NCL serves as a trusted source of information on the safety of nanomaterials being developed for cancer and has facilitated FDA assessment. However, there is a lack of centralized facilities for addressing other areas of nanomedicine and nanobiotechnology. (Chapter 4)
>
> **Recommendation: The National Institutes of Health (NIH) should assess what emerging medical applications, in addition to cancer diagnostics and treatment, rely on engineered nanomaterials. NIH should expand the Nanotechnology Characterization Laboratory to address nanomaterials being developed for these emerging medical applications.** (Chapter 4)
>
> **Recommendation: The National Institute for Occupational Safety and Health, the National Institute of Standards and Technology, and the Environmental Protection Agency should join with the Consumer Product Safety Commission and the National Institute of Environmental Health Sciences to support development of centralized nanobiotechnological characterization facilities, at the Nanotechnology Characterization Laboratory or elsewhere, to serve as trusted sources of information on potential environmental, health, and safety implications of nanomaterials.** (Chapter 4)

HUMAN INFRASTRUCTURE FOR NANOTECHNOLOGY

Human capital, and the infrastructure required to produce it, is essential to the realization of the full value of nanotechnology advances. The nanoscale science and engineering education ecosystem must have sufficient breath to address not only the education of future nanoscale science and engineering researchers, but also, for example, business and government leaders who can make informed decisions to accelerate the adoption of nano-enabled technologies, workers with skills needed for nanomanufacturing, and a public that is sufficiently knowledgeable to make informed decisions on the benefits and risks. To achieve such a broad swath of goals, it will be necessary to address all the stages of education, including K-12, post-secondary (community colleges, undergraduate, and graduate), worker training and re-training, and informal education. A 2015 NSF-funded workshop report *Nanoscale Science and Engineering Education (NSEE)—The Next Steps*[4] provides a suite of recommendations toward that end; the committee endorses the workshop report.

NNI investment in research leads naturally to incorporation of nanotechnology principles in higher education. Incorporation of nanotechnology at the K-12 level will be increasingly helpful in preparing students for post-secondary education and also can serve to excite and interest students in the study of science, technology, engineering and mathematics disciplines in general. However, incorporating nanotechnology in K-12 curricula is challenging. The Commonwealth of Virginia has led in the development of a model for including nanotechnology in its State Standards of Learning; this model is worthy of assessment and adaptation by others.

Education curricula vary from state to state and even at the classroom level. Educators at all levels can benefit from access to materials developed by others. The NNI supports not only the development of educational materials, but also supports platforms for sharing such information.

> **Finding:** The NNI has funded the development of a diversity of formal and informal educational materials suitable for various levels and ages. Nanotechnology-focused educational programs at universities around the country, some of which have received substantial state funding, also are developing materials for K-12 students and teachers. (Chapter 5)

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[4] J. Murday, 2014, *Nanoscale Science and Engineering Education (NSEE)—The Next Steps*, http://nseeducation.org/2014-documents/NSEE%20The%20Next%20Steps-Final.pdf.

> **Recommendation: NNI-funded researchers and others who have developed educational materials should be required to deposit the information content on the nanoHUB.org website and to explore affordable commercial availability for laboratory and classroom demonstration materials.** (Chapter 5)

In summary, the NNI, including the interagency bodies and the NNCO, continues to add value to the portfolio of activities across participating agencies. Looking ahead, the NNI can significantly increase that value by focusing on both basic and applied research that will enable progress and success in other advanced technology areas of priority, especially advanced manufacturing. At the same time, the NNI agencies are called on to sustain investment in and facilitate access to physical infrastructure and to take steps to realize the full value of educational materials and programs. In the course of identifying areas in which to focus, NNI agencies have the opportunity to consider the goals of the initiative and the criteria for continuing to invest resources in its coordination and management.

1

Introduction

Nanoscale science, engineering, and technology, often referred to simply as "nanotechnology," is the understanding, characterization, and control of matter at the scale of nanometers, the dimension of atoms and molecules. Advances in nanotechnology promise new materials and structures that are the basis of solutions—for example, for improving human health, optimizing available energy and water resources, supporting a vibrant economy, raising the standard of living, and increasing national security. A more appropriate term for the diversity of nanoscale science and engineering applications is perhaps nano-enabled technologies.

NNI OVERVIEW

The National Nanotechnology Initiative (NNI) is the U.S. government's interagency program for coordinating, planning, and managing research and development (R&D) in nanoscale science, engineering, and technology. It was codified into law by the 2003 21st Century Nanotechnology Research and Development Act (Section 2, Line 2). The NNI not only advances the frontiers of nanoscience and nanotechnology, but also serves the public good through technology transfer, assessing and mitigating the risk of using nanotechnology, educating students at all levels, reaching out to and informing the public about nanotechnology, developing the nanotechnology workforce, and supporting the prominence of the United States in commercial applications for economic benefit.

The vision of the NNI is as follows[1]:

> To expedite the discovery, development and deployment of nanoscale science and technology to serve the public good through a program of coordinated research and development aligned with the missions of participating agencies.

The NNI has the following four high-level goals:

1. Advance a world-class nanotechnology research and development program;
2. Foster the transfer of new technologies into products for commercial and public benefit;
3. Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology; and
4. Support responsible development of nanotechnology.[2]

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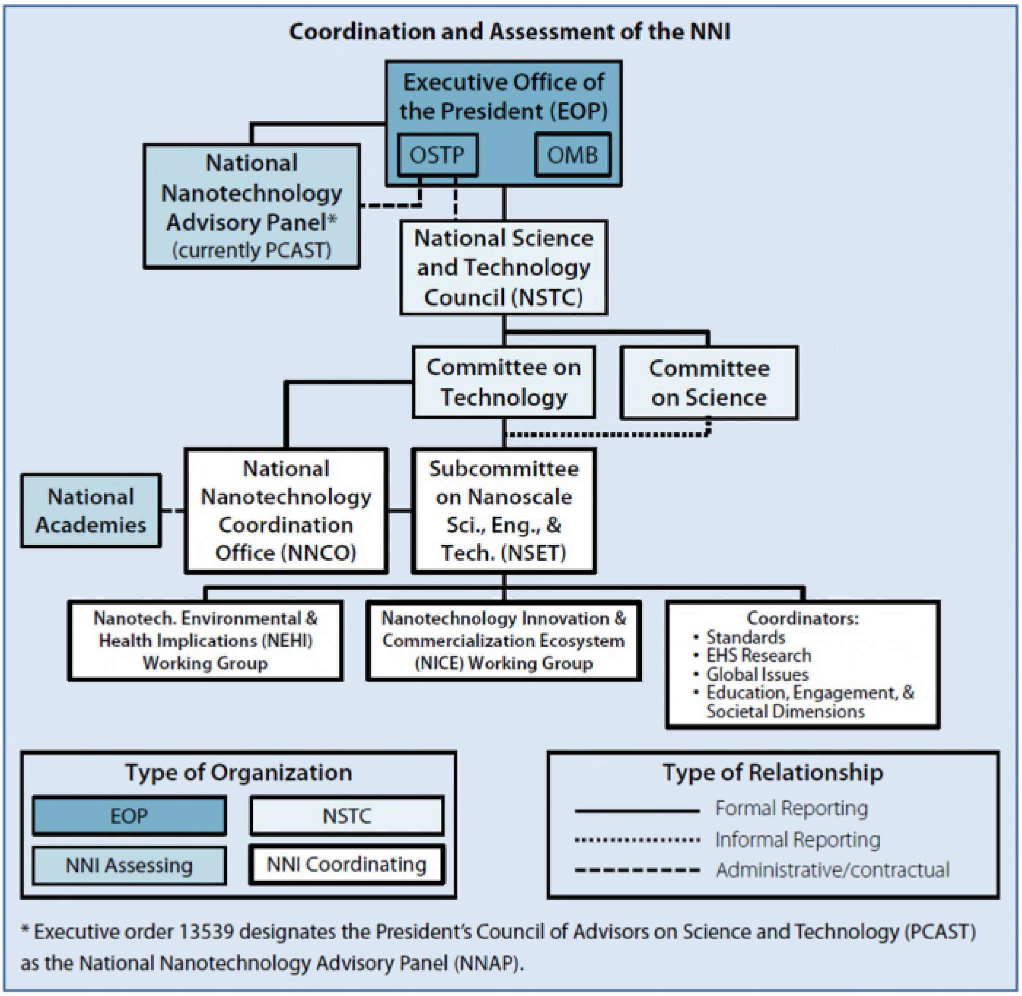
[1] National Nanotechnology Initiative Strategic Plan (2014), p. 5., available at http://www.nano.gov/sites/default/files/pub_resource/2014_nni_strategic_plan.pdf.

[2] National Nanotechnology Initiative, "NNI Vision, Goals, and Objectives," http://www.nano.gov/about-nni/what/vision-goals, accessed August 31, 2016.

These broad goals clearly show that the scope and aim of the NNI goes beyond a mere collection of federal agency research projects and individual agency programs.

The management and oversight structure of the NNI and the relationships between the various federal stakeholders are depicted in Figure 1.1. Central to NNI management and oversight is the interagency Nanoscale Science, Engineering, and Technology (NSET) Subcommittee under the National Science and Technology Council's (NSTC's) Committee on Technology. The NSET is made up of representatives from each NNI participating agency and is co-chaired by an agency representative (a position rotated among the NNI agencies) and a representative from the White House Office of Science and Technology Policy (OSTP). It meets at periodically to share projects, plans, strategies, and results. The NSET currently has two working groups and four coordinators to enable enhanced focus on specific cross-cutting issues important to the NNI.



* Executive order 13539 designates the President's Council of Advisors on Science and Technology (PCAST) as the National Nanotechnology Advisory Panel (NNAP).

FIGURE 1.1 Organizations associated with coordination and assessment of the National Nanotechnology Initiative. NOTE: EHS, environmental, health, and safety; NNI, National Nanotechnology Initiative; OMB, Office of Management and Budget; OSTP, Office of Science and Technology Policy. SOURCE: National Science and Technology Council Committee on Technology Subcommittee on Nanoscale Science, Engineering, and Technology, National Nanotechnology Initiative Strategic Plan, February 2011, p. 34, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf.

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 provides public outreach on behalf of the NNI. The NNCO is funded by contributions from those federal agencies supporting its research, in proportion to the level of funding reported. Accurate determination of nanotechnology-related spending can be difficult in cases where nanotechnology is a critical enabling technology but the program is not categorized as a "nanotechnology" activity. The arrangement for funding the NNCO provides a disincentive to including such investments. It falls to the NSET and the NNCO, as experts in nanotechnology, to strive to convince managers of other programs to invest in nanotechnology solutions and to encourage the agencies to report those investments to the Office of Management and Budget as part of their NNI activities.

Since the establishment of the NNI in 2001, participating federal agencies have grown from 8 agencies in the late 1990s to some 27 agencies today.[3] The annual federal budget for nanotechnology research has grown from ~$0.5 billion in 2001 to ~$1.4 billion in the President's 2017 budget request. Cumulative NNI investments since fiscal year (FY) 2001 (including the 2017 request) total nearly $24 billion.[4]

By coordinating, sharing, and promoting the advancement of nanotechnology research and commercialization, the NNI has fostered a U.S.-led international nanotechnology ecosystem that supports the efforts of nanotechnology researchers, entrepreneurs, business people, educators, and policymakers. The NNI has achieved notable successes in several areas, including fundamental nanoscale science and engineering (NSE); nanoengineered materials; manufacturing; tools and instruments; environment, health, and safety; and education. Examples of successes are documented in the annual Supplements to the President's Budget[5] and numerous workshop reports. See, in particular, *Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook*.[6]

NNI investments, and similar investments in many other countries, have supported substantial scientific activity, stimulated global economic development in a wide range of industries and markets, and provided a foundation for continued innovation and commercial development—that is, they have created a global nanoscale science and engineering innovation ecosystem. Nearly 10,000 firms are engaged in nanotechnology-related R&D and manufacturing worldwide. Nanotechnology firms include organizations that are engaged in R&D, manufacturing, or marketing of nanotechnology products, methods, or services. These firms may be engaged at different stages of the value chain and include start-up ventures, manufacturers of intermediary materials and composites, biotech firms whose treatments and cures are based on nanomedicine, and most semiconductor manufacturers.[7] Of the "nanotechnology firms" worldwide, more than half (>5,000) are U.S. firms. This compares to approximately 1,000 nanotechnology firms in Germany[8] and 600 in Japan.[9]

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[3] The number depends on how one counts the various participants. Appendix C identifies 27, including OSTP and OMB.

[4] The National Nanotechnology Initiative: Supplement to the President's 2017 Budget, p. 23.

[5] All budget supplements are available at http://www.nano.gov/node/1071.

[6] Pertinent publications are available at http://www.nano.gov/publications-resources/results.

[7] Semiconductor firms have been incorporating nanocircuits and nanostructures in their chips since the late 1990s.

[8] According to the Federal Ministry of Education and Research, 1,000 German firms are engaged in research and development and marketing of nanotechnology products (Research in Germany, "Nanotechnology," http://www.research-in-germany.org/en/research-landscape/research-areas/nanotechnology.html, accessed January 14, 2016).

[9] M.S. Tomcyzk, *Nanoinnovation: What Every Manager Needs to Know*, Wiley-VCH, Weinheim, Germany, 2014, p. 31.

ASSESSING THE NNI

Fifteen years after the launch of the NNI, this report represents the 2016 National Research Council (NRC)[10] triennial review of the NNI, pursuant to the 2lst Century Nanotechnology Research and Development Act. The statement of task (reprinted in Appendix A) that guided this review of the Committee on Triennial Review of the National Nanotechnology Initiative has two parts.

A. Examine and comment on the mechanisms in use by the National Nanotechnology Initiative (NNI) to advance focused areas of nanotechnology towards advanced development and commercialization, along with the approaches taken to determine those focus areas and to implement the NNI's Signature Initiatives. If warranted, recommend possible improvements.
B. Examine and comment on the physical and human infrastructure needs for successful realization in the United States of the benefits of nanotechnology development. Consider research and development, product design, commercialization, and manufacturing needed both to advance nanoscience and engineering and to grow those portions of the American economy that are spurred by advances in nanotechnologies. If warranted, recommend possible improvements.

Prior reviews by PCAST[11] and NRC[12] committees have called on the NNI to take steps to more efficiently move results into commercial use. In its 2014 review, the President's Council of Advisors on Science and Technology (PCAST) concluded that the "United States will only be able to claim the rewards that come from investing in nanotechnology research and sustaining an overarching federal initiative if the federal interagency process, the Office of Science and Technology Policy (OSTP), and the agencies themselves transition their nanotechnology programmatic efforts beyond supporting and reporting on basic and applied research and toward building program, coordination, and leadership frameworks for translating the technologies into commercial products." In fact, the United States is realizing the economic rewards from investing in nanotechnology research, as illustrated in Figure 1.2. However, there remain substantial opportunities for raising U.S. commercial returns relative to the levels achieved in Asia and Europe.

BACKGROUND FOR ADVANCED DEVELOPMENT AND COMMERCIALIZATION—TASK A

The commercial value of nanotechnology is difficult to estimate. In 2001, government and industry experts predicted that the nanotechnology market would reach $1 trillion in 10 to 15 years. A recent Lux Research report estimates that the global nanotechnology-enabled market exceeded $1 trillion in 2013 and is projected to grow to more than $3 trillion by 2018.[13] Given the typical 10- to 20-year time from discovery to commercialization, the economic impact of NNI research will likely continue beyond 2018. As illustrated in Figure 1.2, the United States currently represents about one-fourth of the nano-enabled product market. Figure 1.2 shows that the annual investment of ~$1 billion per year by the NNI

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[10] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historical context identifying programs prior to July 1.

[11] Report to the President and Congress on the Fifth Assessment of the National Nanotechnology Initiative, Executive Office of the President President's Council of Advisors on Science and Technology, October 2014.

[12] National Research Council, *Triennial Review of the National Nanotechnology Initiative*, The National Academies Press, Washington, D.C., 2013.

[13] H. Flynn, *Nanotechnology Update: Corporations Up Their Spending as Revenue for Nano-enabled Products Increase*, Lux Research, State of the Market Report, February 17, 2014, http://portal.luxresearchinc.com/research/report_excerpt/16215.

in fundamental research and infrastructure is projected to be followed by ~$100 billion annual *growth* in U.S. commercial revenue in the coming years. While complexities in the transition processes from laboratory discovery to commercial product make a quantitative assessment of the return on investment from the NNI funding difficult, it is reasonable to conclude that the NNI has had significant economic consequences.

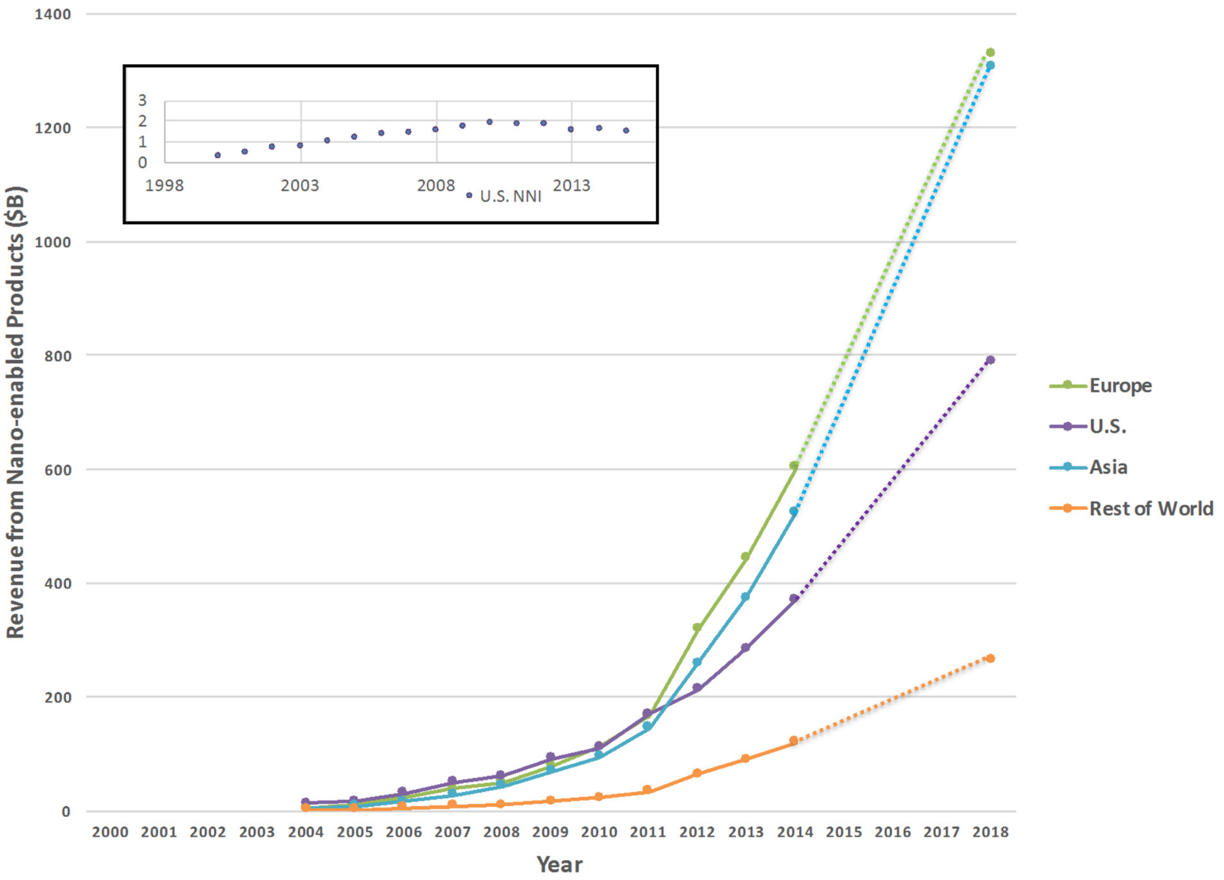

FIGURE 1.2 Revenue from nano-enabled products, delineated by geographical region and the annual U.S. NNI investment as a function of year. Lux Research defines nano-enabled products as finished goods incorporating emerging nanotechnology; it does not include products using nanoscale objects and devices based on long-known processes and technology. SOURCE: H. Flynn, Nanotechnology Update: Corporations Up Their Spending as Revenue for Nano-enabled Products Increase, Lux Research, State of the Market Report, 2015; Nanotechnology Update: Corporations Up their Spending as Revenues for Nano-enabled Products Increase" (Lux Research, Dec 2013); J. Schmidtke, Valuing U.S. Nanotechnology Impact for Future NNI Action, (Lux Research, Nov 2010).

In addition, economic consequences are only part of the success criteria for the NNI. As documented in a report from a word wide study,[14] nanoscale materials are expected to significantly improve quality of life and to attract students into science, technology, engineering, and mathematics (STEM) fields. The United States leads in training nanotechnology scientists and engineers. More than 75 colleges and universities offer nanotechnology degrees, and NNI-sponsored government and corporate programs continue to give students and workers essential knowledge and tools for manipulating atoms and molecules to develop new technologies and applications.

As indicated by the projected nano-enabled market growth, there is more value to be had. Nanotechnology research in advanced materials, medicine, semiconductors, sensors, and other areas is creating exciting new opportunities for commercialization. The NNI mission and goals support commercialization of nanotechnologies to create economic benefit and new sources of employment. And government agencies can use resources and policies to help expedite the transition of technologies from research laboratories to commercial markets.

However, it should be noted that a stronger emphasis on applied research and commercialization does not diminish the need to sustain support for basic research, which is a wellspring of new knowledge and ideas. Many of the commercial opportunities that are being exploited now (e.g., in solar energy, advanced materials, and medicine) are derived from basic research conducted or sponsored by NNI agencies.

Greater focus on enabling innovation may require adjustment to the NNI organization and portfolio. NNI's NSET Subcommittee does have experience in such restructuring. Over time, NNI agency participation reflects (1) the growth in agencies seeking to augment or exploit the growing nanoscale science and engineering knowledge base, (2) the increasing number—albeit still modest—of NSET members who work on technology transition programs, (3) the growing attention by the regulatory agencies (especially those associated with environment, health, and safety, and (4) the growing participation of agencies associated with marketplace (e.g., the U.S. Patent and Trademark Office and the Consumer Product Safety Commission). This evolution is evident in the agency representation over the years, which is shown in Appendix C.

The NNI programmatic emphasis also has changed over time. Table 1.1 shows the evolution as reflected in the reported areas of investment. Fundamental or foundational research has been a major investment throughout the initiative's history. Other areas that have received continuous support are infrastructure and instrumentation, as well as societal aspects, including environment, health, and safety. Focus on specific areas of research motivated by applications, such as medicine, solar energy, and so on, has shifted over time. Whereas such application areas were identified at the outset, following the legislation enacted in 2003, new program component areas (PCAs), defined as major subject areas under which are grouped related projects and activities, were identified. The first set of PCA's are shown in the column labeled "2006" in Table 1.1. These were less focused on application areas and more oriented around investment areas related to and in support of fundamental research. As of FY2015, the Nanotechnology Signature Initiatives (NSIs), which are areas with greater application and commercial potential, are designated as PCAs, along with other areas that continue to be tracked and supported.

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[14] M.C. Roco, C.A. Mirkin, and M.C. Hersam, *Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook*, Springer Netherlands, 2011, doi:10.1007/978-94-007-1168-6. September 30, 2010, version also available from the National Nanotechnology Initiative at http://www.nano.gov/node/948.

TABLE 1.1 Evolution of the NNI Investment Portfolio

2001	2006	2011	2016
Fundamental research	Fundamental phenomena and processes	Fundamental phenomena and processes	Foundational research
Use-inspired research			
	Nanoscale devices and systems	Nanoscale devices and systems	NT-enabled applications, devices, and systems
Materials by design	Nanomaterials	Nanomaterials	
	Nanomanufacturing	Nanomanufacturing	
			Signature Initiatives
Energy conservation and storage			Solar energy
			Sustainable nanomanufacturing
Information devices			Nanoelectronics for 2020 and beyond
			Knowledge infrastructure
Nanosensors for disease and bio threat			Sensors—improving and protecting ESH
Healthcare therapeutics and diagnostics			
Transportation			
Space exploration and industrialization			
Environmental improvement			
National security			
Infrastructure			Research infrastructure and instrumentation
Instrumentation	Instrumentation research, metrology, and standards	Instrumentation research, metrology, and standards	
Metrology			
User facilities	Major research facilities and instrumentation acquisition	Major research facilities and instrumentation acquisition	
Modeling and simulation			
Centers and networks of excellence			
Societal implications and workforce training	Societal dimensions	Education and societal dimensions	
		Environmental health and safety	Environmental health and safety

NOTE: The table material is extracted from the NNI Supplement to the President's Budget for the designated year. The new NNI grand challenge effort was not mentioned in the 2016 supplement, because it was published in early 2015, prior to formal incorporation of grand challenges into the NNI program.

Recommended by PCAST and launched in mid-calendar year (CY) 2015, nanotechnology-inspired grand challenges are intended to capture public attention and engage stakeholders in both public and private sectors. However, the first such grand challenge—Future Computing—highlights a difficulty that the grand challenge mechanism presents to the NNI. Although advances in nanoscale science and engineering certainly will be essential to the development of the envisioned future computational system, there also will have to be major advances in areas outside of nanotechnology, such as architecture and software.

Furthermore, an essential component in any effort toward technology transfer and commercialization is manufacturing. Reflecting that fact, nanomanufacturing has been an area of attention and investment in the NNI since 2004. A recent federal initiative, the National Network for Manufacturing Innovation, seeks to augment the U.S. advanced manufacturing base,[15] with a goal of growing jobs in a sector that is critical to economic wellbeing and national security. Nanotechnology provides new and promising innovative materials and processes, and the NNI can make important contributions to almost any area of advanced manufacturing.

The fact that nanotechnology often is an enabling component of innovative technologies, but is not the sole required advancement, poses a challenge for structuring and managing the NNI portfolio to facilitate technology transfer and commercialization. If NNI investments and activities alone are not sufficient, how can or should the NSET organize and manage the initiative to achieve commercial and public benefits?

In response to part A of the committee's statement of task related to advancing focused areas of the NNI toward advanced development and commercialization, Chapter 2 assesses signature initiatives and grand challenges, as well as other possible approaches. Chapter 3 provides an in-depth look at one focus area of particular importance to commercialization and manufacturing.

BACKGROUND FOR PHYSICAL AND HUMAN INFRASTRUCTURE FOR NANOTECHNOLOGY—TASK B

The ability to perform leading-edge nanoscale science and engineering R&D depends on access to state-of-the-art instrumentation and facilities. The NNI has built a substantial physical infrastructure, including facilities that are widely accessible to academic, industry, and government users. The cost of state-of-the-art fabrication and characterization tools can be prohibitive for small and medium-sized businesses. As nanotechnology-enabled innovation continues to expand, the value of NNI user facilities to this category of users also will grow.

The NNI has been a driver for multidisciplinary activities, and nanotechnology remains a vehicle for bridging traditional science and engineering boundaries. A critical component of NNI's multidisciplinary effort has been a series of National Science Foundation (NSF)-funded centers (Figure 1.3) focused on areas such as nanomanufacturing, materials, nanoelectronics, environment and education. These centers represent a significant element of the NNI physical and human infrastructure activity. However, such centers have a finite lifetime, and diffusion of NSE into traditional disciplines coupled with the tendency for basic research funding over time to seek new areas of emphasis likely will make it more difficult in the future to have larger, center-scale programs specifically focused on NSE. A decrease in NSE centers with their consolidated funding and broad mandate could diminish the availability of instrumentation that often is associated with center-based research and reduce or further dilute NSE education efforts that are part of the broader impact of such centers. Moreover, certain centers serve as resources for the entire nanotechnology community, and their termination may have much broader

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[15] See the Manufacturing.gov portal, operated by the Advanced Manufacturing National Program Office, at http://www.manufacturing.gov/welcome.html, accessed July 4, 2015.

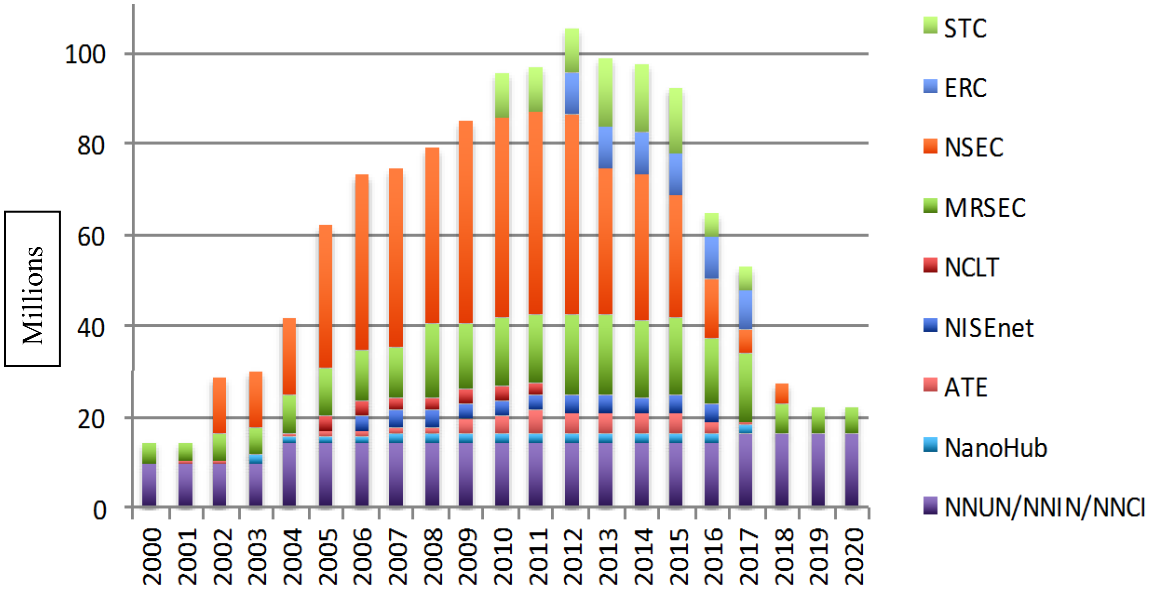

FIGURE 1.3 Evolution of National Science Foundation (NSF)-funded center-scale nanoscale science and engineering projects—programs of record. NOTE: The funding drop shown for 2016 and forward will not be quite as severe as shown here, because there will be some new programs. For instance, the NSF Engineering Research Center solicitation NSF 15-589 includes Nanosystems Engineering Research Centers (NERCs); those centers were not yet announced when this figure was compiled. However, the funding for one or two new NERCs only serves to slightly reduce—not eliminate—the precipitous drop in funding due to ending of the NSECs[16]., Advanced Technological Education (ATE); Engineering Research Center (ERC); Materials Research Science & Engineering Centers (MRSEC); Nanotechnology Center for Learning and Teaching (NCLT); National Informal STEM Education Network (NISEnet); National Nanotechnology Infrastructure Network (NNIN); National Nanotechnology Coordinated Infrastructure (NNCI); National Nanofabrication User Network (NNUN); and the Nanoscale Science and Engineering Center (NSEC).

impact. For example, nanoHUB.org, which is part of the Network for Computational Nanotechnology and described in greater detail in Chapter 4, is a repository for research and educational materials developed, shared, and used by all. Current funding is scheduled to end in 2018.

Chapter 4 addresses one part of the committee's statement of task, providing an evaluation of the NNI-funded physical infrastructure—including facilities funded by the Department of Energy, the National Institute of Standards and Technology, and the National Cancer Institute, as well as NSF – and and recommendations for sustaining it in order to support U.S. leadership in NSE research and commercialization.

STEM education and workforce training is a topic that encompasses NSE education. In his 2013 State of the Union address, President Obama issued a call to better equip U.S. graduates for the demands of a high-tech economy, noting that STEM is crucial to the nation's economic future and that students with STEM skills will be a driving force making the United States competitive, creative, and innovative.[17]

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[16] The demise of the existing NSEC's can be determined by a search of the NSF awards database for active vice archived projects at http://nsf.gov/awardsearch/advancedSearch.jsp with Element Code: 1675.

[17] Office of Science and Technology Policy, "OSTP Initiatives," https://www.whitehouse.gov/administration/eop/ostp/initiatives#STEM%20Education, accessed March 4, 2015.

As advances in nanotechnology lead to commercial opportunities, NSE-knowledgeable workers will be needed at all levels. These trained workers will be needed to keep the United States competitive in STEM-related research, entrepreneurship, and commercial development.[18] There will be increasing demand for workers who understand how to (1) safely handle atoms, molecules, and nanostructures; (2) preserve the unique properties that only occur at the nanoscale; and (3) integrate nanomaterials into macro or "bulk" materials and products. Therefore, including NSE in STEM education will be increasingly important.

NSE education can also play a role in getting students interested in STEM. Nanotechnology represents an intriguing new environment—including the ability to manipulate atoms, molecules, and nanoparticles like building blocks. It can provide exciting examples of technology solutions for societal problems that will catch the attention of students, including underrepresented communities. If presented properly, with interesting educational materials, nanotechnology can stimulate interest among students who might not be interested in traditional STEM topics. Unfortunately, most K-12 classrooms cannot offer hands-on nanoscale instruction to students because instruments to observe or manipulate at the nanoscale are too expensive and nanotechnology curriculum support is not yet widely available. The NNI and its collaborating agencies can help ameliorate these problems.

Nanotechnology education should be not limited to classrooms; nanotechnology is increasingly embedded in many areas where nanoscale skills were previously not needed. Quality control engineers use nanoscale characterization methods to examine wear and tear on injector systems in car engines. Cement makers embed nanoparticles to make concrete flexible and waterproof. Nanoscale features are present in most biological structures that can cause—and cure—disease. Nanoelectronics are facilitating flexible displays and smartphones that bend and fold. These are only a few examples of industries that are using nanotechnology. New methods are needed to provide nanotechnology proficiency to the existing workforce.

As nanomaterials are incorporated into more products in the commercial market, there is concern for the environmental, safety, and health implications. To make informed risk management decisions, it will be important for *everyone* to be informed about the basic principles of NSE.

To meet the needs indicated above, NSE needs to be incorporated into education at all levels and integrated into new and existing STEM initiatives. The second element of the committee's statement of task part B related to the development of the necessary human infrastructure is addressed in Chapter 5, including recommendations for strengthening NNI activities in NSE education.

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[18] National Academy of Engineering, *Making Value for America: Embracing the Future of Manufacturing, Technology and Work*, The National Academies Press, Washington, D.C., 2015.

2

From Research to Commercialization: Need for NNI Focus

As outlined in Chapter 1, the National Nanotechnology Initiative (NNI) has a broad, high-level mission to expedite discovery, development, and deployment of nanoscale science and technology for public good and a stated goal (Goal 2) to "foster the transfer of new technologies into products for commercial and public benefit." NNI spending, however, has been predominantly in support of research, including user facilities and equipment used by researchers. This NNI investment has built and sustained a diverse multidisciplinary research enterprise in universities, federal laboratories, and industry. A question framed by the committee's statement of task is, How can NNI better advance focused areas of nanotechnology toward advanced development and commercialization? In many ways, commercialization of nanotechnology is similar to that of any new technology. Therefore, in order to address this question, it is helpful to review how advanced development and commercialization occurs in general and then to consider how the NNI can accelerate the processes in targeted areas.

THE INNOVATION ECOSYSTEM

Technology-based innovation—that is, converting discovery to commercially valuable application—is a driver of the U.S. and global economy, fueling diverse sectors, including automotive, aerospace, defense, medicine, semiconductors, and electronics. Emerging technologies, such as nanotechnology, may lead to evolutionary improvements in existing products and processes, or may lead to entirely new and revolutionary products, businesses, and even industries. As a quantified illustration of this process, the involvement and importance of academia and industry in research related to commercial contributions to the information technology sector has been documented and shown graphically in reports of the National Research Council's (NRC's) Computer Science and Telecommunications Board. A figure tracking research investments and the development of technologies that reached a market size of more than $1 billion in sales (e.g., microprocessors and cloud computing) over time was first published in 1995[1] and most recently updated in 2012.[2]

Whether evolutionary or revolutionary, innovation is the outcome of a complex set of interconnected activities, spanning basic and applied research to development (design and engineering), scaling up to manufacture, and marketing and sales. Innovation activities involve an ecosystem of participants and institutions from the public and private sectors and with expertise in various areas and disciplines, including technology, manufacture, intellectual property, venture capital, industrial hygiene. Figure 2.1 illustrates the relationship among components of the nanotechnology innovation ecosystem, from research and education infrastructure to commercial products and applications. Beginning with the U.S. government establishment of the NNI, governments around the world have invested in the

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[1] National Research Council, *Evolving the High Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*, National Academy Press, Washington, D.C., 1995.

[2] National Research Council, *Continuing Innovation in Information Technology*, The National Academies Press, Washington, D.C., 2012.

infrastructure and research to advance nanotechnology with the goal of capturing the economic and public benefits.

The innovation ecosystem of Figure 2.1, which requires coordinated efforts by many individuals or entities, is facilitated when the process of new technology development is organized into a series of stages. The technology readiness level (TRL) scale describes the steps from research through successful implementation. Developed originally by NASA and adapted by the Department of Defense (DOD), the scale provides a framework for discussing or tracking the transition from research to application and use. Similar to TRLs, manufacturing readiness levels (MRLs) describe the development of an ability to manufacture. Ideally, a technology would move to higher TRL and MRL roughly in parallel. The TRL and MRL scales are shown in Table 2.1. Although developed for purposes of managing the development of large space and defense systems, this framework is equally applicable to the development of nano-enabled products, processes, and applications.

The federal government plays a particularly vital role as a primary funder of basic and applied research corresponding to TRL 1-3. The development of commercial products and processes (TRL 7-9) is generally the domain of the private sector, although some federal agencies like DOD and NASA can support such efforts where essential to their mission.

The emerging focus in the NNI on "translational research" is specifically intended to develop better ways to translate basic research discoveries and advancements into commercial application. There are multiple pathways by which new technology finds its way through the TRL stages and into a commercial product or process, and this applies to nanotechnologies and nano-enabled products and applications.

An idea resulting from basic research that is at TRL 1-2 is sometimes characterized as a "hammer in search of a nail." Typically, the goal of basic research is to advance knowledge, and while the researcher may be aware of the potential for commercial use, this is not the main motivation. Results may be "pushed" toward application after the research is done—for example, by forming a startup or by licensing to an existing company. The process of transitioning a technology by pushing it toward a particular application often requires resources that, if not forthcoming, can lead to the technology being caught in the "valley of death."

On the other hand, the commercial sector usually starts with a technology need and seeks to "pull" in a technology solution, either from an in-house research group or from the broader innovation ecosystem. Recognizing that research is fundamental to innovation, the federal government provides businesses tax credits for investing in research.

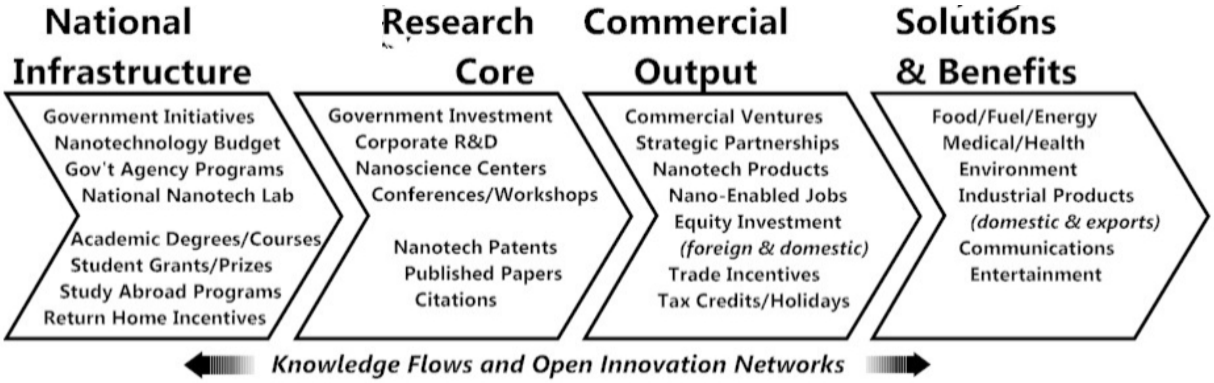

FIGURE 2.1 National nano innovation ecosystems include national infrastructures, a research core, avenues for commercialization, and mechanisms for providing commercial solutions and benefits. The NNI provides a framework for linking these components in the U.S. ecosystem. SOURCE: M.S. Tomczyk, *NanoInnovation: What Every Manager Needs to Know*, Wiley, 2015.

TABLE 2.1 Technology Readiness Levels (TRLs) and Manufacturing Readiness Levels (MRLs)

Level	Definition	Hardware (TRL)	Manufacturing (MRL)
1	Basic principles observed and reported.	Scientific research begins to be translated into applied research and development (R&D).	N/A
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative.	N/A
3	Analytical and experimental critical function and/or characteristic proof of concept.	R&D includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology.	N/A
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together.	The new technology has been demonstrated in a laboratory environment on simple design parts using similar types of materials that would be used in the intended application.
5	Component and/ or breadboard validation in a relevant environment.	The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment.	The new technology has been demonstrated in a laboratory environment on design parts of the same level of complexity and using the same types of materials that would be used in the intended application.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system is tested in a relevant environment.	The new technology has been demonstrated in a preproduction environment on design parts of the same level of complexity and using the same types of materials that would be used in the intended application.
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system.	The new technology has been demonstrated in a relevant production environment on design parts of the same level of complexity and using the same types of materials that would be used in the intended application.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions.	The new technology has been demonstrated in a pilot production environment on production-representative parts of the same level of complexity and using the same types of materials that would be used in the intended application.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions.	Process has been proven and under control for production.

SOURCE: Technology Readiness Assessment Deskbook, Department of Defense, May 2005.

Both dimensions, the push provided by research and the pull provided by commercial markets, have a role in the innovation process. Addressing a defined technical requirement can promote quite fundamental research and lead to novel solutions. Progress toward a solution that will be economically competitive improves the likelihood for sustained funding and decreases that of getting trapped in the valley of death.

An ongoing challenge for policy makers is to provide appropriate incentives and deploy resources where needed to help ideas resulting from government-funded research move out of the laboratory into practical application and commercial use.

Finding pathways to couple TRL 1-2 discoveries with eventual integration at TRL 6+ requires substantial alignment in the value chain. The incubator model is one that can help the early stage technology creator access the necessary learning and support infrastructure to fill the gaps until later stage investors engage. Incubators often are supported by state or regional economic development agencies and frequently are located near a research university. Incubators targeting local strengths and opportunities abound across the country. Examples that are engaged in the nanotechnology include the Oregon Nanoscience and Microtechnologies Institute, the Ben Franklin Technology Partners of Southeastern Pennsylvania, and MassChallenge (see Box 2.1).

The innovation processes sketched above are general but pertain to the development and commercialization of nanotechnology. Crossing the gap from research to commercialization poses a variety of challenges—most notably, the inability of innovators such as start-up companies and entrepreneurs to secure resources needed to bridge the gap from TRL 3-4 to TRL 6-7, the valley of death. Recognizing this impediment, federal agencies have a number of programs (see Figure 2.2) to help move very early stage ideas closer to a level where they will be attractive to private investors.

Such programs are a potential source of support for nanotechnology innovation.

BOX 2.1
MassChallenge: Accelerating Start-Ups by Empowering People

Successful incubators (also called “accelerators) such as MassChallenge focus on bringing together broad-based expertise in many different fields with a focus on outcomes and downstream funding access rather than more narrow models which “dig in” to help the innovators with their specific businesses. MassChallenge is a nonprofit, no-equity startup accelerator that operates in many countries. By running their incubator as a competition, the entrepreneurs are always in “winning” mode and excited about exploring networking opportunities while honing their skills and polishing their pitches.

MassChallenge competitions focus on teaching entrepreneurs a broad-based set of skills in program management, communication, fundraising, and process validation as part of the competition. Members of different teams get to know each other, share capabilities, and form partnerships. Understanding the pitfalls of concepts can generate quicker fails (at the technology readiness level [TRL] 3-5 level rather than when significant time, effort, and money have been spent at later stages) and allow more rapid pivots that will lead to better outcomes. A typical 6-month competition involves hundreds, or even 1,000 or more, startup teams at a time, providing a substantive value proposition to the community. MassChallenge competitors have included nanotechnology-based concepts.

SOURCE: MassChallenge, Inc., http://masschallenge.org, accessed January 14, 2016.

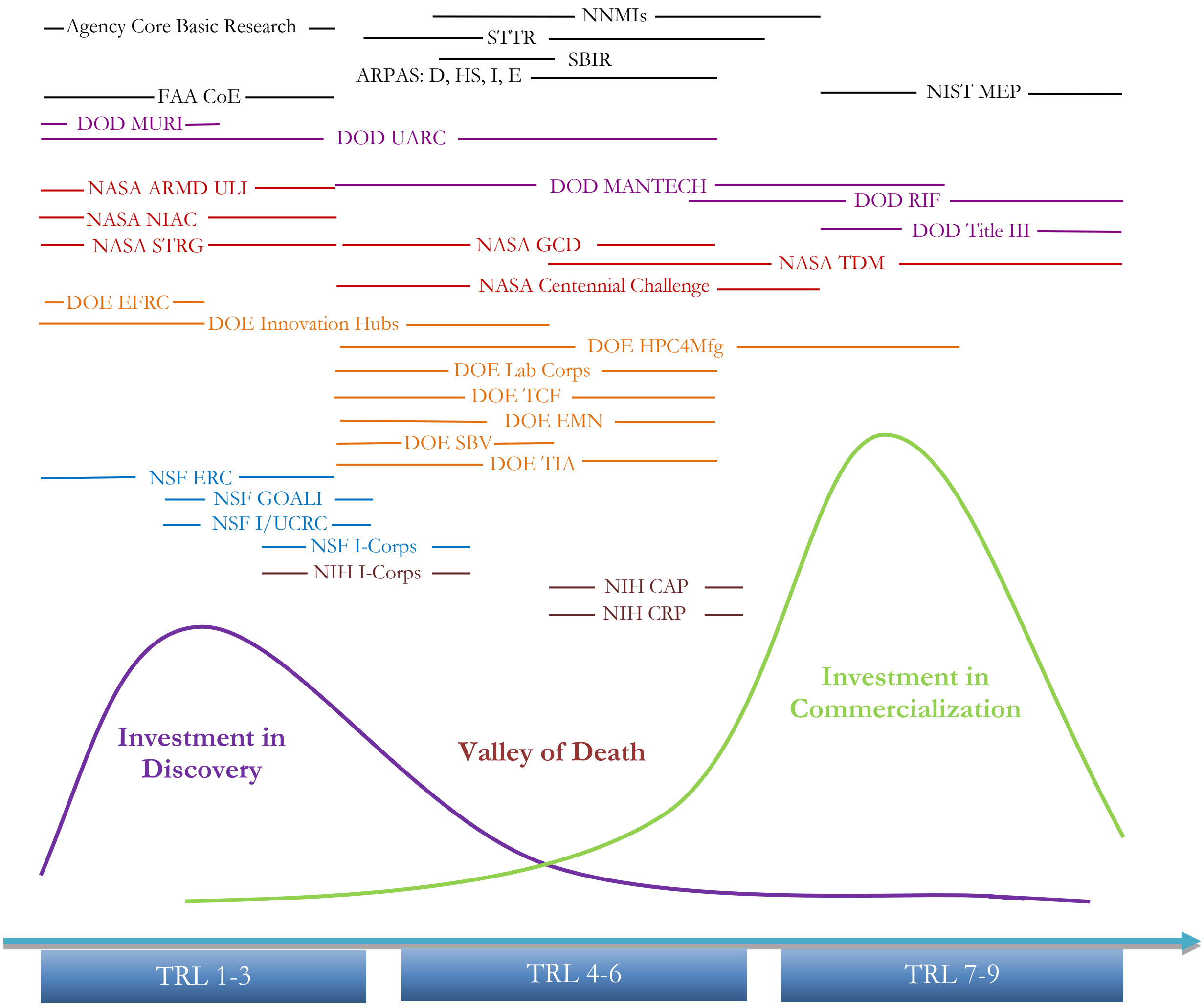

FIGURE 2.2 Illustration of the many federal programs specifically addressing technology transition as part of the manufacturing-innovation process, shown with the technology readiness levels (TRLs) at the bottom of the figure. The lower center of image depicts the "valley of death" between the principal government research funding in grey and the principal industry funding in green. In the upper center there is a suite of color-coded federal programs (blue, NSF; red, NASA; purple, DOD; green, DOE; black, others) designed to bridge that gap and their approximate position on the TRL scale. NOTE: AMTech, Advanced Manufacturing Technology; CEMI, Clean Energy Manufacturing Initiative; CoE, Center of Excellence; DOD, Department of Defense; DOE, Department of Energy; EFRC, Energy Frontier Research Center; ERC, Engineering Research Center; FAA, Federal Aviation Administration; FNC, Future Naval Capability; GCD, Game Changing Development; GOALI, Grant Opportunities for Academic Liaison with Industry; I/UCRC, Industry/University Cooperative Research Center; I-Corps, Innovation Corps; NNMI, National Network for Manufacturing Innovation; IQT, MANTECH, Manufacturing Technology; MURI, Multidisciplinary University Research Initiative; NASA, National Aeronautics and Space Administration; NIAC, NASA Innovative Advanced Concepts; NSF, National Science Foundation; ONR, Office of Naval Research; RIF, Rapid Innovation Fund; SBIR, Small Business Innovation Research; STRG, Space Technology Research Grant; STTR, Small Business Technology Transfer; TCF, Technology Commercialization Fund; TDM, Technology Demonstration Mission; TIA, Technology Investment Agreement; UARC, University Affiliated Research Center; ULI, University Leadership Initiative.

In fact, NNI participating agencies have utilized programs shown in Figure 2.2, specifying nanotechnology as a topic of interest. For example, the National Science Foundation (NSF), DOD, the Department of Energy (DOE), and the National Institutes of Health have cited nanotechnology as a topic of interest in calls for proposals under their Small Business Innovation Research and Small Business Technology Transfer programs. And in 2015, NSF called for proposals focused on nanosystems under the broad Engineering Research Center (ERC) program, defined as follows.

> A Nanosystem Engineering Research Center (NERC) must be focused on a transformational engineered system(s) that could not be achieved without a significant level of fundamental knowledge of nanoscale phenomena that feeds into devices and components needed to realize the targeted engineered system(s). A NERC must build on a significant fundamental discovery or engineering breakthrough in nanotechnology and/or nanomanufacturing research that is ready to feed into proof-of-concept engineered system test beds within the 10-year life span of an ERC.[3]

How can the NNI better couple to innovation programs, such as those shown in Figure 2.2, in order to grow the funding for nanotechnology innovation and to ensure the United States captures the value of the substantial NNI investment in nanotechnology research? The interagency Nanotechnology Innovation and Commercialization Ecosystem (NICE) Working Group under the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee is the logical entity to take the lead. The working group has the stated purpose “to promote the advancement and acceleration of nanotechnology innovation within U.S-centric commercial industries,” including by “stimulating nanotechnology innovation in and by federal government agencies, for their use and in transferring technology to the private sector.” One function of the NICE working group is to “promote collaboration between federal agencies to shepherd promising technologies from lab to market.”

> **Finding 2.1:** The federal government plays a significant role in discovery, applied research, and early stage development; the private sector plays a dominant role in product development and commercialization. A challenge for nanotechnology, like other emerging technologies, is to bridge from research to practical application. There are federal programs that provide support for advancing ideas to a level that is more likely to attract private investment.
>
> **Recommendation 2.1: The Nanotechnology Innovation and Commercialization Ecosystem Working Group should identify federal programs that assist with transitioning early-stage concepts to more advanced technology readiness. The Nanoscale Science, Engineering, and Technology Subcommittee, with support from the National Nanotechnology Coordination Office, should inform the basic research community about these programs and also communicate to federal program managers about how investment in advancement of nano-enabled technologies can provide opportunities for achieving their program and agency missions.**

In addition to promoting connections across the broad portfolio of NNI research to programs that can assist in moving technologies to higher TRLs, the NNI can—and to some extent does—focus on areas that are timely for development and commercialization. The 2014 NNI Strategic Plan included as an objective under its Goal 2: “Increase focus on nanotechnology-based commercialization and related support for public-private partnerships.” At present, the NNI seeks to focus the program primarily through two mechanisms: Nanotechnology Signature Initiatives (NSIs) and Nanotechnology-Inspired Grand Challenges.

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[3] National Science Foundation, 2015, *Gen-3 Engineering Research Centers (ERC)*, http://www.northeastern.edu/resdev/funding-announcement/gen-3-engineering-research-centers-erc/.

NANOTECHNOLOGY SIGNATURE INITIATIVES

Established in 2010, NSIs are multiagency initiatives designed to focus a spotlight on technology areas of national importance that may be more rapidly advanced through enhanced interagency coordination and collaboration.

According to the 2014 NNI Strategic Plan, NSIs are intended to genuinely affect the agency budget process and dramatically improve ground-level functional coordination and collaboration among agencies. By combining the expertise, capabilities, and resources of multiple federal agencies, the NSIs can accelerate research and development and can overcome challenges to commercialization of nano-enabled products. Each NSI is described, and expected outcomes enumerated, in a white paper available on the NNI website. Contributing agencies have a stated commitment to coordinating research to achieve the expected outcomes in order to avoid duplication of effort and to maximize the return on U.S. research investments.

According to NNI documents, to ensure that adequate focus is maintained on each NSI, a limited number will be active at any one time and topics will be added or removed, as appropriate. New topics for consideration may come from stakeholder suggestions, review committee recommendations, evolving Presidential priorities, and/or agency input. Topics of interest will be developed into proposals by an interagency group represented by at least three agencies and presented to the NSET Subcommittee. The NNI agencies and the Office of Science and Technology Policy (OSTP) select NSI areas based on the following criteria: alignment with national scientific, economic, and environmental priorities; potential impact on the advancement of nanoscale science and technology; and need for enhanced interagency coordination and collaboration (e.g., areas that cannot be adequately addressed by a single agency).

The NNI announced three NSI's in its annual report that accompanied the 2011 budget; the 2014 budget supplement included two additional NSIs, for a total of five. In the 2017 supplement, it was announced that one of those, Nanotechnology for Solar Energy Collection and Conversion, was sunset in 2016. A white paper for a new initiative, Water Sustainability through Nanotechnology, was released in March 2016[4]. The five current signature initiatives are in nanomanufacturing, nanoelectronics, nanotechnology knowledge infrastructure, sensors, and sustainable water. Information about how nanotechnology will play a role in making progress in each of the NSI areas is available on the NNI website.[5] The amount invested in the five NSIs since 2011, as reported in annual budget supplements, is shown in Table 2.2, as well as the percent of the total NNI budget invested in the NSIs overall.

Investment in four of the five NSIs has declined from a maximum in 2012, coinciding with a $200 million drop in the amount of funding reported by DOD, despite a recommendation by President's Council of Advisors on Science and Technology (PCAST) that same year to increase NSI funding. However, the percent of the total NNI budget spent on NSI's from 2012 to 2015 has been roughly constant, ranging between 16 and 19 percent, suggesting that declining NSI budgets are similar to overall declines. Note that figures for 2016 and 2017 in Table 2.2 are not final; in the past, actual investments have often exceeded planned spending.

A progress review of the NSIs is underway; an executive summary and a more detailed progress review of the NSI on solar energy were released in late 2015. The solar energy NSI review lists activities and programs supported by NNI agencies and highlights of the results. It also indicates that in the area of solar energy "[t]he strength of [the interagency] interactions and the active community that has developed make the continued focus of a signature initiative unnecessary. Although these important activities will continue, fiscal year 2016 will be the last year they are reported under the NSI mechanism, and the NSI spotlight will transition to other high-priority areas for the NNI."[6]

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[4] Aforementioned budget supplements can all be found at http://www.nano.gov/node/1071.

[5] An explanation of signature initiatives is accessible at http://www.nano.gov/signatureinitiatives, accessed July 5, 2016.

[6] National Nanotechnology Initiative, "Progress Review of the NNI Nanotechnology Signature Initiatives," http://www.nano.gov/node/1536, accessed September 1, 2016.

TABLE 2.2 Annual Investment in Nanotechnology Signature Initiatives (in $million)

	2011	2012	2013	2014	2015	2016 (Estimated)	2017 (Proposed)
Solar	88	88	74	73	67	0	0
Nanomanufacturing	61	56	35	47	45	37	37
Nanoelectronics	97	92	87	79	96	82	70
Nanotechnology knowledge infrastructure		2	8	16	28	23	22
Sensors		55	77	58	49	30	29
Sustainable water							TBD
Total NSI	246	293	281	273	284	172	158
Total NNI	1847	1857	1550	1574	1496	1435	1443
NSI as a percentage of NNI (%)	13.3	15.8	18.1	17.3	19.0	12.0	10.9

NOTE: TBD, to be determined.

NSI activities reported in the 2015 review and in the annual budget supplement reports[7] are commendable, and the committee heard from NNI agency representatives that facilitation of interagency communication and coordination under the NSI's is of real value. In addition, there has been engagement with the public via workshops and webinars under several of the NSIs.

It can be argued, however, that the full potential of the NSIs to focus the NNI agencies and others in the research community, as well as to speed advancement, has not been met. Such progress requires more than simply stating expected outcomes, it requires defining technical challenges along the way and developing an explicit program to address those challenges. A good example of such an approach is the NNI 2011 Environmental, Health and Safety (EHS) Research Strategy, which clearly identifies the various types of information that are needed to support sound risk management of nanotechnology. Although execution of the EHS research strategy is not owned by a single office or agency, it serves as a guide to researchers and managers in the field.

Coming to a similar conclusion, the 2013 NRC NNI Triennial Review recommended that the NNI agencies develop strategic plans and roadmaps for each NSI. Not only has the recommendation not been implemented, the termination of the solar energy NSI due to the strength of the existing ecosystem (rather than because it met the stated technical goals) suggests that in fact interagency interactions and community building are the primary objectives.

The committee endorses the prior recommendations of PCAST and the NRC regarding the NSIs. If indeed the NNI agencies agree the NSI topics are important and ripe for advancement, more detailed plans and resources should follow; otherwise, progress will lag.

> **Finding 2.2:** Without a plan that has clear targets, goals, and metrics to measure progress, as well as indication of responsible agencies, funding for NSI topics will be more difficult to secure within the NNI agencies and advances will be more serendipitous and less assured.

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[7] All NNI budget supplements can be found at http://www.nano.gov/node/1071.

Recommendation 2.2: Agencies participating in each Nanotechnology Signature Initiative (NSI) should develop a joint strategic plan with roadmaps and interim and end-result goals. The plans should include goals related to facilitating commercialization of research related to the topic of the NSI.

NANOTECHNOLOGY-INSPIRED GRAND CHALLENGES

The NNI is using a new mechanism to focus the initiative and the broader nanotechnology community based on Grand Challenges. The term “grand challenge” does not have a precise definition. In the 2015 President’s Strategy for American Innovation, grand challenges are described as “ambitious but achievable goals that harness science, technology, and innovation to solve important national or global problems and that have the potential to capture the public’s imagination.”[8]

Examples of Grand Challenges

Government-proclaimed grand challenges have proven to be a powerful technological driving force in our nation’s past. A brief survey of some successful grand challenges offers insights and common attributes.

An oft-cited grand challenge is the Manhattan Project, designed to produce the first nuclear weapon during World War II. Fear that Germany was developing a nuclear weapon lent urgency to the U.S. effort. The Manhattan Project began in 1939 and culminated in the bombing of Hiroshima in August 1945. During this period, the project grew to employ more than 130,000 people and cost nearly $2 billion dollars (approximately $26 billion in 2015 dollars).

Perhaps the most well-known Grand Challenge was President Kennedy’s challenge to put a man on the Moon and bring him back safely, announced in May 1961 and motivated by concerns that the Soviet Union was taking the lead in space. In his speech, President Kennedy argued that the United States should not follow but rather should lead in the “race for space” and set an ambitious target of completing the challenge by the end of the decade. Like the Manhattan Project, the Apollo program was a grand challenge backed by robust federal spending and strong governmental coordination and leadership by a single agency, in this case NASA.

A third example of a grand challenge is the Human Genome Project (HGP), proposed and funded by the U.S. government. Motivation for the project emerged from experts in the scientific community via a number of workshops and reports. The $3 billion project was announced in 1990 and co-led and co-funded by DOE and the National Institutes of Health. It was expected to take 15 years, but a working draft of the genome was announced in 2000, and the papers describing it were published in February 2001. A more complete draft was published in 2003, and genome “finishing” work continued for more than a decade. Interestingly, HGP also generated commercial interest. Building on the initial government-funded effort and the resulting data, which were made publicly available, a parallel project by Celera Corporation, or Celera Genomics, was launched in 1998. Although managed separately, Celera’s alternative approach spurred the public HGP to change its own strategy, leading to an acceleration of the public effort.

There are similarities among the three above identified historical grand challenges. First, the problem was sweeping and of importance for maintaining leadership in something deemed critical to the nation. Second, the end points were measurable: build a nuclear bomb; land a man on the Moon; sequence

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[8] National Economic Council, OSTP, *President’s Strategy for American Innovation*, https://www.whitehouse.gov/sites/default/files/strategy_for_american_innovation_october_2015.pdf, accessed August 4, 2015.

the human genome. Third, they were well funded. Fourth, there was clear leadership even when more than one agency was involved. Fifth, achieving the grand challenge led to commercial interest or commercial spillovers that had societal benefits. Lastly, in the course of meeting the challenge, fundamental science was advanced from discovery to application, driven by the clear goal of the program. Except for the Manhattan Project, which was kept secret for national security reasons, the grand challenges outlined above were announced publicly and stimulated considerable public interest and private sector innovation.

Assessing grand challenges from the past provides valuable insights, but it is also helpful to look at current examples. DOE's SunShot Initiative offers a model that the NNI may find useful. SunShot is a collaborative national endeavor to make solar energy cost competitive by the end of the decade without subsidies with other forms of energy. The initiative has a clearly stated goal of an installed system price of $1.00 per watt or electricity cost of $0.06/kWh. Other characteristics of the SunShot Initiative that are consistent with a successful grand challenge include the following:

- A clear timeframe for achieving the goal;
- A single lead organization (DOE Office of Energy Efficiency and Renewable Energy) that is responsible for managing the effort; and
- A suite of activities that engage the diverse community and broad expertise needed to address the problems, including academia, national laboratories, and the private sector.

The SunShot Vision Study[9] published shortly after the initiative was launched, provides a detailed assessment of the potential for solar technologies to meet a significant share of electricity demand in the United States. The report also outlines a roadmap across multiple technologies that are needed in order to reach the goal. Such a detailed roadmap allows progress to be monitored and provides guidance to the broad community of researchers and innovators, even those working outside the government programs. In 2016, DOE published a series of reports that examine the progress made and lessons learned in the first 5 years of the initiative and the challenges and opportunities the industry faces going forward. Figure 2.3 shows the installed photovoltaic system prices in 2010 when the initiative was launched, at the mid-point in 2015, and the targets for 2020. The SunShot team works to achieve its goals by engaging many elements of the innovation ecosystem—funding cooperative research, development, demonstration, and deployment projects by private companies, universities, state and local governments, nonprofit organizations, and national laboratories.

Grand challenges also have been identified by non-government entities. One example is the Grand Challenge in Global Health initiative (GCGH) launched in 2003 by the Bill and Melinda Gates Foundation. GCGH has identified seven global health goals (e.g., improving and creating vaccines) and specific challenges under each goal. In partnership with a number of government agencies around the world, GCGH is investing hundreds of millions of dollars in the form of grants targeting the stated challenges.

Another example of non-government developed grand challenges are the Grand Challenges for Engineering, published by the National Academy of Engineering (NAE) in 2008.[10] This set of 14 challenges was developed by a group of technical experts and represents global problems that can be addressed by advances in engineering. The Grand Challenges for Engineering are aspirational and the end points, such as "secure cyberspace," are not realistically fully achievable. In addition, the National Academies does not fund research programs, but has continued to highlight the challenges by sponsoring

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[9] Department of Energy, 2012, "SunShot Vision Study," Washington, D.C., http://energy.gov/eere/sunshot/sunshot-vision-study.

[10] National Academy of Engineering, 2008, *Grand Challenges for Engineering*, Washington D.C., http://www.engineeringchallenges.org/File.aspx?id=11574&v=ba24e2ed.

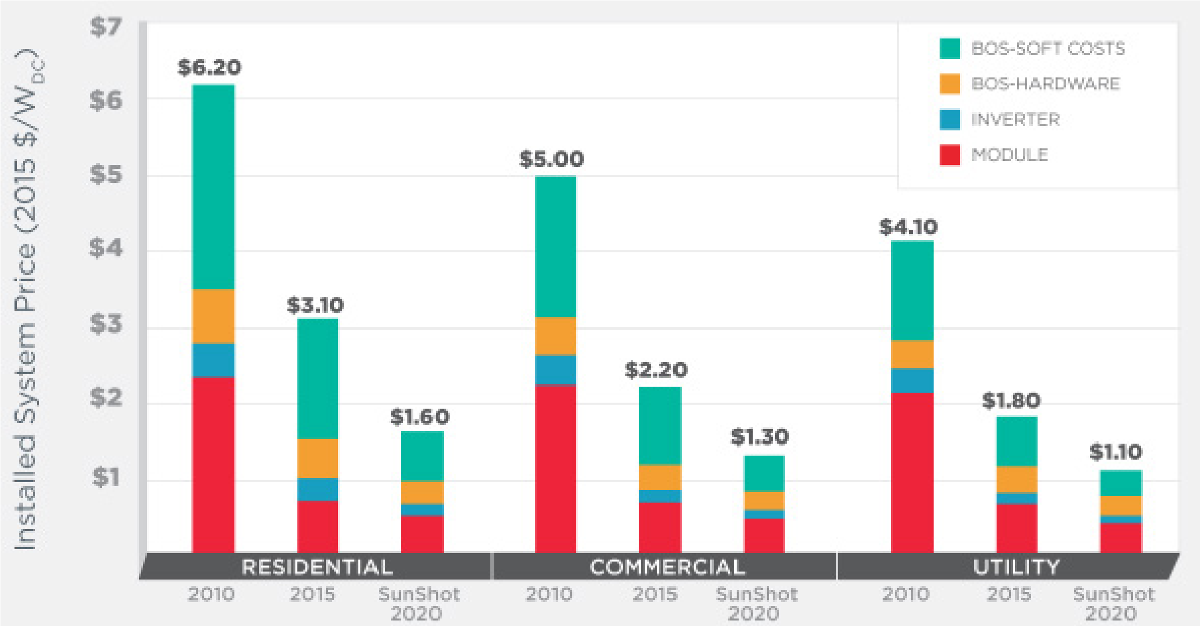

FIGURE 2.3 Installed photovoltaic (PV) system prices in 2010 and 2015 and estimated prices that will meet SunShot 2020 targets. NOTE: BOS, balance of system, including all components other than the PV panels, such as wiring, mounting hardware, batteries for storage, and so on. Source: "The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs," (2016) National Renewable Energy Laboratory NRL/TP-6A20-65872, p. 15. (available at http://www.nrel.gov/docs/fy16osti/65872.pdf), accessed on October 15, 2015.

events that bring together leaders from the engineering community and through a website (http://www.engineeringchallenges.org/). This approach can focus attention, but is not able to do what needs to be done in order to realize the goals.

Using NNI Grand Challenges to Transition to NNI 2.0

The *Report to the President and Congress on the Fifth Assessment of the National Nanotechnology Initiative* in October 2014 from PCAST called for the next phase of nanotechnology development that it called NNI 2.0. The report stated that "after 13 years, the success of the first phase of activities and the maturation of the research field has placed the field of nanotechnology at a critical transition point." This point is reinforced by the inflection point in 2011 for nano-enabled product revenue shown in Figure 1.2. The rate at which revenues grew annually after 2011 was approximately twice what it was before.

To further the transition to NNI 2.0, the PCAST report recommended the construct of grand challenges. These grand challenges were to be "instantiated across the NNI ecosystem and in the management of federal activities to focus NNI participants on significant problems of major national interest that, by commercializing the associated science and technology, will benefit society."[11] The report went on to say that organizing activities around grand challenges would be a major community rallying point and would provide additional tools to manage and measure the effectiveness of NNI 2.0.

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[11] PCAST, 2014, Report to the President and Congress on the Fifth Assessment of the National Nanotechnology Initiative, October, p. 26.

The PCAST Report also articulated important characteristics that grand challenges exhibit, including the following:

- They have a measurable endpoint. It is clear when they have been reached. As such, they also have a finite, albeit relatively long (probably a decade), lifetime.
- They require advances in fundamental scientific knowledge, tools, and infrastructure for successful completion. In short, when a grand challenge is begun, all the resources needed to complete it are not known. As such, it is necessary to recognize and articulate the risks of the undertaking and to mitigate those risks to the maximum extent possible.
- There must be clear milestones en route to the final grand challenge goals that are both measurable and valuable in their own right. It is only through monitoring these deliverables that it is possible to tell whether or not the effort is on track to achieve its ultimate objective.
- They are integrating. Their solutions require bringing together multiple disciplines—in many cases, disciplines that do not typically interact. In addition, grand challenges span from fundamental science to engineering demonstration and, upon completion, to commercialization.
- Though led by a single agency, the grand challenges are too big to be undertaken by a single, or even a few, institutions. In fact, one way of mitigating the risk inherent in taking on an effort of this magnitude may be to pursue more than a single approach to the problem, thus involving even more institutions than would be engaged in a single approach.

With these characteristics in mind, PCAST recommended that OSTP and the NSET establish grand challenges not just to harness, but to focus and amplify the impact of federal nanotechnology activities. PCAST further enumerated "essential elements" for the identification of nanotechnology-related grand challenges, including the following:

- The investment of the public, industrial, academic, national laboratory, investor, financial, and communication sectors;
- A strong leader who is a member of NSET and who can set a vision for a challenge and convene stakeholders toward its development;
- Identification of critical challenges in the mission space of agencies participating in NNI that have a solution requiring significant advances in nanoscience and technology;
- Understanding of the global landscape in the problem area;
- Engagement of broad swaths of stakeholders in the dialogue leading up to grand challenge selection, including researchers, research managers, and agency representatives; and
- After allowing for significant community engagement, a fairly small set of subject-matter experts and senior advisors should select the grand challenges.

It is worth noting that these elements focus on how to identify—not how to implement—grand challenges. In June 2015, OSTP, working with the federal agencies that participate in the NNI, issued a request for information (RFI) to gather information from external stakeholders about potential grand challenges that would help guide the science and technology priorities of federal agencies, catalyze new research activities, foster the commercialization of nanotechnologies, and inspire different sectors to invest in achieving the goals.

After considering more than 100 responses, on October 20, 2015, OSTP announced the Nanotechnology-Inspired Grand Challenge for Future Computing, "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."[12] The White House announcement of the grand challenge goes on to state the following:

> While it continues to be a national priority to advance conventional digital computing—which has been the engine of the information technology revolution—current technology falls far short of the human brain in terms of both the brain's sensing and problem-solving abilities and its low power consumption. Many experts predict that fundamental physical limitations will prevent transistor technology from ever matching these twin characteristics. We are therefore challenging the nanotechnology and computer science communities to look beyond the decades-old approach to computing based on the Von Neumann architecture as implemented with transistor-based processors, and chart a new path that will continue the rapid pace of innovation beyond the next decade.
>
> There are growing problems facing the Nation that the new computing capabilities envisioned in this challenge might address, from delivering individualized treatments for disease, to allowing advanced robots to work safely alongside people, to proactively identifying and blocking cyber intrusions. To meet this challenge, major breakthroughs are needed not only in the basic devices that store and process information and the amount of energy they require, but in the way a computer analyzes images, sounds, and patterns; Interprets and learns from data; and identifies and solves problems.
>
> Many of these breakthroughs will require new kinds of nanoscale devices and materials integrated into three-dimensional systems and may take a decade or more to achieve. These nanotechnology innovations will have to be developed in close coordination with new computer architectures, and will likely be informed by our growing understanding of the brain—a remarkable, fault-tolerant system that consumes less power than an incandescent light bulb.

Although this grand challenge meets many of the characteristics of a grand challenge as identified in the 2014 PCAST report, important characteristics and elements are missing. These have to do primarily with guiding the grand challenge forward. First, clear milestones en route to the final grand challenge goal that are both measurable and valuable in their own right have not been articulated. Second, the global landscape has not been adequately mapped so as to provide prioritization and to identify gaps and areas in which U.S. leadership is threatened or may already be lost.

Importantly, there is an absence of any dedicated funding or a lead agency responsible for making this grand challenge a reality. If these deficiencies are not remedied, this grand challenge will be similar to the NAE Grand Challenges for Engineering, that is, clear statements of need without the resources to address them. A more likely scenario is that agencies will report activities that align with the grand challenge, but such activities will only be coordinated, not led, nor show progress toward specific goals.

Also, as noted in Chapter 1, a glaring obstacle to the NNI participating agencies tackling the grand challenge is the fact that it requires advances in areas other than nanotechnology, such as computer science and engineering and neurobiology. In fact, the grand challenge announcement highlights the relationship to other Presidential initiatives, in particular the National Strategic Computing Initiative and the BRAIN Initiative. The representatives to the NSET do not have the entire expertise or programmatic influence/control to support the full breadth of research that is needed to achieve the grand challenge. Conversely, those other initiatives depend on continued progress in nanotechnology, while the managers of programs and activities leading those initiatives may not have deep knowledge of the nanoscale.

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[12] L. Whitman, R. Bryant, and T. Kalil, "A Nanotechnology-Inspired Grand Challenge for Future Computing," Office of Science and Technology Policy, October 20, 2015, https://www.whitehouse.gov/blog/2015/10/15/nanotechnology-inspired-grand-challenge-future-computing.

Meeting the nano-inspired grand challenge both depends on and supports progress toward the objectives of these other initiatives.

An example where such symbiosis has been recognized is in the area of water sustainability. The NNI recently announced an NSI on "Water Sustainability through Nanotechnology: Nanoscale Solutions for a Global-Scale Challenge." This NSI is part of a broader federal effort focused on "Commitments to Action on Building a Sustainable Water Future."[13] The NSI will address nanoscale properties such as the increased surface area and reactivity of engineered nanomaterials to create precious-metal-free catalysts for water purification, the enhanced strength-to-weight properties of nanocomposites to make stronger, lighter, and more durable piping systems and components, and nanoscale porosity for cost-effective purification or desalination.

> **Finding 2.3:** The NNI is investing in technology areas that are critical to the goals of other federal initiatives, and vice versa. The various initiative leaders and managers both inside and outside of the NNI may not have the entire expertise or programmatic influence or control to efficiently achieve their respective initiative goals.
>
> **Recommendation 2.3: The Nanoscale Science, Engineering, and Technology Subcommittee should strengthen engagement with the leadership of other high-priority initiatives in order to determine critical nano-enabled technological dependencies. The subcommittee then should focus NNI efforts to address those dependencies.**

Possible mechanisms to focus NNI efforts on areas that relate to other initiatives include developing plans with goals and milestones to address specific nanotechnology needs of the initiatives, establishing an NSI, or—as described below—sponsoring a prize competition.

PRIZES: A MECHANISM FOR PROVIDING FOCUS AND IMPLEMENTING GRAND CHALLENGES

In recent years, there has been an increased interest in and use of open innovation prizes that engage a broader community of innovative thinkers to develop solutions to a variety of hard problems and grand challenges.

Prizes are an example of technology or innovation "pull" that has been used in the public and private sectors dating back centuries. An entity poses a challenge or problem, states the prize, and the criteria by which the prize will be awarded. Prizes are typically cash, but often come with other benefits, such as access to investors and customers, and free publicity. They also can raise awareness and attract attention to a new area in science or engineering. An attractive feature of prize competitions is that the entity offering the prize only pays if the success criteria are met, and often those attempting to solve the challenge—even just those who are successful and receive the prize—spend much more than the amount of the prize in the process of achieving the goal. Another benefit of prizes is that they tend to engage nontraditional innovators that can elicit novel solutions.

Perhaps the best known innovation prize is the XPrize, founded in 1994 by Peter Diamandis. The first XPrize was announced in 1996 and offered a $10 million prize to the first privately financed team that could build and fly a three-passenger vehicle 100 kilometers into space twice within 2 weeks. The

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[13] Executive Office of the President, 2016, *Commitments to Action on Building A Sustainable Water Future*, Washington, D.C., https://www.whitehouse.gov/sites/whitehouse.gov/files/documents/White_House_Water_Summit_commitments_report_032216_v3_0.pdf.

challenge spurred 26 teams to invest more than $100 million, and in October 2004 the prize was won by Mojave Aerospace Ventures. Today, the XPrize Foundation manages millions of dollars in public prize competitions with the mission to bring about "radical breakthroughs for the benefit of humanity." In 2013, XPrize launched a nonprofit spin-off called HeroX, a version of XPrize that uses crowdsourcing to identify and fund challenges of social value and benefit.

InnoCentive is another organization that facilitates innovation incentive prizes by matching anonymous "solution seekers," who may be corporations or government agencies, with "problem solvers" who compete for a cash prize from anywhere in the world. Reward amounts can range from $1,000 to $1 million. Government agencies have posted challenges on InnoCentive.

According to the InnoCentive website, they have developed a methodology called Challenge Driven Innovation, "an innovation framework that accelerates traditional innovation outcomes by leveraging open innovation and crowdsourcing along with defined methodology, process, and tools to help organizations develop and implement actionable solutions to their key problems, opportunities, and challenges." Over the years, InnoCentive has established a pool of solvers eager to work on interesting problems and a platform for posting diverse challenges. Problem solvers are vetted to qualify them in advance. Copyright and patent ownership is addressed as part of the process. Cash awards are given to the problem solver with the best solution, in the opinion of the solution seeker. InnoCentive keeps sponsor identities anonymous to help prevent competitors from using the solicitation to learn what the sponsor is working on, or concerned about. The goal is to significantly decrease the time to find a solution by putting it out for anyone to tackle.

XPrize and InnoCentive provide advice and expert support in the development of a good prize-based competition and could be resources to the NNI. These examples confirm that it is essential to clearly define the problem and the specific objective, along with evaluation criteria. Whereas the goal must be specified, the approach should not be. Some competitions give a timeframe within which proposals will be considered. Others are open ended and flexible enough to change.

Prizes that reward novel solutions to posed challenges are an alternative and complementary mechanism to the traditional proposal and selection process typically used to determine how to spend federal funds on research and development. Although nontraditional, the 2010 American COMPETES Act granted all federal agencies the authority to award innovation incentive prizes and the General Services Administration has created a website[14] to be a "one stop shop" for agencies wanting to access innovative problem solvers in the private and academic sectors. Defense Advanced Research Projects Agency (DARPA) Grand Challenges are among the best known government-sponsored prizes in recent years. Examples include autonomous vehicle and robotic challenges. DARPA challenges typically culminate in an event where finalists who have cleared preliminary hurdles come together to demonstrate their concepts and compete head to head.

NASA has sponsored innovation competitions, most notably Centennial Challenges, which provide cash prizes for non-government-funded technological achievements by U.S. teams. The contest is named "Centennial" in honor of the 100 anniversary of the Wright Brothers' first flight in 1903. Examples of NASA Centennial Challenges include the Sample Return Robot Challenge (an autonomous rough-terrain robot) and the Mars Ascent Vehicle Prize.

PCAST recommended in its 2014 assessment that the NNI offer innovation prizes that reward the first person or group to achieve a grand challenge milestone. Although achieving the Grand Challenge for Future Computing requires advances in areas other than nanotechnology, certain elements or milestones will have a clear dependence on nanoscale science or engineering.

The NNI is using a sort of prize to attract attention to, and stimulate interest in, nanotechnology at the K-12 level. For example, EnvisioNano is a contest for students who submit striking nanoscale images with thoughtful, concise descriptions of the science. Another example is "Generation Nano: Small Science, Superheroes," a competition that asks individual high school students to submit an original idea

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[14] Ibid.

for a superhero, using modern nanotechnology research to inspire unique nano-enabled "gear" for their hero. Winners received cash prizes and the opportunity to showcase their creation at the 2016 USA Science and Engineering Festival in Washington, D.C.

> **Finding 2.4:** XPrize, InnoCentive, and other organizations have well developed, proven strategies for managing innovation incentive prize competitions using cash awards and well defined procedures to engage a diverse array of people and organizations, stimulate additional spending, and produce results.
>
> **Recommendation 2.4: NNI agencies should use innovation incentive prizes to engage a broader community to solve technical problems, particularly those underlying grand challenges and other national initiatives. NNI agencies can offer prizes directly, or work through existing organizations.**

THE ROLES OF REGULATION AND POLICY IN PROMOTING OR INHIBITING COMMERCIALIZATION

Support of basic research has been the prime focus of the NNI to date, with the results of such basic research generally published in the open scientific literature and thereby rapidly distributed globally. Technology development for commercial purposes, however, is associated with protecting information. There are four levels of information constraint and protection: trade secrets, patents, process know how, and open literature. If NNI increases investment and emphasis on technology development, then issues related to intellectual property, export control, and other regulatory regimes will require greater consideration as well

At the various fact-finding sessions held in the preparation for this report, there was frequent mention of concern over the potential impact on commercialization of regulatory policy and procedure, especially the Environmental Protection Agency (EPA) handling of nanoscale materials under the Toxic Substances Control Act (TSCA). TSCA requires manufacturers of new chemical substances to provide specific information to the Agency for review prior to manufacturing chemicals or introducing them into commerce. EPA can take action to ensure that chemicals that may or will pose an unreasonable risk to human health or the environment are effectively controlled. But, as with the usage of nanomaterials for cancer treatment those who are developing technologies for commercial uses will be more likely to make the necessary investments if clear in standards and protocols for the appropriate characterization of nanostructures and their environmental impact.

3

Focus on Nanomanufacturing

Nanomanufacturing is a focus area of nanotechnology related to advanced development and commercialization that warrants special attention. It also is an area that is integrally related to other high-profile federal initiatives focused on advanced manufacturing.

Nanomanufacturing is a specialized aspect of advanced manufacturing involving nanoscale materials and processes.

The President's Council of Advisors on Science and Technology (PCAST) has identified manufacturing as a matter of fundamental importance to the United States—economically and, in some sectors, for national security.[1] In June 2011, PCAST released the report *Ensuring American Leadership in Advanced Manufacturing*.[2] Shortly thereafter, President Obama launched the Advanced Manufacturing Partnership (AMP), a national effort bringing together industry, universities, and the federal government to invest in the emerging technologies, such as nanotechnology, that will create high-quality manufacturing jobs and enhance U.S. competitiveness. In February 2012, the National Science and Technology Council (NSTC) released *A National Strategic Plan for Advanced Manufacturing*,[3] which was followed in October 2014 by the PCAST report *Accelerating U.S. Advanced Manufacturing*.[4]

Motivation for this concerted effort was the precipitous decline in U.S. manufacturing jobs, facilities, and infrastructures in many key sectors. For example, the United States lost 5 million manufacturing jobs between January 2000 and December 2014.[5] Also, the United States is no longer the lead producer of manufactured goods. Today, Chinese-based businesses lead the world in total output of manufactured goods, with $2.3 trillion compared to $1.8 trillion from U.S.-based businesses.[6] While the speed at which manufacture of many items moved overseas has been alarming, there are signs that reports of the demise of U.S. manufacturing may be premature. Although non-U.S. competitors are gaining, the United States still leads the world in high-tech manufacturing—for example, aircraft, spacecraft, communication products, computers, pharmaceuticals, semiconductors and technical instruments—and U.S. manufacturing job growth is currently the highest it has been in decades.

Traditionally, manufacturing refers to making or producing something on a large scale. During the past few decades, manufacturing has evolved from the basic concept of simply "making things" into a complex *value chain* of global ecosystems that covers the entire life cycle of a product, from research and

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[1] See http://www.manufacturing.gov/advanced_manufacturing.html, accessed September 12, 2015.

[2] President's Council of Advisors on Science and Technology (PCAST), 2011, *Report to the President on Ensuring American Leadership in Advanced Manufacturing*, Washington, D.C., June, https://www.whitehouse.gov/administration/eop/ostp/pcast/docsreports.

[3] National Science and Technology Council, 2012, A National Strategic Plan for Advanced Manufacturing, Executive Office of the President, Washington, D.C.

[4] PCAST, 2014, Report to the President: Accelerating U.S. Advanced Manufacturing, Washington, D.C.

[5] Office of the Press Secretary, "President Obama Launches Competition for New Textiles-Focused Manufacturing Innovation Institute; New White House Supply Chain Innovation Initiative; and Funding to Support Small Manufacturers," Fact Sheet, release date March 18, 2015, https://www.whitehouse.gov/briefing-room/statements-and-releases.

[6] Robert E. Scott, 2015, *Manufacturing Job Loss*, Economic Policy Institute.

development and product design to manufacturing, software, applications and disposal or recycling. A great deal of new science and engineering knowledge will be necessary to realize processes that (1) facilitate manufacturing of nano-enabled products with reliable specification tolerances, (2) have an acceptable cost, and (3) are compatible with value chain requirements. As technologies and ecosystems continue to evolve, policymakers and practitioners will need to develop standards, rules, and regulations associated with manufacturing environmental, health, and safety issues.

NANOMANUFACTURING AS A PILLAR OF THE NATIONAL NANOTECHNOLOGY INITIATIVE

Development of the capability to manufacture nanoscale materials and devices, as well as their incorporation into products, is key to realizing the potential benefits of nano-enabled technology for society. National Nanotechnology Initiative (NNI) leaders recognized the importance of nanomanufacturing from the outset, holding a number of NNI-sponsored workshops in the 2002 to 2004 time frame.[7,8] The 2007 NNI report *Manufacturing at the Nanoscale* lists the following major areas as essential to expedite progress in nanomanufacturing:

- *Research for hierarchical nanomanufacturing.* Hierarchical integration will be used across dimensional scales, from atoms to molecules to the human length scale, to incorporate nanostructures into microscale architectures and macroscale products. Bottom-up, directed molecular or particulate assembly techniques will need to be combined with top-down, high-resolution, and high-speed macroscopic fabrication techniques. Various hierarchical systems architectures will create various technology platforms for nanomanufacturing.
- *Infrastructure development.* There is a need for geographically distributed nanomanufacturing research centers and user facilities with a variety of manufacturing tools to allow work on systems. These centers and shared facilities should network with existing nanoscience centers (e.g., those funded by the National Science Foundation [NSF], the Department of Energy [DOE], the National Institute of Standards and Technology [NIST], and the Department of Defense), serve as a resource for technology transfer for small and large business, and facilitate education and workforce training.
- *Modeling, simulation, and design.* Current molecular dynamics models are limited in time and space, such that prediction of realistic manufacturing processes is not feasible. New multiscale models need to be developed that can predict both yield and performance. Design tools using these multiscale models, equivalent to computer assisted design (CAD) or finite element analysis (FEA), are needed to enable rapid product development.
- *Tool development.* New metrology tools and manufacturing tools are needed to measure and manipulate nanostructures and nanocomponents, with an emphasis on in-line, real-time manufacturing rate capabilities to ensure high yield and precision.
- *Environmental and occupational health and safety.* In order to realize the benefits of nanomanufacturing, it is necessary to better understand the ramifications for workers, users, and the environment of health, safety, and environmental issues related to nanomaterials, nanomanufacturing processes, and nanotechnology-based products and their disposal. Any potential issues or problems should be addressed proactively.
- *Education and societal impact.* The new nanotechnology-based processes will likely continue the manufacturing trend of decreasing physical and increasing information-processing requirements. An appropriately educated workforce, both for making the next-generation discoveries and for

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[7] Chemical Industry Vision2020 Technology Partnership, Energetics, Inc., 2003, *Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function*, December, http://www.nanowerk.com/nanotechnology/reports/reportpdf/report17.pdf.

[8] Manufacturing at the Nanoscale, Report of the NNI Workshops 2002-2004, 2007, http://www.nano.gov/node/246.

> operating the nanomanufacturing processes, is vital to the continued economic success of the country. In addition, educating the general public about nanotechnology and nanomanufacturing is critical to achieving acceptance and realization of the promise of nanotechnology, its capabilities and risks.[9]

The 2003 *Chemical Industry R&D Roadmap for Nanomaterials by Design* report had similar recommendations to *Manufacturing at the Nanoscale*, with one additional top priority worth noting: "develop unit operations and robust scale-up and scale-down methodologies for manufacturing."

The NSET agencies initiated a number of efforts to address these recommendations, including the Nanomanufacturing Program in the NSF Engineering Directorate (established in 2002), four NSF funded Nanoscale Science and Engineering Centers (NSECs), and the NIST National Nanomanufacturing and Nanometrology Facility (see Table 3.1).

In 2006, the NNI initiated a Program Component Area (PCA) in nanomanufacturing, including all means that have the capability to reproducibly transform matter—from a bulk form and from individual atoms, molecules, and supramolecular structures—into nanoscale or nanostructured materials, devices, or systems with desired properties and performance characteristic typically in large quantities. Additionally, the PCA on nanomanufacturing included the capability to integrate such nanoscale materials and devices into systems spanning nanoscale to macroscale dimensions. The funding evolution for that PCA is shown in Table 3.2.

In 2011, the NNI complemented the Nanomanufacturing PCA with an NSI, "Sustainable Nanomanufacturing—Creating the Industries of the Future," and in 2013 dropped nanomanufacturing as a PCA separate from the NSI. The NSI is to accelerate the development of industrial-scale methods for manufacturing functional nanoscale systems. The two key thrusts of this initiative are (1) design of scalable and sustainable nanomaterials, components, devices, and processes and (2) development of nanomanufacturing measurement technologies (metrologies).

TABLE 3.1 Centers Specifically Directed Toward Nanomanufacturing

Year	Center/Facility
2003	Scalable and Integrated Nanomanufacturing, University of California, Los Angeles—now University of California, Berkeley
	Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems Center, University of Illinois at Urbana-Champaign
2004	High-Rate Nanomanufacturing, Northeastern University
2005	Hierarchical Nanomanufacturing, University of Massachusetts, Amherst
	National Nanomanufacturing and Nanometrology Facility, National Institute of Standards and Technology

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[9] National Science and Technology Council, 2007, *Manufacturing at the Nanoscale: Report of the NNI Workshops 2002-2004*, Arlington, Va., p. vii.

TABLE 3.2 NNI Agency Nanomanufacturing Investment (in $millions)

Agency	Program Component Area Year								Signature Initiative Year				
	2006	2007	2008	2009	2010	2011	2012		2013	2014	2015	2016 Est.	2017 Prop.
NSF	20.3	26.6	20.7	21.9	21.4	44.8	44.4		22.7	30.7	34.1	26.4	28.4
NIST	6.9	12.4	10.8	10.6	27.2	14.6	9.2		3.0	5.6	6.1	5.4	4.9
DOD	3.1	7.5	7.8	25.3	26.4	24.3	42.2		3.7	2.3	0.9	0.5	0
DOE	0.5	0.5	6.8	4.9	6.5	5.0	0		0	0	0	0	0
HHS/ NIH	1.7	0.8	0.7	0.7	0.8	1.3	5.7		0	1.0	1.0	1.0	1.0
USDA/ FS	0.2	0.2	0.2	0.2	0.2	1.0	1.0		1	1.2	1.2	1.5	1.5
USDA/ NIFA	0	0.1	0.1	0.2	0.2	0	0		1.2	0.6	1.0	1.0	1.0
NASA	1.0	0	0	0	2.1	1.0	2.6		3.2	5.9	0.6	0.9	0.6
Total PCA	33.7	48.1	47.1	63.8	84.8	92	105.1						
Total NSI						*61*	*56*		34.8	47.2	44.9	36.7	37.4

NOTE: NSF, National Science Foundation; NIST, National Institute of Standards and Technology; DOD, Department of Defense; DOE, Department of Energy; HHS/NIH, Health and Human Services/National Institutes of Health; USDA/FS, U.S. Department of Agriculture—Forest Service; USDA/NIFA, United States Department of Agriculture—National Institute of Food and Agriculture; NASA, National Aeronautics and Space Administration.
SOURCE: Data from the "actual" data in the NNI Supplements to the President's Budget, available at http://www.nano.gov/node/1071, unless otherwise designated.

Resources and support from the NNI and its participating agencies are needed to assure continuing U.S. leadership in nanomanufacturing. But there are signs that those resources may not be forthcoming under the NNI. The 2014 update to the NNI strategic plan eliminated the objective under Goal 2 to "develop robust, scalable nanomanufacturing methods necessary to facilitate commercialization by doubling the share of the NNI investment in nanomanufacturing research over the next five years." A review of the annual budget reports show an apparent drop in nanomanufacturing funding from 2012 to 2013. "Apparent" because it appears the NSET funding agencies relabeled some of the efforts from manufacturing into other PCAs or signature initiatives. For instance, in the 2013 NNI supplement, DOD reports 10 Multidisciplinary University Research Initiatives (MURIs) in 2011 as supporting nanomanufacturing (see Box 3.1). MURI efforts are on the order of $1 million to $1.5 million each and last 5 years (with rare exceptions). But the reported actual DOD support for nanomanufacturing drops from $42 million in 2012 to $3.7 million in 2013, which is not enough monies to account for those 10 MURIs alone. Such changes in accounting call into question the credibility of the reported numbers as a means to assess the NNI investment in nanomanufacturing.

Finding 3.1: Budget figures in support of nanomanufacturing as reported in the NNI supplements to the President's budget have been inconsistent, and progress made toward recommendations of the 2004 *Manufacturing at the Nanoscale* report is not clear.

Recommendation 3.1: The Nanoscale Science, Engineering, and Technology Subcommittee should prepare a report that provides a self-consistent record of the NNI nanomanufacturing program, the status relative to the recommendations of the 2004 *Manufacturing at the Nanoscale* report, and the NNI plans to move forward.

BOX 3.1
Department of Defense 2011 MURIs Reported in Support of Manufacturing

- Roll-to-Roll High Speed Printing of Multi-functional Distributed Sensor Networks for Enhancing Brain-Machine Interface
- Tailoring of Atomic-scale Interphase Complexions for Mechanism-Informed Materials Designs
- Synthesis and Characterization of 3D Carbon Nanotube Solid Networks
- Nanofabrication of Tunable 3D Nanotube Architectures
- BioProgrammable One-, Two-, and Three-Dimensional Materials
- Control of Thermal and Electrical Transport in Organic and Composite Materials Through Molecular and Nanoscale Structure
- Investigation of 3-D Hybrid of Integration of CMOS/Nanoelectronic Circuits
- Integrated Hybrid Nanophotonic Circuits
- Understanding the Interaction of Peptides and Proteins with Abiotic Surfaces: Towards Water–Free Biologics
- Atomic Layers of Nitrides, Oxides, and Sulfides.

SOURCE: National Nanotechnology Initiative Supplement to the President's 2013 Budget, page 15, http://www.nano.gov/node/748; Assistant Secretary of Defense, 2011, "DoD Awards $191 Million in Research Funding", Washington, DC, http://www.acq.osd.mil/rd/news/docs/fy11_muri_pr.pdf.

BASIC RESEARCH IN SUPPORT OF VIABLE NANOMANUFACTURING

Several government agencies sponsor programs in fundamental research on nanomanufacturing methods and techniques, including research on methods for retaining nanoscale properties when scaling up for use in larger products and components. Examples include the NSF's core Sustainable Nanomanufacturing Program; the NSF nanoscale science and engineering centers, which includes the National Nanomanufacturing Network (NNN); and DARPA's Atoms to Product (A2P) Program.

Scalable Nanomanufacturing Program (NSF)

Initiated in 2002, the NSF nanomanufacturing program supports fundamental research in novel methods and techniques for batch and continuous processes and top-down (addition/subtraction) and bottom-up (directed self-assembly) processes leading to the formation of complex heterogeneous nanosystems. In 2011, this program was followed by the Scalable Nanomanufacturing Program,[10] which supports basic research in nanostructure and process design principles, integration across length-scales, and system-level integration. The program leverages advances in the understanding of nano-scale phenomena and processes (physical, chemical, electrical, thermal, mechanical, and biological), nanomaterials discovery, novel nanostructured architectures, and new nanodevice and nanosystem concepts. It seeks to address quality, efficiency, scalability, reliability, safety, and affordability issues that are relevant to manufacturing. To address these issues, the program encourages research on processes and production systems based on computation; modeling and simulation; use of process metrology; sensing, monitoring, and control; and assessment of product (nanomaterial, nanostructure, nanodevice, or

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[10] National Science Foundation, "Scalable Nanomanufacturing (SNM) Program Solicitation, https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf16513 Accessed on September 1, 2016.

nanosystem) quality and performance. The program also supports education of the next generation of researchers and encourages building a workforce trained in nanomanufacturing systems. It is also interested in understanding long-term environmental, health, and safety (EHS) implications of large-scale production and use of nanoscale materials, devices, and systems.

Nanoscale Science and Engineering Centers/National Nanomanufacturing Network

Nanomanufacturing collaborations have been the focus of the NNN. The NNN was started in 2006 when NSF funded the Center for Hierarchical Manufacturing (CHM). The four NSECs (see Table 3.1) became the core NNN, which today includes the DOE Center for Integrated Nanotechnologies at Sandia National Laboratory and the NIST Center for Nanoscale Science and Technology.

According to the NSF nanomanufacturing program director, the work funded through the NNN NSECs is one step closer (up to technology readiness level [TRL] 3) to commercialization than basic science (TRL1-2).[11] For example, the NNN led the effort to create the International Organization for Standardization (ISO) Technical Committee 229 Nanomanufacturing Terminology Standard, a project involving participants from 31 countries. This document, OSI/TS 80004-8[12], lists 156 terms and definitions focusing on various types of nanomanufacturing processes. Standard terminology is key to any industry, and having this new ISO standard enables everyone to speak the same nanomanufacturing language. Processing tools were developed, such as the cluster tool for directed assembly and transfer developed at the Center for High-Rate Nanomanufacturing. The CHM provides tool sets that its partners can use to demonstrate process feasibility and scalability.[13] The NNN also sponsored a series of workshops on nanoinformatics, an enabling technology for process control, streamlined product and manufacturing design, and experimental design and analysis.

NNN research results, along with other nanomanufacturing related information, have been curated on the website InterNano.org. The database of processes for materials, devices, and structures is particularly informative. However, the future of InterNano.org and access to the information it contains is uncertain because funding for the last NSEC of the NNN is scheduled to end in 2016.

Atoms to Product Program (DARPA)

In late 2015 the DARPA Defense Science Office launched its A2P program, with the goal of developing technologies and processes to assemble nanometer-scale pieces—whose dimensions are near the size of atoms—into systems, components, or materials that are at least millimeter-scale in size. At the heart of that goal was a frustrating reality: Many common materials, when fabricated at nanometer-scale, exhibit unique and attractive “atomic-scale” behaviors—including quantized current-voltage behavior, dramatically lower melting points, and significantly higher specific heats—but they tend to lose these potentially beneficial traits when they are manufactured at larger “product-scale” dimensions, typically on the order of a few centimeters, for integration into devices and systems. This effort directly addresses one

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[11] K. Cooper, NSF Nanomanufacturing Program Activities, presentation to the committee September 9, 2015.

[12] International Organization for Standardization, 2013, Nanotechnologies: Vocabulary: Part 8: Nanomanufacturing Processes.

[13] M. Tuominen, The National Nanomanufacturing Network presentation to the committee September 9, 2015; NSF Center for Hierarchiacal Manufacturing, http://chm.pse.umass.edu/, accessed September 18, 2015.

of the high-priority recommendations of the *Chemical Industry R&D Roadmap for Nanomaterials by Design* report.[14]

> **Finding 3.2:** Basic research programs focused on nanomanufacturing have been a strength of the NNI. NSF centers focused on nanomanufacturing have more adequate budgets for facilities and education than do single investigators who have smaller awards. Ending support for nanomanufacturing centers will lead to a decrease in coordinated education and facility efforts.
>
> **Recommendation 3.2: The National Science Foundation should find ways to continue some nanomanufacturing center-scale efforts. Such centers might be explicitly tasked to pursue early-stage research in support of advanced manufacturing programs, such as the Manufacturing Innovation Institutes.**

APPLIED RESEARCH AND DEVELOPMENT IN SUPPORT OF NANOMANUFACTURING

Applied research and development is by definition aimed at creating new systems to address a targeted need. Such efforts generally are agnostic as to the technical solution, nanotechnology, or otherwise. However, nanotechnology can be part of the solution to many system-level challenges. Therefore, more applied federal programs can benefit from focused investment by the NNI. There are several examples of such programs. The semiconductor industry is actively partnering with federal agencies to fund research that will lead to future nano-enabled information technologies.[15] DOD and NASA are invested in the manufacturing of nanostructures for structural materials and coatings; the U.S. Department of Agriculture Forest Service is investing in the manufacture of innovative nanocellulose products; and DOE is pursuing the manufacture of nanostructures for renewable energy conversion and storage. The National Institutes of Health is investing in biologic nanoparticles and nanoparticle-based drugs to fight cancer and other diseases.

To regain manufacturing momentum and grow jobs for the United States, in 2012 the U.S. government initiated a national manufacturing initiative and established a National Advanced Manufacturing National Program Office at NIST. Two key components of the initiative are (1) fostering public/private partnership supported Manufacturing Innovation Institutes (MIIs) and (2) the creation of the NIST Advanced Manufacturing Consortia Program (AMTech). The MIIs are an example where "pull" from a higher TRL program can provide focus for the NNI. Each MII has a unique focus (see Box 3.2), with a common goal to create, showcase, and deploy new capabilities and new manufacturing processes. The institutes seek to bridge the funding gap (manufacturing readiness level [MRL] 4 to 7) for applied research and development. These institutes are coordinated by the Advanced Manufacturing National Program Office located at NIST and serve as a point of private-public collaboration for suppliers, schools, colleges, and other organizations to develop and scale particular manufacturing technologies and processes.

The creation of an MII focused solely on nanomanufacturing was considered but not pursued; however, nearly all of the existing MIIs will benefit from—or even depend on—nanotechnology or nanomanufacturing advances. NNI sponsored research is a source of TRL 1-3 concepts for these institutes.

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[14] Chemical Industry Vision 2020 Technology Partnership, 2003, *Chemical Industry R&D Roadmap for Nanomaterials By Design: From Fundamentals to Function*, http://www.nanowerk.com/nanotechnology/reports/reportpdf/report17.pdf.

[15] See the Nanoelectronics Research Initiative and STARnet research programs which are collaborations with federal agencies and the Semiconductor Research Corporation.

BOX 3.2
Manufacturing Innovation Institutes

Nine institutes for manufacturing innovation have been created, to accelerate U.S. advanced manufacturing thru shared contributions of public, private, and academic partners and bridge the gap between research and commercialization. These Manufacturing Innovation Institutes (MMIs) and areas of focus include the following:

- America Makes - 3D Printing
- Digital Manufacturing and Design Innovation Institute
- LIFT: Lightweight Innovations for Tomorrow – metals
- AIM: Photonics – end-to-end integrated photonics
- PowerAmerica - wide bandgap semiconductors
- Institute of Advanced Composites Manufacturing Innovation
- NEXTFLEX – Flexible Hybrid Electronics Manufacturing Institute
- Revolutionary Fibers and Textiles
- Smart Manufacturing: Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Additional institutes are pending. The Department of Energy is to sponsor two new institutes, one on reducing embodied energy and decreasing emissions, and one on modular chemical process intensification. The Department of Defense is to sponsor two new institutes, one on advanced tissue biofabrication manufacturing and one on robotics in manufacturing environments. The National Institute of Standards and Technology is to sponsor two additional MIIs without topic constraint imposed by the sponsor.

SOURCE: http://manufacturing.gov.

Advanced Manufacturing Technology Program

AMTech, launched in 2013, aims to establish new, or strengthen existing, industry-driven consortia that address high-priority research challenges impeding the growth of advanced manufacturing in the United States. The AMTech program funds broad participation across the value chain including companies of all sizes, universities, and government agencies. After two rounds of funding, there are 35 planning awards, totaling ~$17 million, to identify critical gaps in advanced manufacturing technology infrastructure and create industry-driven technology roadmaps for addressing those gaps. Each award supports an industry-driven consortium to develop research plans and chart collaborative actions to solve high-priority technology challenges and to accelerate the growth of advanced manufacturing in the United States. As with the MIIs, many of the AMTech-funded projects address topics in which nano-enabled technology will be beneficial, if not critical.

The relationship between NNI-funded basic research and the more applied research and development programs described above is illustrated in Figure 3.1. As discussed in Chapter 2, the push of new ideas as well as the pull of product-based needs both contribute to innovation. Connections between the NNI and advanced manufacturing programs such as the MII program and AMTech can accelerate progress toward the goals of those programs.

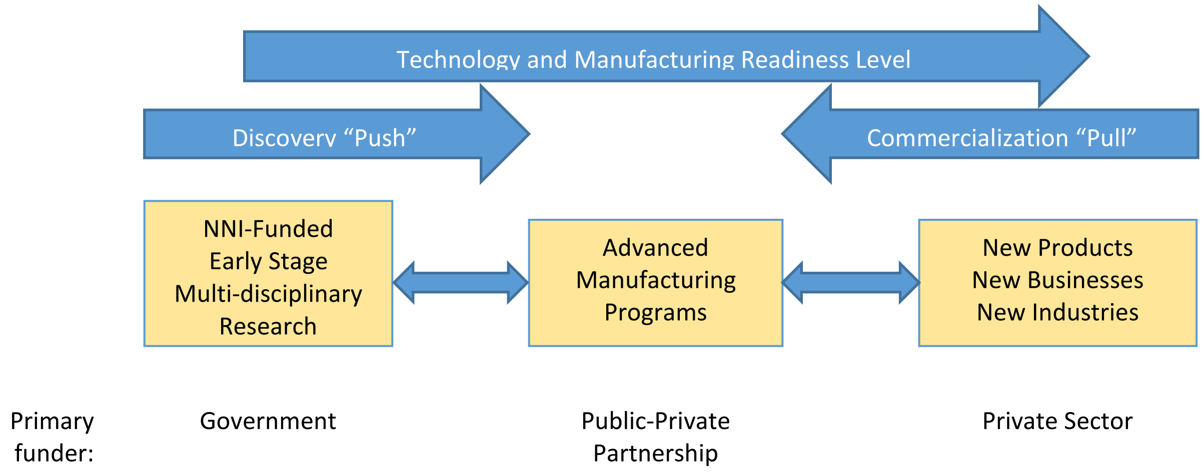

FIGURE 3.1 Relationships between stages of manufacturing research and development.

Finding 3.3: In many cases, progress or success in the MIIs and in implementation of the roadmaps developed under the AMTech program will require advances in nanomanufacturing.

Recommendation 3.3a: NNI-participating agencies should explicitly support the early-stage (technology readiness level 1-3) nanomanufacturing research needed to enable the roadmaps and goals of current advanced manufacturing programs, in particular the existing Manufacturing Innovation Institutes.

Recommendation 3.3b: The Nanoscale Science, Engineering and Technology Subcommittee should form a nanomanufacturing working group to identify nanoscale research needs of advanced manufacturing, coordinate efforts between the NNI and the federal programs focused on advanced manufacture, and foster greater investment by those programs in nano-enabled technologies.

The roles of the nanomanufacturing working group could include the following.

- Engage with the NSTC Subcommittee on Advanced Manufacturing to inform the subcommittee about implications of nanotechnology in various areas of manufacturing.
- Work with the MII and AMTech consortia to understand their TRL 4-7 roadmaps and identify and support relevant underlying TRL 1-3 nanoscale research needs.
- Work with the various mission agency leaders and managers responsible for the applied research and advanced development programs to identify opportunities for, and encourage investments in, nanotechnology-enabled technology solutions.
- Identify and report as part of the NNI annual report activities underway within the NNI-participating agencies in support of MIIs.

Other existing federal programs that target manufacturing could be—and in some cases are being—used to advance nanomanufacturing technology. As noted in Chapter 2, several agencies have called for Small Business Innovation Research/Small Business Technology Transfer proposals related to nanotechnology. More specific to nanomanufacturing, the DOD Defense Production Act Title III, a DOD-wide program under the Deputy Assistant Secretary of Defense, Manufacturing and Industrial Base Policy, has been used to initiate several nanomanufacturing facilities (see Table 3.3 and Box 3.3).

TABLE 3.3 Defense Production Act Title III Projects

Facility	Year	Company	Government Funds ($million)	Company Cost Share ($million)
Advanced Carbon Nanotube Volume Production	2011	Nanocomp Technologies	22	9.2
Conductive Composites (Nickel-based nanomaterials)	2011	Conductive Composites	10.2	2.8
Atomic Layer Deposition (ALD) Hermetic Coatings	2007	Raytheon RF Component	5.4	0.5
Hybrid Plastics and POSS Nanotechnology	2005	Hybrid Plastics	21.2	2.2

NOTE: Last column is the company contribution.
SOURCE: http://www.dpatitle3.com/dpa_db/index.php.

BOX 3.3
Nanocomp Technologies

Since 2011, Nanocomp Technologies, Inc., has been awarded approximately $22 million under the Defense Production Act Title III program, supplemented by approximately $9 million in contractor cost share, to supply carbon nanotube yarn, sheet, tape and slurry materials for the Department of Defense (DOD) as well as commercial industrial markets.

The Defense Production Act Title III program creates assured and affordable production of products that are essential for national defense, and where U.S. industry has not demonstrated an ability to deliver due to market conditions or other fiscal barriers.

Previous DOD grants helped the company build a 30,000-square-foot pilot plant and relocate its headquarters to Merrimack, New Hampshire. Government funding is helping to support expansion of commercial facilities and applications.

Nanocomp was one of the first ventures to commercialize carbon nanomaterials. The company was formed in 2004 as a spinout, with initial funding from its founders and contracts from the Office of Naval Research, the U.S. Army, and later a Small Business Innovation Research grant from the U.S. Air Force.

Nanocomp was the first (and currently only) commercial producer of sheets, tapes, and yarns made with high concentrations of carbon nanotube fibers. In addition to military and commercial applications, Nanocomp's carbon nanotube sheets have been used to insulate spacecraft (Juno mission to Jupiter).

This is a good example of how government support is helping to fund U.S. nanomanufacturing.

Other programs that could support nanomanufacturing research and development are the DOD MANTECH programs,[16] the Defense-wide Manufacturing Science and Technology Program, the Air Force Research Laboratory Manufacturing and Industrial Technologies program, the DOE Office of Energy Efficiency and Renewable Energy Advanced Manufacturing Program, the DOE Technology Commercialization Fund,[17] the Oak Ridge National Laboratory Manufacturing Demonstration Facility,[18] and the NASA Space Technology Mission Directorate.

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[16] DOD, ManTech, https://www.dodmantech.com/.

[17] DOE, Technology Commercialization Fund, http://energy.gov/technologytransitions/technology-commercialization-fund.

[18] Oak Ridge National Laboratory, Manufacturing Demonstration Facility, http://web.ornl.gov/sci/manufacturing/mdf/.

NANOMEDICINE MANUFACTURING: AN EMERGING OPPORTUNITY

Many biological structures and processes are inherently nanoscale, and nanotechnology research related to medicine and health applications is starting to bear fruit. For example, some drugs, including cancer-fighting drugs such as Docetaxel, are more soluble and move through cell walls and membranes to disease sites more easily if they are nanoscale.[19] Nanomedical breakthroughs include increasing success in gene therapy and development of new antiviral vaccines (hepatitis C, pneumonia). Most of these novel disease-fighting solutions are still in early stages; in 2015, there were more than 250 nanomedicine projects in clinical trials.[20]

At the same time, three relatively new federal initiatives address biologically inspired challenges—the BRAIN Initiative, Precision Medicine, and the “moonshot” program to find a cure for cancer announced in the 2016 State of the Union address. Tools and techniques for nanoscale synthesis and characterization will be important for research under these initiatives and nanotechnology-based diagnostic and therapeutic products are likely outputs.

The 2014 PCAST assessment of the NNI includes an appendix on “Manufacturing Nanomedicine” that states the following:

> A significant emphasis must be placed early in the commercialization pathway on refining or replacing laboratory fabrication procedures with reliable, consistent, and economically viable manufacturing methods that can be scaled up for clinical development and, ultimately, to reliably generate commercial drug supply.
>
> Start-ups frequently must focus considerable time and capital on developing these methods. The need to scale up is likely to occur early on the product development timeline since animal testing in the relevant disease models and understanding of how these nanotherapies are distributed in the body are required for making the decision to proceed toward clinical development.
>
> Another important consideration in manufacturing nanomedicines is the need to conduct preclinical toxicity studies and any subsequent clinical trials using drug supply generated under Good Manufacturing Practice (GMP) conditions in an approved facility. Thus this investment must be made prior to knowing whether the nanomedicine will be effective in humans for its intended indication. Depending on the novelty and complexity of the manufacturing process, there may be few options to source the manufacturing to outside parties. In the absence of established nanomanufacturing facilities in which to explore methods, for preclinical studies, complete method validation, or deploy a GMP-based manufacturing scale-up protocol, the start-up has no alternative but do this internally.
>
> Clearly, access to manufacturing facilities for scaling up nanomedicines in the amounts necessary for animal testing and preclinical development would accelerate the transition of these novel therapies to proof-of-concept human testing in clinical development.

With more than 250 nanomedicines in clinical trials, now is the time to expand the study of nanomedicine manufacturing. Although many scale up and manufacturing hurdles for a new nanomedicine are similar to those of any new therapeutic, manufacturing nanomedicines poses special issues. Perhaps the most prevalent is the need for nanoscale characterization at all stages of discovery, development, and commercialization. In addition, nanomaterials that meet medical-grade requirements for purity and reproducibility can be difficult to obtain. It is not uncommon for expensive nanomedicines, produced under FDA current good manufacturing practices (cGMPs), to not meet specifications or give poor efficacy reproducibility. Safety extends not only to dosage and clinical results, but also to manufacturing and the need to avoid contamination and toxicological factors.

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[19] J.S. Murday, R.W. Siegel, J. Stein, and J.F. Wright, 2009, Translational Nanomedicine: Status Assessment and Opportunities, *Nanomedicine: Nanotechnology, Biology, and Medicine* 5:251-273.

[20] M. Tomczyk, 2015, Nanoinnovation: What Every Manager Needs to Know, Wiley.

The United States currently leads the world in nanomedicine. In 2012, the United States accounted for 53 percent of nanomedicine patent applications, followed by Europe (25 percent) and Asia (12 percent). Drug delivery represented the largest segment in nanomedicine, accounting for 76 percent of publications and 59 percent of nanomedicine patents. The second-largest segment was in vitro diagnostics (11 percent of publications and 14 percent of patent filings).[21] In addition to the obvious health benefits, nanomedicine is a sizable "industry" that is projected to grow to over $130 billion in 2016, compared to $63.8 billion in 2010.

To retain U.S. leadership in nanomedicine, a sustainable medical nanomanufacturing infrastructure is needed to move innovative medical research, including in cell and gene therapies, into commercial use. For instance, there are few contract manufacturing organizations with capabilities for cGMP manufacturing of nanomedicines, quality assurance/quality control (QA/QC) testing protocols are inadequate, and there are few services with the ability to incorporate small molecule drugs in FDA-approved, bio-compatible nanoparticle-based formulations.

Within the NNI, NCI supports the Alliance for Nanotechnology in Cancer, designed in part to expedite movement of discoveries of cures and treatments from laboratory bench to patient bed (see Box 3.4). A component of the alliance that is especially vital to the translation of research toward application is the Nanotechnology Characterization Laboratory (NCL). By developing and performing a standard set of appropriate tests for nanomaterials proposed for cancer diagnosis or treatment, NCL has greatly expedited the development, trial, and regulatory review process. As highlighted by NCL Director Scott McNeil in his presentation to the committee,[22] the obvious strengths of NCL notwithstanding, there is a serious "opportunity gap" with respect to the ability of developers to move beyond sub-gram quantities of material that are readily produced in an individual laboratory, to the kilogram quantities required for preclinical safety assessments and Phase I clinical trials. Any advantage held by the United States is being challenged, for example, by the European Union's Framework for Research and Innovation Programme, known as "Horizon 2020," which clearly articulates a set of goals that addresses the challenge of scale-up for the generation of nanomedicines.[23]

The updated NIH/NCI Nanotechnology Cancer Plan released in 2015 includes a section on Commercialization of Nano-Products for Cancer and Manufacturing Challenges of Nano-Products.[24] The plan focuses only on the manufacture of nanoparticles, not nanoscale devices or other medical applications of nanotechnology. It notes that "perhaps the most frequent shortcoming manufacturers encounter in the advancement of therapeutic nanoparticles is a lack of thorough characterization of the product and the identification, to the extent possible, of the critical quality attributes. This requires, among other things, an early emphasis on the appropriate analytical methods, which is something that is frequently neglected." While the plan does a good job of outlining the challenges related to manufacturing nanoparticles for medical use, the alliance (and NIH in general) is not set up to support manufacturing research.

In addition to the Alliance for Nanotechnology in Cancer, the Translation of Nanotechnology In Cancer (TONIC) Consortium was established in 2011 to bring together Alliance-funded research centers, pharmaceutical and biotechnology companies, and patient advocacy groups to promote collaboration between academia and industry and share knowledge about best practices in translating nanotechnology from the laboratory to the marketplace. The consortium has formed a working group on nanodrugs to develop clinical protocols for testing nanoparticle drugs in patients, while in the process addressing limitations and gaps specific to nanoparticle therapeutics.

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[21] Morigi et al., 2012, Nanotechnology in Medicine: From inception to market domination, *Journal of Drug Delivery*.

[22] Scott McNeil, NCL Director, "Critical Infrastructure Gap in Nanomedicine: Scale Up & cGMP Manufacturing," presentation to the committee on July 29, 2015.

[23] See http://ec.europa.eu/programmes/horizon2020/, accessed August 19, 2016.

[24] See http://nano.cancer.gov/about/plan/, accessed August 19, 2016.

BOX 3.4

Advancing Nanomedicine for Cancer Treatment

The National Cancer Institute (NCI) is the home of the Alliance for Nanotechnology in Cancer. The goals of the alliance are to (1) rapidly advance new nanotechnology discoveries into cancer-relevant applications in clinical practice, (2) aid nanoparticle characterization and standardization of characterization methods to enable technology transfer from university laboratories to companies that bring these technologies to patients, and (3) develop the next generation of cancer researchers in the area of nanotechnology.

To accelerate the transition of basic nano-biotech research into clinical applications, NCI established the Nanotechnology Characterization Laboratory (NCL). NCL is a collaboration of the NCI, the National Institute of Standards and Technology, and the Food and Drug Administration.

NCL is working to provide an “analytical cascade for nanomaterial characterization.” NCL facilitates clinical development and regulatory review of nanomaterials for cancer clinical trials; identifies and characterizes critical parameters related to nanomaterial absorption, distribution, metabolism, and excretion and toxicity profiles; and examines multicomponent/ combinatorial aspects.

NCL also facilitates academic and industrial-based knowledge sharing of nanomaterial performance data and behavior resulting from pre-clinical testing.

SOURCE: nano.cancer.gov.

Another program that is related to manufacturing for nanomedicine and nanohealth is the Nano-Bio Manufacturing Consortium (NBMC) funded by the Air Force Research Laboratory. The mission of NBMC is to mature an integrated suite of nano-bio manufacturing technologies and transition it to industry. The program envisions the convergence of nanotechnology, biotechnology, advanced (additive) manufacturing, and flexible electronics enabling real-time, remote physiological and health/medical monitoring. Early research is focused on developing a technology platform for human performance monitors for military and civilian personnel in high stress situations such as pilots, special operations personnel, firefighters, and trauma care providers.

> **Finding 3.4:** Nanomedicine manufacturing is an essential step in realizing the benefits of the considerable investment in nanomedicine research under the NNI. Nanomedicine manufacturing poses a number of specific challenges that are not being met by other NNI manufacturing efforts. Two reports—the NIH NCI *Cancer Nanotechnology Plan 2015* and the PCAST *Report to the President and Congress on the Fifth Assessment of The National Nanotechnology Initiative* (Appendix II, Manufacturing Nanomedicine)—provide a sound basis for NNI focus on this topic.
>
> **Recommendation 3.4: The National Institutes of Health should lead the development of a roadmap, in collaboration with the nanomedicine industry, to identify technical barriers to scaling up the manufacture of nanomedicines, as well as areas in which research is needed to overcome those barriers.**

4

Physical Infrastructure for Nanotechnology

One of the key areas in which the National Nanotechnology Initiative (NNI) has provided, and should continue to provide, value is through *creating and maintaining publically accessible infrastructure for nanoscale science, engineering and technology research and development.* This infrastructure (see Figure 4.1) comprises both physical and computational tools: characterization and fabrication facilities and online simulation and education resources. The existence and quality of these infrastructure resources are key factors in reducing barriers to research discovery and technological innovation, and in developing and retaining the U.S. science, technology, engineering, and mathematics talent pool. This chapter addresses the first element of part B of the committee's statement of task relating to the physical infrastructure required for nanotechnology research, development, and commercialization.

Over the 15-year history of the NNI, the strongest agency participation in nanotechnology infrastructure development has come from the Department of Energy (DOE), National Institute of Standards and Technology (NIST), and the National Science Foundation (NSF), each of which have established and maintained extensive user facilities. In addition, the Nanotechnology Characterization Laboratory (NCL) was founded jointly by the National Cancer Institute (NCI), NIST and the Food and Drug Administration (FDA), to address the growing need for development and testing of nanomaterials for cancer diagnosis and treatment. Other NNI partner agencies, including the Department of Defense, maintain nanotechnology facilities for internal agency use in nanoscience research and development. Descriptions of the available nanotechnology centers, both user and other facilities, is described below.[1]

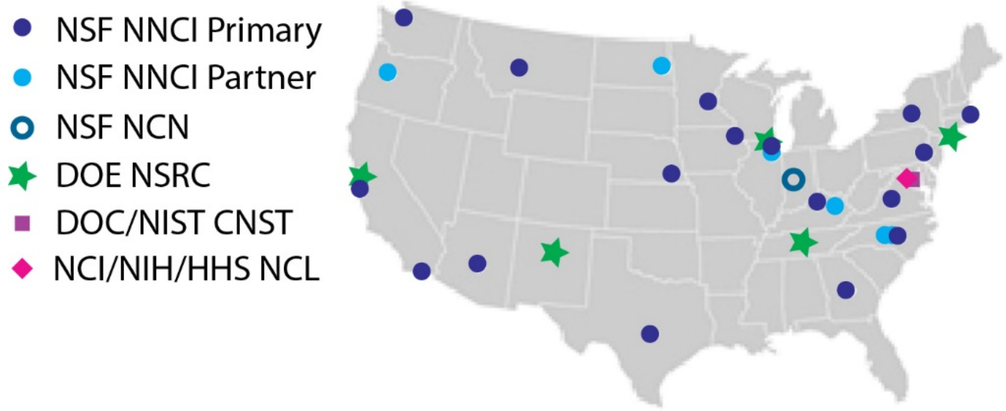

FIGURE 4.1 Locations of major nanoscience and technology user facilities operated by NNI participants as of September 2015. NOTE: CNST, Center for Nanoscale Science and Technology; DOC, Department of Commerce; DOE, Department of Energy; HHS, Department of Health and Human Services; NCI, National Cancer Institute; NCL, Nanotechnology Characterization Laboratory; NCN, Network for Computational Nanotechnology; NIH, National Institutes of Health; NIST, National Institute of Standards and Technology; NSF, National Science Foundation; NSRC, Nanoscale Science Research Center. SOURCE: Data from http://www.nano.gov/centers-networks.

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[1] More detail can be found at http://www.nano.gov/centers-networks.

NANOSCIENCE USER FACILITIES

The network of nanoscience user facilities is geographically broad (see Figure 4.1) and sizable in scope (see Figure 4.2), with more than 11,000 researchers served at the NSF, DOE, and NIST user facilities alone. It should be noted that the rate of growth of the user base at all the facilities is limited to varying degrees by budget constraints. In 2014, more than 13,000 individual users were accommodated at the NSF, DOE, and NIST user facilities. The dip in total user numbers for 2015 is primarily due to difficulties in meeting user demand during the transition at NSF from the National Nanotechnology Infrastructure Network (NNIN) to the National Nanotechnology Coordinated Infrastructure (NNCI) program.

National Nanotechnology Infrastructure Network/
National Nanotechnology Coordinated Infrastructure (NSF)

In 2004, NSF initiated NNIN as a successor to the preceding National Nanofabrication User Network. The NNIN was an integrated partnership among 14 user facilities that provided unparalleled opportunities for nanoscience and nanotechnology research. The network provided extensive support in nanoscale fabrication, synthesis, characterization, modeling, design, computation, and hands-on training in an open environment available to all qualified users. In 2013, the NNIN trained more than 2,000 new users, serving a total base of more than 6,000 researchers[2] at 14 sites nationwide. The user population distribution has been roughly constant over time, at 82 to 85 percent academic, 15 to 17 percent industrial, and 1 to 2 percent government.

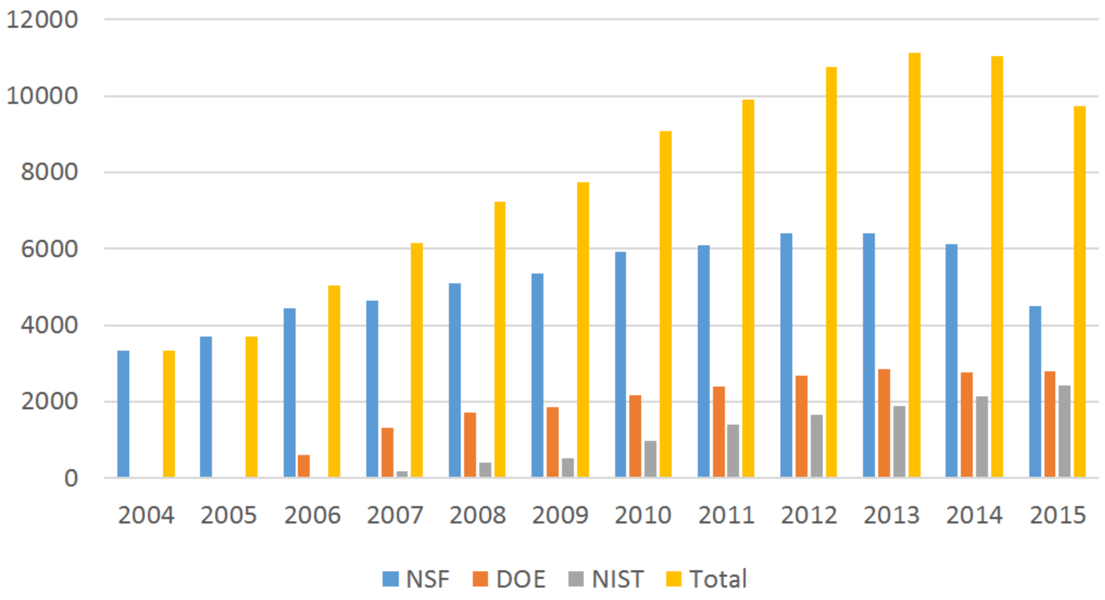

FIGURE 4.2 Usage of selected NNI facilities from 2004-2015.

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[2] Dan Ralph, Principal Investigator, and Roger Howe, Network Director, 2013, *National Nanotechnology Infrastructure Network-NNIN Annual Report Year 10 (partial)*; new users in Figure 21; total users on page 9.

In 2015, after soliciting community input via individual and workshop formats,[3] NSF replaced the NNIN program with the NNCI program. The sites (shown on Figure 4.1) were announced in September 2015. Georgia Institute of Technology was selected in 2016 as the host site for the coordination office for the NNCIs. Of the 16 primary NNCI institutions announced, 8 are entirely new sites, and 8 are located at prior NNIN primary institution sites. This mix of sites strikes a balance between continuity in operations for sites with complex and demanding architectural and environmental requirements and flexibility in establishing facilities to address emerging technological needs. The legacy NNCI sites (Stanford University, Cornell University, Georgia Institute of Technology, University of Minnesota, Twin Cities, Arizona State University, Harvard University, University of Washington, and University of Texas, Austin) all have established nanoscience and technology facilities with proven track records in user facility operation. The new NNCI centers (University of Pennsylvania, University of Kentucky, Montana State University, Northwestern University, Virginia Polytechnic Institute and State University, North Carolina State University/Duke University/University of North Carolina, Chapel Hill, and University of Nebraska, Lincoln) capitalize on recent investments at the respective host institutions. For example, the Mid-Atlantic Nanotechnology Hub for Research, Education and Innovation at the University of Pennsylvania leverages the establishment of the Krishna P. Singh Nanotechnology Center that opened in 2013.

Center for Nanoscale Science and Technology (NIST)

The Center for Nanoscale Science and Technology (CNST) supports the U.S. nanotechnology enterprise from discovery to production by providing industry, academia, NIST, and other government agencies with access to world-class nanoscale measurement and fabrication methods and technology. Since the inception of the facility in 2007, the fraction of non-government users has steadily increased, reaching 55 percent academic, 16 percent industrial, and 30 percent government in 2015. The CNST's shared-use NanoFab gives researchers economical access to and training on a commercial state-of-the-art tool set required for cutting-edge nanotechnology development. Looking beyond the current commercial state of the art, CNST's NanoLab offers opportunities for researchers to collaborate on creating and using the next generation of nanoscale measurement instruments and methods. The CNST reached more than 2,100 users in 2014, representing 464 unique institutions, including 168 private companies.[4] Because industry and academia need access to the latest generation of instrumentation as they try out new processes, procedures, and standards that might be incorporated into a manufacturing capability, NIST includes funds for instrument recapitalization in the CNST budget line.

Nanoscale Science Research Centers (DOE)

The Nanoscale Science Research Centers (NSRCs) offer a comprehensive approach to addressing nanotechnology challenges, including theory, synthesis, characterization, fabrication, and platform integration. Strategic plans for the 2015 to 2019 timeframe for these facilities are posted on the individual center webpages. Each center has identified science focus areas that include growth, processing, characterization, and theory and computation. The five DOE NSRC sites are all located within larger DOE laboratories: the Molecular Foundry at the Lawrence Berkeley National Laboratory; the Center for Integrated Nanotechnologies at Sandia and Los Alamos; the Center for Nanoscale Materials at Argonne National Laboratory; the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory;

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[3] NSF Dear Colleague Letter, DCL 14-068, Report on Workshop for a Future Nanotechnology Infrastructure Support Program, August 18-19, 2014, Arlington, Va., https://www.src.org/newsroom/src-in-the-news/2014/656/.

[4] From report presented to committee by CNST Director Robert Cellotta.

and the Center for Functional Nanomaterials at Brookhaven National Laboratory. These DOE laboratories are home to major user facilities, such as X-ray and neutron sources. The combination of NSRC instrumentation, staff scientist expertise, and world-class light and neutron facilities comprise a unique asset for the nanoscience research community. Recently, DOE merged the electron beam microscopy centers with the NSRCs to further consolidate nanoscale characterization capabilities.

The annual user base served by the five DOE NSRCs exceeds 2,000, with nearly 2,800 in combined electron beam center and nanomaterial center users in 2014[5] from the United States and 45 countries worldwide.[6] In addition to access to the physical infrastructure, these user facilities provide online and in-person training for use of the available experimental tools. The combined annual user population of the NSRCs is on par with that of individual light source user facilities and represents approximately one-fifth of the 14,000 of total users at the DOE Office of Science facilities. The distribution of NSRC users in 2014 was approximately 60 percent academic, 5 percent industrial, and 35 percent government.

Network for Computational Nanotechnology (NSF)

The Network for Computational Nanotechnology (NCN), established in 2002 by NSF as part of the NNI, focuses on the delivery of education, training, and research support through a web-based platform entitled nanoHUB.org. Through web access—even using smartphones, tablets, and other devices—more than 13,000 annual users run simulation tools that appear to be like smartphone apps but are powered by a powerful cloud-based computational infrastructure. These simulation tools are typically outcomes—from a computational Ph.D. thesis or from community codes—that have been adapted for delivery via a user friendly graphical interface. The interface allows these tools to be operated by experimentalists or to be adopted in formal classroom training and education. The median adoption time of these research tools into the classroom is less than 6 months.

NanoHUB user behavior analysis (see Figure 4.3) reveals that more than 24,600 students in more than 1,268 courses at 185 institutions globally have utilized simulation tools on nanoHUB in formal classroom settings over the past 10 years. About 50 percent of the simulation users reside in the United States.

Lectures, tutorials, and research seminars hosted by nanoHUB attract more than 300,000 users annually. More than 4,000 resources are hosted on nanoHUB, including over 100 complete courses in various aspects of nanotechnology. These lectures, and even complete courses, are utilized globally and integrated into new and modified curricula.

Nanotechnology Characterization Laboratory (NIH/NCI)

While not a user-facility per se, the NCL is yet another example of physical facilities that are contribute significantly to progress in nanotechnology—in this case, nanomedicine. NCI's investment in the NCL in Frederick, Maryland, has resulted in standardization of characterization protocols, the reformulation of a number of useful active pharmaceutical ingredients (APIs), and the creation of sensors, contrast agents, devices, and hybrid medical products for the treatment of cancer and other diseases.[7,8] The development of a large number of these new pharmaceutical entities was made possible and

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[5] NSRC annual report.

[6] See https://nsrcportal.sandia.gov/Home/Communities#map.

[7] V. Wagner, A. Dullaart, A.-K. Bock, and A. Zweck, 2006, The emerging nanomedicine landscape, *Nature Biotechnology* 24:1211-1217.

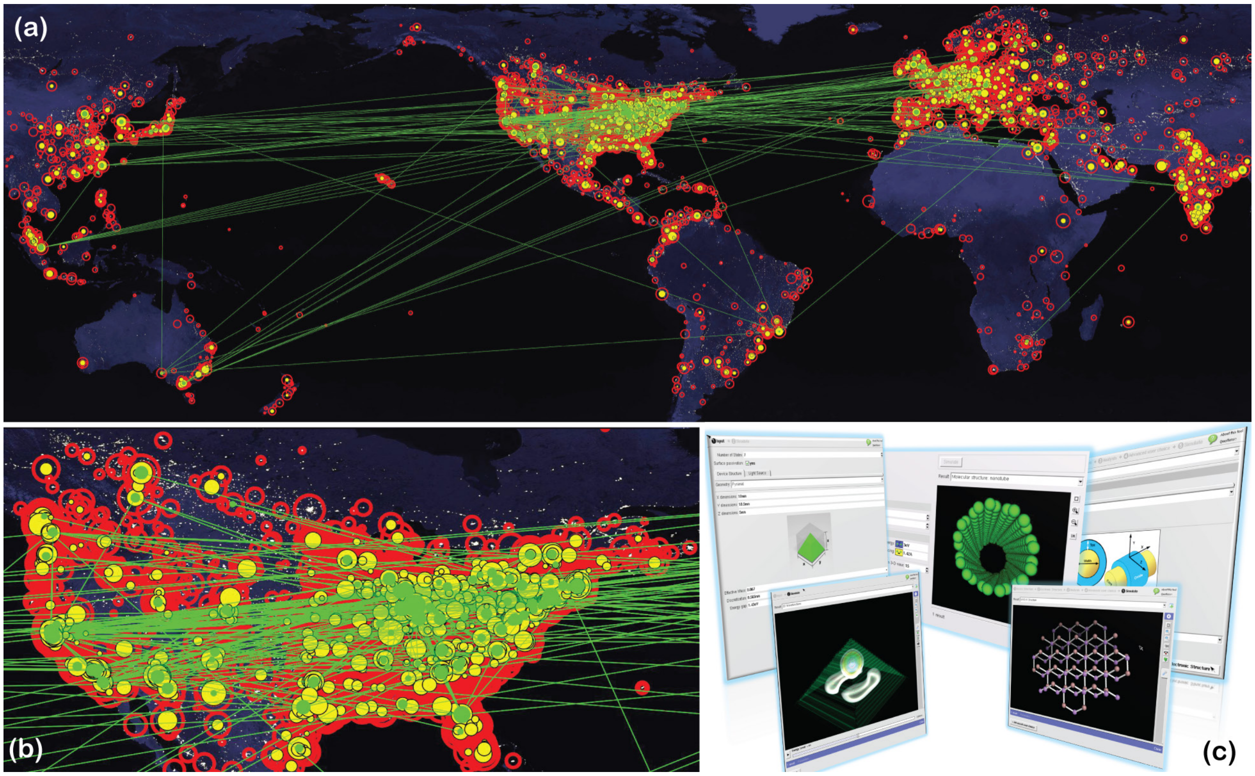

FIGURE 4.3 (a) nanoHUB user map in the year 2011 superposed on NASA's world at night. Red circles designate users viewing lectures, tutorials, or homework assignments. Yellow dots are users of simulation. Green dots indicate authors of more than 720 scientific publications citing nanoHUB. Dot size corresponds to the number of users, and lines show author-to-author connections proving intense research collaboration networks. (b) United States, enlarged. (c) A collage of typical nanoHUB interactive tool sessions and three-dimensional-rendered interactively explorable results (quantum dots, carbon nanotubes, nanowires). SOURCE: Courtesy of Nathan Denny, Daniel Mejia, Hanjun Xian, Swaroop Samek, Krishna Madhavan, Lynn Zentner, and Gerhard Klimeck; Network for Computational Nanotechnology, Purdue University.

supported by the human and physical infrastructure provided by the NCL. This somewhat unique arrangement has arguably become a major catalyst in the submission to the FDA of standardized information on nanomedicines and devices on which the FDA may make evidence-based regulatory decisions throughout the life cycle of a product (e.g., preclinical–Phase IV).

> **Finding 4.1:** The NNI agencies fund a substantial set of facilities that support experimental, computational, and educational activities and users from academia, industry, and government. While information about each facility or center is available on the NNI website, there is little evidence of coordination among the agencies to facilitate access and use by the community at large.

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[8] N.K. Mehra, K. Jain, and N.K. Jain, 2015, Design of multifunctional nanocarriers for delivery of anti-cancer therapy, *Current Pharmaceutical Design.* [Epub ahead of print]

Recommendation 4.1: User facilities should strive to better serve the collective nanoscience research community by (1) sharing—perhaps via a central web-based portal— training materials and simulation and computational tools developed at the individual user facilities and (2) creating a common proposal form and process that facilitate users moving between facilities to access the more expensive or specialized instrumentation.

LEADING-EDGE CAPABILITIES AT RISK

In recognition that infrastructure needs to evolve over time, NNI agencies have arranged the funding and management of facilities and sites to consolidate functions, eliminate duplication, and achieve cost efficiencies. For instance, in 2013 DOE moved to incorporate the electron microscopy user facilities with the nanomaterials user facilities, which were previously managed separately. The DOE-led TEAM project,[9] and other DOE-funded developments in electron microscopy[10] enabled revolutionary advances in electron beam-based materials characterization through the development of aberration-correction technology, low-voltage operation, and new detector designs. The integration of these facilities, fully realized in 2015, brings leading-edge nanoscale characterization tools together. The merger has the potential for positive impact on the nanomaterials user community. Specifically, it enables researchers to submit a single comprehensive research proposal for fabrication and characterization, rather than individual proposals, to separate evaluation boards, thus lowering the burden to researchers and laboratory staff, as well as accelerating the pace of innovation.

A major challenge for the DOE NSRCs going forward is how to maintain the leading-edge level of service to the user community provided during the initial NNI 10-year period, as the present instrumentation approaches obsolescence. As NNI moves forward, funding for development of new instrumentation to fully realize three-dimensional atom-by-atom materials design, or other opportunities identified in the *Future of Electron Scattering and Diffraction Workshop* report,[11] has not yet been identified. Nor is there a plan for recapitalizing the commercially acquired instruments, which become outdated over time.

NSRC operating budgets have remained roughly constant since 2010, with infrastructure funding for fabrication, characterization, and computational tools and upgrades limited to the discretionary funding within the individual center budgets. The relative size of the operating budgets compared to the cost of the core instruments (individual major tools are more than $2 million, or 10 percent of each center budget, and new nanoscience instrument development projects are of order approximately $5 million; 25 percent of a center operating budget) makes major upgrades prohibitively expensive without additional sources of funds.

The challenges imposed by budget constraints are illustrated in the 2015-2019 Strategic Plan for the Center for Functional Nanomaterials, Resource Section:

> The operation of the CFN is primarily funded by a DOE's Office of Science block grant, currently at approximately $20M annually. In the past, this level of funding has covered the operations of the CFN and allowed for very modest investments in new equipment. The full implementation of the Strategic Plan will require a sustained budget increase over the next five years and considerable funds for equipment recapitalization. If resources were more limited, the scope of the

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[9] P. Preuss, 2008, *Transmission Electron Aberration-corrected Microscope*; http://www2.lbl.gov/Science-Articles/Archive/MSD-NCEM-TEAM05.html.

[10] Krivanek et al., 2010, Atom-by-atom structural and chemical analysis by annular dark-field electron microscopy, *Nature* 464:571.

[11] Basic Energy Sciences Workshop on the Future of Electron Scattering and Diffraction, 2014, *Future of Electron Scattering and Diffraction*, http://science.energy.gov/~/media/bes/pdf/reports/files/Future_of_Electron_Scattering.pdf.

> Strategic Plan would be adjusted accordingly. The CFN would establish priorities based on progress among its science themes, growth of high-impact facility usage, and input from the SAC and the user community, to ensure that the CFN fulfills its core mission and continues to thrive.[12]

Similar challenges are faced at each of the centers.

Tightening budgets are not limited to DOE; with the end of the NNIN and launch of the NNCI, NSF has moved to an integration and coordination approach to maximize the value of infrastructure dollars. In the NSF NNCI planning process, the community highlighted the conflict between the desire for state-of-the-art facilities and the realities of budget constraints. With a total budget of $81 million in 2016 dollars over 5 years for 16 selected sites, the annual award budgets range from $0.5 million to $1.6 million for the individual sites.[13] In comparison the NNIN budget for its 14 sites in the period 2004-2014 was ~ $180 million.[14] The purchase of an individual tool for lithography at sub-20 nm resolution (>$1 million) or a single aberration-corrected electron microscope (>$2 million) for a given site is outside the budget scope. Thus, the planning report made strong recommendations that selection preference be given to sites with significant existing infrastructure and established user communities, geographically located for greatest local community impact, and specifically recommending against investment in aberration-corrected electron microscopes. This recommendation was based on the consensus that the level of funding available prevented NNCI from building new nanofabrication centers from the ground up. However, the NNCI funding can provide critical support to enable public access to diverse nanofabrication and characterization facilities that have been established through other funding mechanisms. Similar to the DOE centers, the NSF NNCI budgets do not have adequate monies for equipment recapitalization. NSF does have a Major Research Instrumentation program that is designed to procure instruments in the range of $0.1 million to $4 million. However, a search of the awards made by this program since 2005 show that 75 out of 580 have had a nanoscience or engineering focus, with only one granted to a NNIN center.

Additional measures recommended in the NNCI planning workshop report[15] in order to achieve maximum impact per grant dollar include the use of computation and simulations to model and predict processes, and close integration with the national laboratories for access to the unique, or more expensive characterization tools. These recommendations are in agreement with Recommendation 4.1 of this report. However, while the coordination with DOE user facilities can no doubt help cut down on expensive duplication or eliminate underutilized facilities—and given the lack of clear funding for recapitalization of the equipment, such as electron lithography and microscopy tools at the DOE facilities—there is a serious risk that no agency has the sufficient resources to maintain the level of advanced instrumentation provided during the past 10 years of the NNI.

> **Finding 4.2:** There is a clear lack of identified funds for the development of new leading-edge instrumentation or recapitalization of commercial tools at NNI-sponsored user facilities, with the exception of CNST. As a result, there is a real risk of obsolescence of the physical and computation infrastructure available to the nanoscience and technology research enterprise, and a corresponding decrease in the user value.

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[12] Brookhaven National Laboratory, "Five-Year Strategic Plan," https://www.bnl.gov/cfn/strategicplan/resources.php, accessed August 22, 2016.

[13] NSF press release 15-112, September 16, 2015, http://www.nsf.gov/news/news_summ.jsp?cntn_id=136211.

[14] Information from Dr. Lawrence Goldberg, NSF.

[15] See *Workshop for a Future Nanotechnology Infrastructure Support Program*, August 18-19, 2014, Arlington, Virginia, available at https://www.src.org/newsroom/src-in-the-news/2014/656/, accessed on June 8, 2016.

Recommendation 4.2: The National Science Foundation and the Department of Energy, in concert with other NNI agencies with instrumentation programs, should identify funding mechanisms for acquiring and maintaining state-of-the-art equipment and computational resources to sustain leading-edge capabilities at their nanoscale science and engineering user facilities.

NANOMEDICINE AND NANOBIOTECHNOLOGY

There is growing recognition that investment is needed in areas of nanoscale science and technology beyond those of traditional micro- or nanoelectronics fabrication. For example, the range of science topics and technological capabilities of the new NSF-sponsored NNCI sites has expanded to include centers of expertise in two-dimensional materials, additive 3D manufacturing, hybrid hard-soft materials, nanoparticle-based photonics, environmental and geological nanoscience, and biological and medical nanotechnology. In particular, the NNCIs will provide much greater capabilities than the prior NNIN for soft, biological, and medical nanotechnologies.

As nanomaterials and nanotechnologies are increasingly developed for medical and other applications that involve contact with the body or the environment, there also will be an increasing need to establish manufacturing standards for nanomaterials and guidelines for assessing and managing environmental, health, and safety (EHS) impact in manufacturing and end use environments, as well as following disposal at the end of the product life cycle.

EHS research, tools, and standards are being addressed by various NNI agency efforts. The NCL plays an important role in facilitating the development of safe nanomaterials specifically for cancer diagnosis and treatment. NIST has developed protocols for nano-EHS research and testing.[16] In 2015, the National Institute for Occupational Safety and Health (NIOSH) and the State University of New York Polytechnic Institute's Colleges of Nanoscale Science and Engineering announced a joint Nano Health and Safety Consortium to advance research and guidance for occupational safety and health in nanotechnology-related industries. The National Institute for Environmental Health and Safety (NIEHS) established the Centers for Nanotechnology Health Implications Research (NCNHIR) Consortium. The NCNHIR Consortium seeks to coordinate research efforts among NIEHS grantees with the overarching goals of gaining fundamental understanding on how the physical and chemical properties of nanomaterials influence their interactions with biological systems and to develop computational models to better predict potential health risks associated with nanomaterial exposure.

Other health and environmental aspects of nanomaterials are subject to study at various sites, including two centers for the environmental implications of nanotechnology jointly funded by NSF and the Environmental Protection Agency (EPA)—at Duke University and the University of California, Los Angeles. Other environmental implication studies are funded, however in an uncoordinated fashion.

Infrastructure gaps pose important barriers to success in the development of nanomedicines. Some lessons and ideas for nanomedicine infrastructure support can be drawn from the development of ultrahigh-purity chemistries by the electronics industry.[17] In addition, the organization MOSIS (which originally stood for Metal Oxide Semiconductor Implementation Service) is an example of a service supported by industry and academic researchers that has reduced development and prototyping costs by allowing multiple integrated circuit designs to be fabricated on a single silicon wafer.[18] Researchers are able to fabricate and test research designs that otherwise would be too costly to manufacture using commercial-scale services. This process offers flexibility and efficiency through the multiplexing of large

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[16] National Institute of Standards and Technology, "Protocols for Nano-EHS," last updated June 30, 2015, http://www.nist.gov/mml/nanoehs-protocols.cfm.

[17] See https://www.electronicmaterials.com/semiconductor/electronic-chemicals/, accessed August 22, 2016.

[18] The MOSIS Service, "About Us", https://www.mosis.com/what-is-mosis, accessed August 22, 2016.

numbers of high-fidelity small-scale processes in a pooled batch or lot. Such sharing of infrastructure and collaboration should be supported for a broad spectrum of soft nano-bio materials.

NCI's NCL, with support from NIST and the FDA, has been successful in developing tiered analyses and providing data that help in the assessment, by both developers and the FDA, of the safety of nanoparticles for cancer therapeutics and diagnostics. This demonstrated approach could be expanded to address nanomaterials for other medical applications. NCL also could be expanded or replicated to develop standard analyses and provide information at an early stage of development of nanomaterials in general, for assessment of potential risks to humans and the environment. Along these lines, the FDA National Center for Toxicological Research (NCTR) in Jefferson, Arkansas, is the site of a new nanotechnology core facility. The facility serves the needs of NCTR by supporting nanotechnology toxicity studies, developing analytical tools to quantify nanomaterials in complex matrices, and developing procedures for characterizing nanomaterials in FDA-regulated products. Unlike the NCL, these facilities are not accessible to commercial developers. In addition, the 2017 NNI budget includes Consumer Product Safety Commission funding for a new nanotechnology center at NIEHS to conduct research in exposure and risk assessment of engineered nanomaterials in consumer products. Access by commercial developers to this center has not been established.

Finding 4.3: NCL serves as a trusted source of information on the safety of nanomaterials being developed for cancer and has facilitated FDA assessment. However, there is a lack of centralized facilities for addressing other areas of nanomedicine and nanobiotechnology.

Recommendation 4.3a: The National Institutes of Health (NIH) should assess what emerging medical applications, in addition to cancer diagnostics and treatment, rely on engineered nanomaterials. NIH should expand the Nanotechnology Characterization Laboratory to address nanomaterials being developed for those other medical applications.

Recommendation 4.3b: The National Institute for Occupational Safety and Health, the National Institute of Standards and Technology, and the Environmental Protection Agency should join with the Consumer Product Safety Commission and the National Institute of Environmental Health Sciences to support development of centralized nanobiotechnological characterization facilities, at the Nanotechnology Characterization Laboratory or elsewhere, to serve as a trusted source of information on potential environmental, health, and safety implications of nanomaterials.

In addition to the need for physical infrastructures to support development of nanomedicines and related medical devices, there is also a need for better understanding of and tools for integration of nanotechnology into existing technological platforms. In general, most successful nanotechnologies are adopted in the commercial sector by integration into existing products (e.g., in composites and as coatings, rather than in isolated nanoparticle form). Thus, a physical infrastructure to serve these integration needs will need to be developed at current and future user facilities.

5

Human Infrastructure for Nanotechnology

The third goal of the National Nanotechnology Initiative (NNI) states: “Develop and sustain educational resources, a skilled workforce, and a supporting infrastructure and tools to advance nanotechnology.” Human capital, and the infrastructure required to produce it, constitutes an essential component of the nanotechnology ecosystem that is needed in order to realize the full value of nanotechnology advances. That ecosystem must have sufficient breath to address not only the education of nanoscale scientists and engineers involved in research, but also business and government leaders who can make informed decisions to accelerate the adoption of nano-enabled technologies, workers who are knowledgeable in the idiosyncrasies of nanomanufacturing, and a public that is sufficiently knowledgeable to make informed decisions on the benefits and risks.

To provide an education ecosystem capable of delivering on such a broad swath of goals, it will be necessary to address all the stages of education listed in Table 5.1. A National Science Foundation (NSF)-funded workshop report *Nanoscale Science and Engineering Education (NSEE)—The Next Steps*[1] provides a suite of recommendations toward that end. This committee endorses this workshop report.

TABLE 5.1 Stages of Education in the United States

Grade	
Primary (K-5)	Basic literacy and numeracy; establishment of foundations in science, mathematics, geography, history, and other social sciences
Secondary (6-12)	Develop the skills required in an increasingly complex society, including the dependence on science and technology
Community/ Technical College (13-14)	Transfer education—move to a four-year institution to pursue a BS/BA degree; career education; associate degree and directly enter the workforce; developmental remedial education for high school graduates; industry training—company pays to provide specific training or courses for employees
Undergraduate (BS/BA) (13-16)	Career education—decision makers in business, government, finance, etc.
Graduate (MS/MA/PhD)	Research toward the discovery of new knowledge
Continuing Education	Rounding out the knowledge needed for career goals; changing career paths
Informal Science Education (ISE)	Complement to formal education venues

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[1] J. Murday, 2014, *Nanoscale Science and Engineering Education (NSEE)—The Next Steps*, National Science Foundation, December, http://nseeducation.org/2014-documents/NSEE%20The%20Next%20Steps-Final.pdf.

This chapter briefly reviews science, technology, engineering and mathematics (STEM) workforce and education trends and considers the role of, and implications for, nanoscale science and engineering education within this broader context. The committee assesses how the NNI is meeting the needs for human talent with nanotechnology skills and knowledge, and how these efforts can be strengthened. An in-depth analysis of various data related to STEM education, sponsored by U.S. News and Raytheon,[2] along with data obtained directly from government reports, in particular the 2016 Science and Engineering Indicators (SEI2016) published by the National Science Board,[3] provide a picture of STEM employment and education in the United States and globally.

TRENDS IN STEM EMPLOYMENT

STEM employment figures in the United States are generally positive. According to the U.S. News/Raytheon analysis[4], the number of STEM jobs increased 20 percent between 2000 and 2014. Looking ahead, the U.S. Bureau of Labor Statistics (BLS) projects that between 2012 and 2022, employment in occupations that NSF classifies as science and engineering (S&E) will increase 15 percent, although the estimate varies from ~8 percent for engineers to nearly 20 percent for computer scientists.

As reported in SEI2016, STEM occupations are distributed across sectors. In 2013, roughly 70 percent of scientists and engineers worked in business or industry, 20 percent in education, and 10 percent in government. Of those working in business, about one-fourth are employed by companies with fewer than 100 employees. Those for whom the highest degree is a bachelor's or master's degree work predominantly at for-profit businesses, while those with doctorates are primarily employed by 4-year educational institutions and secondarily by for-profit business. The predominant sector of employment also varies by field, with engineers and computer scientists more likely to work in industry compared to physical, biological, or social scientists.

National innovation capacity and competitiveness may be measured in part by the number of skilled workers that conduct research. Therefore, it is worthwhile to examine how the United States compares to other nations and to establish if, as a nation, we are in a position to capitalize on emerging technologies such as nanotechnology.

Figure 5.1 shows the number of researchers over a 14-year period in selected countries.[5] Although the United States has grown, the European Union and China both have larger populations of researchers.

A more valid measure of a nation's commitment to growing its technology-based innovation is not the absolute number of researchers but the fraction of workers who are employed in research. As indicated in Figure 5.2,[6] the percentage of researchers for South Korea has displayed a sharp increase since 2004, while the United States, the European Union, and China show more gradual increases. The United States has a relatively high fraction of workers employed in research (between 7 and 9 percent); however, the figure has been relatively flat, especially since 2009.

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[2] Available at http://www.usnews.com/news/stem-index/articles/2015/06/29/the-2015-us-news-raytheon-stem-index, accessed August 22, 2016.

[3] See http://www.nsf.gov/statistics/2016/nsb20161/#/, accessed August 22, 2016.

[4] See http://www.usnews.com/news/articles/2016-05-17/the-new-stem-index-2016, accessed November 12, 2015. Note: this online document is updated annually.

[5] See https://www.nsf.gov/statistics/2016/nsb20161/#/figure/fig03-39, accessed September 1, 2016.

[6] See https://www.nsf.gov/statistics/2016/nsb20161/#/figure/fig03-40, accessed September 1, 2016.

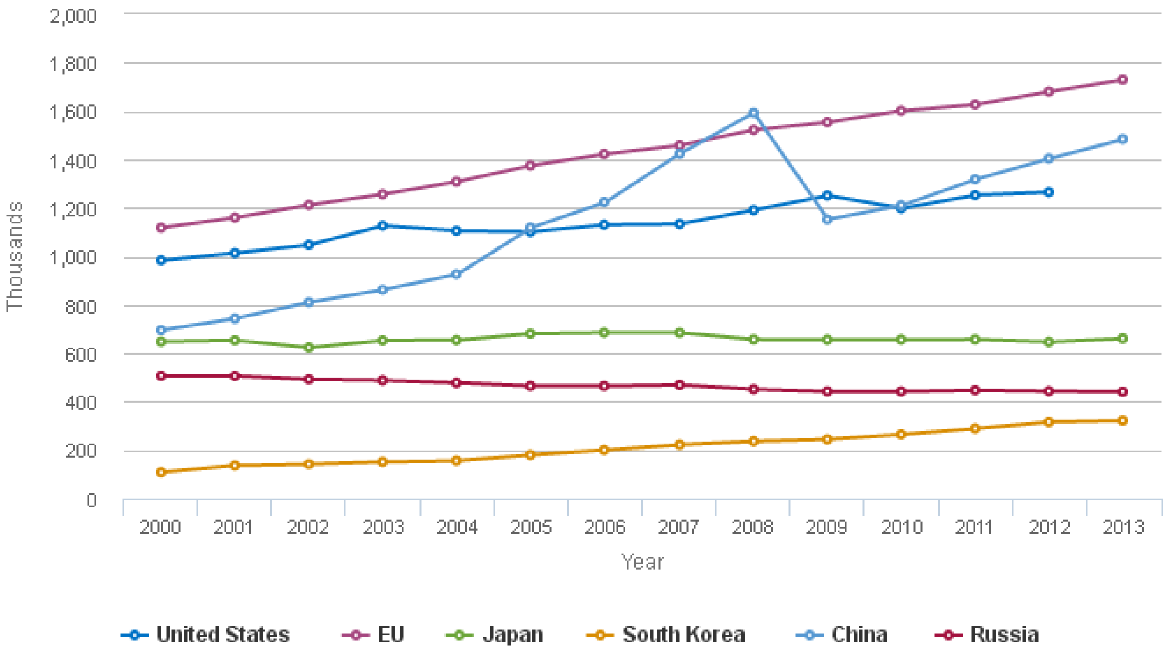

FIGURE 5.1 Estimated numbers of researchers in selected countries or regions, 2000-2013. NOTE: Counts for China before 2009 are not consistent with Organization for Economic Cooperation and Development standards. Counts for South Korea before 2007 exclude social sciences and humanities researchers. SOURCE: National Science Board, 2014, Science and Engineering Indicators 2014, NSB 14-01, National Science Foundation, Arlington Va.

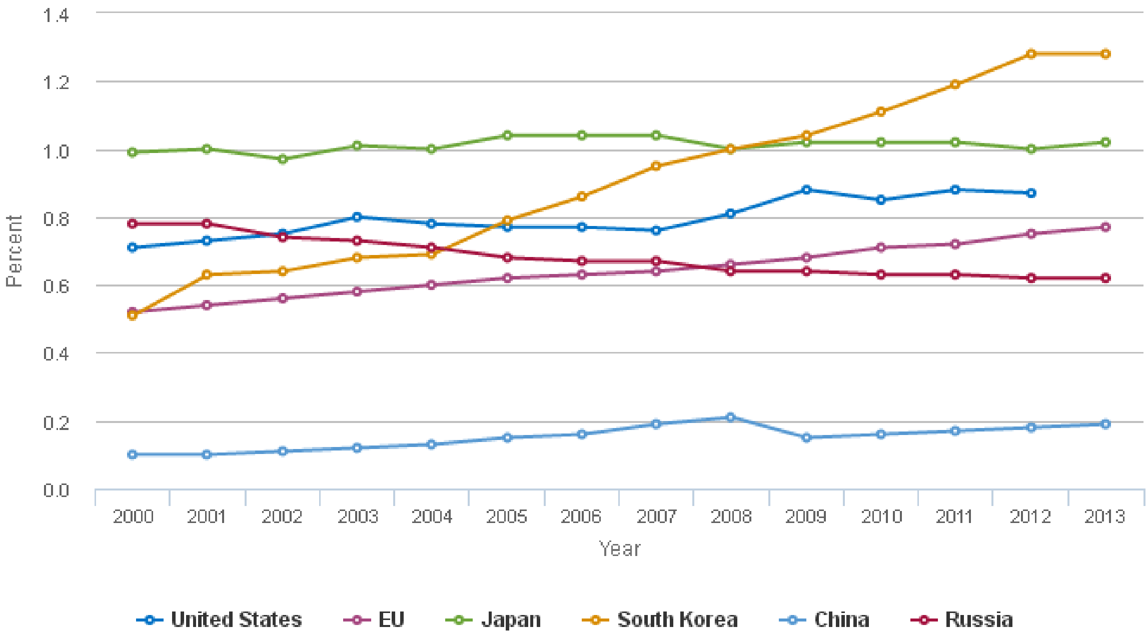

FIGURE 5.2 Researchers as a share of total employment in selected countries or regions, 2000-2013. NOTE: Counts for China before 2009 are not consistent with Organization for Economic Cooperation and Development standards. Counts for South Korea before 2007 exclude social sciences and humanities researchers. SOURCE: National Science Board, 2014, Science and Engineering Indicators 2014, NSB 14-01, National Science Foundation, Arlington Va.

TRENDS IN U.S. UNDERGRADUATE AND GRADUATE SCIENCE AND ENGINEERING EDUCATION

Significant highlights from the SEI2016 related to higher education in the United States include the following:

- The number of STEM bachelor's degrees has risen steadily between 2000 and 2013, reaching a new peak of more than 615,000 in 2013, whereas the proportion of all bachelor's degrees awarded in STEM, not including social and behavioral sciences, relative to degrees in all fields has remained stable at about 17 percent during this period.
- The number of international undergraduate students in the United States increased by more than 50 percent between fall 2008 and fall 2014. In the 2013/2014 academic year, the number of international students enrolled in undergraduate programs in U.S. academic institutions rose 9 percent from the previous year, to approximately 370,000. Although their numbers have increased rapidly, undergraduate students from overseas remain a small fraction of the approximately 20 million undergraduate students at U.S. academic institutions (up from 15.5 million in 2000).
- Graduate enrollment in STEM fields, not including social and behavioral sciences, is up 26 percent between 2000 and 2013. However, the number of graduate students who are U.S. citizens or permanent residents in these fields is up only 14 percent, whereas the number of international students in these fields is up 54 percent.
- There was a 13 percent increase in international graduate students from November 2013 to November 2014 enrolled at U.S. institutions in all fields; approximately 60 percent of those students were enrolled in STEM fields. Between fall 2013 and fall 2014, the number of international graduate students enrolled in STEM fields increased most in computer sciences and engineering combined, which accounted for more than 75 percent of the total increase in international enrollment in this period.
- Whereas international students received 37 percent of all STEM advanced degrees, the figures in certain fields are much higher. In 2013, international students earned 57 percent of engineering doctorates, 53 percent of computer sciences doctorates, and 44 percent of physics doctorates.

The National Norms survey administered by the Higher Education Research Institute at the University of California has conducted surveys regarding freshman choices for their career paths. Data for the period 2001-2014, shown in Table 5.2, indicate that the percentage of freshman who intended to study a science or engineering subject increased nearly 15 percent, from approximately 30 percent to 45 percent, between 2005 and 2014. Among those interviewed in 2014, 14 percent indicated biological/agricultural sciences and 14 percent engineering as their choice; only 2.5 percent identified physical sciences and 5 percent mathematical sciences as the preferred course of study. The responses from male versus female students varied by subject area. Men expressed interest disproportionately in physical sciences, engineering, and math/statistics/computer science. Women were more interested in biological/agricultural sciences and social/behavioral sciences.

A number of trends emerge from the statistics outlined above. The number of students enrolled in undergraduate and graduate STEM degree programs is increasing; however, the percent of enrolled students that study STEM is flat. Women are more attracted to life sciences and social sciences; men are more attracted to math, physical sciences, and engineering. The fraction of undergraduate and graduate students who are from outside the United States is rising. In engineering and computer science, more than half of doctorates are awarded to students who do not have U.S. citizenship or permanent residency and, therefore, cannot remain in the country upon graduation unless they obtain another visa. The United

States has a national initiative to address improvements in STEM education.[7] Hopefully, this will engender a robust supply of native-born STEM students. In the interim (it takes time for a pipeline to be filled), the United States will continue to depend on individuals from abroad.

TABLE 5.2. National Norms Survey of Preference Towards Science and Engineering (S&E) at the Undergraduate Level (percentage of respondents)

Field and Gender	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
All intending S&E major	33.5	33.5	32.6	33.1	30.9	32.0	31.9	34.7	36.2	38.4	40.1	39.2	41.6	44.6
Biological/agricultural sciences	7.5	7.8	7.7	8.3	8.1	8.8	9.1	9.8	10.4	11.6	11.4	12.9	14.7	13.8
Mathematics/statistics/computer sciences	5.4	3.8	3.1	2.7	2.0	2.4	2.5	2.3	2.5	2.4	2.6	3.1	3.7	4.9
Physical sciences	1.9	2.0	2.0	2.3	2.8	2.3	2.4	2.4	2.5	2.7	2.8	2.5	2.4	2.5
Social/behavioral sciences	9.6	10.4	10.5	10.2	9.6	10.5	10.4	10.9	11.1	11.4	11.3	10.4	9.6	9.6
Engineering	9.1	9.5	9.3	9.6	8.4	8.0	7.5	9.3	9.7	10.3	12.0	10.3	11.2	13.8
Male	42.2	41.2	39.6	40.8	37.0	37.9	37.3	41.1	43.4	44.1	47.0	45.8	47.4	49.0
Biological/agricultural sciences	6.5	6.6	6.7	7.4	7.2	8.1	8.2	8.8	9.7	10.0	9.9	10.8	12.4	11.4
Mathematics/statistics/computer sciences	9.5	6.8	5.6	5.1	4.0	3.9	4.4	4.0	4.1	4.0	4.3	5.2	5.9	7.8
Physical sciences	2.4	2.4	2.5	2.9	2.7	2.8	2.9	3.1	3.3	3.4	3.4	3.1	3.0	3.2
Social/behavioral sciences	7.1	7.5	7.7	7.5	7.5	8.6	8.1	8.2	8.7	8.8	8.4	8.4	7.2	7.5
Engineering	16.7	17.9	17.1	17.9	15.6	14.5	13.7	17.0	17.6	17.9	21.0	18.3	18.9	19.1
Female	26.7	26.7	26.2	26.3	27.0	27.2	27.7	29.5	30.3	33.3	34.8	33.5	36.7	37.5
Biological/agricultural sciences	8.3	8.5	8.5	9.0	8.7	9.6	9.7	10.4	11.0	12.4	12.8	14.3	16.5	15.8
Mathematics/statistics/computer sciences	2.2	1.6	1.1	1.0	1.5	1.0	1.1	1.1	1.1	1.1	1.2	1.4	1.8	2.1
Physical sciences	1.5	1.6	1.7	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.1	1.9	1.9	2.1
Social/behavioral sciences	11.7	12.0	12.0	11.5	12.3	12.1	12.3	12.8	12.8	13.6	14.5	12.0	11.7	11.7
Engineering	3.0	3.0	2.9	2.9	2.6	2.5	2.6	3.1	3.3	4.0	4.2	3.9	4.8	5.8

SOURCE: From the 2016 NSF S&E Indicators report, (Appendix Table 2-16) with data for 1998-2014 the source of the data from the NSF S&E Indicators report is “Higher Education Research Institute, University of California, Los Angeles, special tabulations (2015) of The American Freshman: National Norms.”, accessed on August 30, 2016.

GROWING COMPETITION TO RETAIN THE BEST AND BRIGHTEST

Based on the data above, the United States continues to attract students from around the world to study in STEM fields, as it has for the decades after World War II. Many of these students take jobs in the United States—in academia and industry—after they graduate, enriching the broad STEM innovation ecosystem. However, economic growth in many countries, along with policies aimed at recruiting their students who study abroad and ex-patriates that live and work abroad to return to their home country, provide opportunities and reasons to leave the United States. A recent study by the National Center for

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[7] See https://www.whitehouse.gov/administration/eop/ostp/initiatives#STEM%20Education, accessed August 3, 2016.

Science and Engineering Statistics (NCSES) of NSF shows that many foreign-born scientists who find jobs in the United States return to their home country 4 to 10 years after graduation.[8]

Many factors, including perceived opportunities in the United States versus their home country, individual assimilation experience, and family expectations, contribute to an individual's decision whether to stay or return home. A widely accepted model of the observed data is a "push-pull model."[9] Push factors compel students to study abroad and are the result of limited opportunities and financial constraints in their country of origin. Pull factors arise from family ties and the recent improvement of academic institutions at home, which induce these scientists and engineers to return. The economic benefits afforded by these highly skilled workers have not been overlooked by these countries, and programs to incentivize highly educated citizens to return have been established. An example is Brazil's "Young Talent Program," which funds students to study abroad with the requirement that they return home after graduating. Other countries offer tax breaks, grants, and many other incentives to persuade ex-patriates to return. Appendix D lists some of the programs intended to recover or prevent the so-called "brain drain."

Arguments about whether the pipeline of STEM graduates is sufficient often fail to consider new demand created by emerging technologies, such as nanotechnology. New technologies that lead to new products, new businesses, and new jobs are impossible to predict or quantify. What is certain is that individuals with a STEM education base are the ones who are likely to make the discoveries and technology innovations that will create new businesses and jobs. And regardless of the number of STEM workers that are needed, it is desirable that the quality be as high as possible. Therefore, it is in the national interest to attract and retain the best brain power.

Efforts to change U.S. immigration policies to make it easier for international students who received advanced degrees from U.S. institutions to stay have not been successful. In 2015, bipartisan legislation providing for comprehensive immigration reform that included allowing many graduates with advanced degrees in STEM fields to be granted permanent residency was introduced in both the House and Senate. Concerns have been raised regarding the use of universities as gatekeepers for access to residency, among other consequences of the proposed policy changes. Moreover, such efforts are met with skepticism by some who do not believe the United States has or is facing a shortage of STEM workers, at least in some STEM fields such as life sciences. In contrast, others note that wages for STEM occupations are higher than many other professions, and job vacancies for STEM occupations are more difficult to fill. The committee strongly endorses the 2012 report *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security: Summary.* Recommendation 10 of the report states the following:

> The United States should consider taking the strong step of granting residency (a green card) to each non-U.S. citizen who earns a doctorate in an area of national need from an accredited research university.[10]

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[8] National Science Foundation, 2014, "Employment Decisions of U.S. and Foreign Doctoral Graduates: A Comparative Study," Info Brief NSF 15-302, National Center for Science and Engineering Statistics, December 4, https://www.nsf.gov/statistics/2015/nsf15302/#.

[9] X. Han, H. Stocking, M. Gebbie, and R. Appelbaum, 2015, Will they stay or will they go? International graduate students and their decisions to stay or leave the US upon graduation, *PLoS One*, http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0118183.

[10] National Academies of Sciences, Engineering, and Medicine, 2012, *Research Universities and the Future of America*, The National Academies Press, Washington, D.C.

STEM EDUCATION AT THE NANOSCALE: GRADUATE AND UNDERGRADUATE

The principal means by which the pipeline of STEM educated researchers is filled is through federal funding of S&E research. A large fraction of those funds support students who perform much of the research as part of their graduate education. On the positive side, the United States invests substantial resources in university research.[11] In 2013, universities received approximately $65 billion in research and development funding, of which about 60 percent (nearly $40 billion) came from federal sources. Other sources of support include state and local governments, universities, foundations, and industry.

While research budgets continue to be supported, trends in the STEM higher education landscape are cause for concern. First, more STEM students, especially graduate students in certain fields but also undergraduate students, are from outside the United States. Second, other countries are actively seeking to attract scientists and engineers who are studying and/or living abroad to return home. The long-term implications of these trends on U.S. leadership in technology innovation is unclear. One impact that already is being felt is the decreasing pool of talent available to some employers, in particular federal and national laboratories and the defense industry. These entities perform research in areas that are essential to national security. However, many jobs in these organizations require a level of security clearance that mandates the employee be a U.S. citizen or permanent resident. One committee member with Department of Defense laboratory experience related finding only non-U.S. citizens qualified for a position that required nanotechnology expertise and, as a result, postponing a hiring action. To meet these needs, the education system must focus on growing the indigenous STEM student population—at the undergraduate, community college, and high school levels.

Many programs have the goals to attract top students to study STEM subjects and to provide research experiences that help them succeed in graduate school or in the workplace. Examples of federally funded programs that target undergraduate STEM students include the NSF Research Experience for Undergraduates (REU) program, the National Institute of Standards and Technology Summer Undergraduate Research Fellowship, Department of Energy and NASA internships, and the Department of Defense (DOD) Science, Mathematics and Research for Transformation (SMART) program. In addition, the Federal Science, Technology, Engineering and Math (STEM) Education 5-Year Strategy released in May 2013[12] outlined a number of initiatives. These programs are managed in a variety of ways, some as a separate program, some providing supplemental funds to other programs.

One of the largest programs supporting undergraduate research is the NSF REU program, which grants approximately $70 million annually. NSF-funded researchers may request supplemental funding to support an additional undergraduate student on the project. Similarly, the Research Experience for Teachers (RET) program provides supplemental funds to support a K-12 teacher to spend time working on an NSF-funded research project. In order for the NNI to boost the use of REU and RET program funds for nanotechnology-related research, it is necessary for NSF to identify the awards that it considers part of the NNI and then encourage the investigators on those awards to apply for an REU or RET grant.

The NNI website lists some education programs that are available, for example, for support at the undergraduate and graduate level.[13] The list identifies a few of the broader STEM education programs; however, many of the largest programs, such as the NSF REU program (other than the nano-specific National Nanotechnology Infrastructure Network REU) and the DOD SMART program, are not included.

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[11] See http://www.nsf.gov/statistics/herd/, accessed August 22, 2016.

[12] Committee on STEM Education, 2013, *Federal Science, Technology, Engineering, and Mathematics (STEM) Education: 5-Year Strategic Plan,* Washington, D.C., https://www.whitehouse.gov/sites/default/files/microsites/ostp/stem_stratplan_2013.pdf.

[13] See http://www.nano.gov/education-training, accessed on September 1, 2016.

> **Finding 5.1:** There are existing programs at many of the NNI-participating agencies that support STEM undergraduate students. The NNI could take better advantage of these programs toward achieving the NNI Goal 3, thereby augmenting nanoscale S&E education.
>
> **Recommendation 5.1: The Nanoscale Science, Engineering and Technology Subcommittee, working with the National Nanotechnology Coordination Office, should gather from the NNI participating agencies information about their programs that support science, technology, engineering, and mathematics undergraduate students, identify opportunities for increasing the fraction of such program funds going to students engaged in nanotechnology-related activities, and publicize those programs on the NNI website.**

A traditional STEM university degree may not be enough. Many disruptive technological advances will find their way into practical application via a small company or startup. University education can play an important role toward enabling this pathway to commercialization. Entrepreneurially inclined students benefit not only from traditional STEM education, but also from education in skills that are essential to success in business. Universities have begun to recognize this need and are establishing various programs aimed at providing such skills, including co-op programs, on-campus startup competitions, and courses on entrepreneurship, sometimes in collaboration with schools of engineering and business and technology transfer offices. Given the projected growth in nano-enabled products shown in Figure 2.1, and the larger European Union and Asia product output also shown in that figure, entrepreneurial skill sets for U.S. students will be important for the United States to be competitive in the commercialization of nanotechnology.

STEM EDUCATION AT THE NANOSCALE: K-12

Development of the human capital with appropriate nanotechnology skills and knowledge is needed in many areas. For example, researchers are needed to push forward the frontiers of science, and technologies are needed to implement results in products and services, while teachers are needed to impart knowledge to the youngest students. With its focus on world-class research, the NNI has built a substantial academic research ecosystem that is educating future Ph.D.-level researchers for industry and academia. Nanotechnology education at levels below the university level is less widely available. As nanotechnology becomes part of more jobs, it needs to be introduced to students at younger ages. It will be essential for the NNI, the NNCO, and the nanotechnology stakeholders across the education ecosystem to collaborate to make that happen.

The state of K-12 education is the subject of many reports. Various federal, state, and local programs aim to improve K-12 STEM education. The President's 2017 budget called for more than $3 billion in discretionary and $4 billion in mandatory spending in programs across the federal government on STEM education[14]. The question addressed by this panel is, What should the NNI do at the K-12 level to insure a robust pipeline of workers prepared for nanotechnology-related jobs emerging from all levels of education with the knowledge and skills needed?

While Goal 3 of the NNI strategic plan includes the development and sustainment of educational resources to advance nanotechnology, most of the participating agencies have only a modest commitment, if any, to pre-college education. The NNI efforts in support of K-12 nanoscale S&E (NSE) education have been primarily funded by NSF, including the National Center for Learning and Teaching in Nanoscale Science and Engineering that ended in 2011. At present, few programs appear to be focused on K-12

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[14] White House fact sheet summarizing FY2017 STEM education budget request, available at https://www.whitehouse.gov/sites/default/files/microsites/ostp/stem_fact_sheet_2017_budget_final.pdf, accessed August 22, 2016.

education; rather, such activities are ad hoc or minor components of larger centers or research projects. That is not to diminish the impact of such activities, but their sustainability and their likelihood of being scaled up is questionable.

With the substantial investment in nanotechnology research and research infrastructure at universities and government laboratories, it is time for a renewed effort to transition NSE into K-12 education. Developing nanotechnology education materials, facilities, and affordable instruments for K-12 schools will (1) prepare young students for nanotechnology before they reach college, (2) create demand for nanotechnology programs and facilities at universities, (3) leverage the "wow factor" of nanotechnology to help stimulate interest in STEM in general, and (4) support the "starter nano niche" where the youngest students have an opportunity to gain exposure to nanotechnology.

In business marketing terms, the nanotechnology community needs to focus more attention on the "introductory" or "starter" segment of the nanotechnology education market, namely K-12. If more resources are directed now to K-12, those students will be attracted to programs at the university level, driving further post-secondary education and research and use of infrastructures, which in turn will help address the anticipated need for nanotechnology workers. The report *Nanoscale Science and Engineering Education (NSEE)—The Next Steps*[15] summarizes the discussions compiled from a workshop that brought together several segments of the nanotechnology community. The importance of education to the development of nanoscale science and technology was widely recognized. Contributors to the workshop report produced a list of the main challenges in K-12 NSE that can be summarized as follows:

1. Scale-up and sustainability. In many cases local NSEE efforts are linked to NSF-funded centers and even individual investigator awards. Curricular and financial issues often restrict larger scale implementation.
2. Changing technologies used to support the learning process compel continual attention.
3. Transfer of knowledge about nanotechnology from higher levels of education into K-12.
4. Introducing NSE to current curricula without removing other important components.

Workshop participants felt NSE nurtures creativity, innovation, and the skills needed for the 21st century. The interdisciplinary nature of NSEE can impact positively future career paths considered by young students and make them aware of more choices and options.

At the international level, K-12 NSEE initiatives have been implemented by several countries.

- Taiwan established a national activity in NSE education in 2004, which is funded by allocation of 2.5 percent of its total nanotechnology funding (~2-3 million U.S. dollars per year to NSEE). The country has been working to include NSE in the K-12 curricula and provides teacher training at summer workshops. Textbooks have been revised to cover the area of nanoscience.[16] Taiwanese teachers are responsible for incorporating various aspects of nanotechnology into their teaching material.
- Korea is developing a NSEE curriculum and an e-learning program called NanoSchool.
- In Thailand, the National Nanotechnology Center has established a Nanotechnology Learning Center (NanoPlus Learning Center), which has produced 250,000 trainees since 2008. Many new teaching tools have been developed; however, the tests have only covered a small student population, and the effectiveness of such teaching aids has yet to be determined.

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[15] James Murday, 2014, *Nanoscale Science and Engineering Education (NSEE)—The Next Steps*, http://nseeducation.org/2014-documents/NSEE%20The%20Next%20Steps-Final.pdf.

[16] D.J. Yao, Nanotechnology Education and Training Project, National Program on Nanotechnology, NSC, Taiwan, poster presented at the Nanoscale Science and Engineering Education—The Next Steps Workshop, Arlington, Virginia, 2014.

- In September 2014 LEGO2NANO took place, the third in a series of China-U.K. summer schools between Tsinghua University, Peking University, and the University College London. Undergraduate and graduate students worked together for 5 days to design and build a low-cost atomic force microscope suitable for use in Chinese high schools.[17]
- Europe has an EduNano effort as part of its Tempus Project. The Tempus Program is the European Union co-operation scheme for higher education.

These examples show how other nations consider investment in K-12 education a priority.

BOX 5.1

Grade 6-12 Nano Education in Virginia

Since the development of the curriculum in 2007, more than 50 nanoscience lessons with corresponding inquiry-based activities have been developed by the Math Science Innovation Center (MSiC).

The MSiC has trained three cohorts of teachers grades 6 to 12 (approximately 25 teachers in each cohort) with a fourth cohort beginning in August 2015.

These teachers, while using the curriculum in their schools, have collectively reached more than 5,000 students and 250 colleagues.

Pre- and post-professional development program assessments indicate significant growth in understanding of nano concepts, particularly in the areas of size and scale and properties of matter.

MSiC faculty provide the 13 consortium school divisions with classroom instruction in nanoscience through their weekday programs, reaching thousands of students annually.

Out-of-school programs, such as the MSiC Summer Regional Governor's School and Camp Innovation, have engaged hundreds of middle school students in nanoscience and nanotechnology explorations.

Educator conferences and Let's Innovate! student conferences bring in nanoscience researchers to conduct workshops exploring new innovations in nanoscience.

Development of adjunct nano faculty expands the outreach as well as the imaginenano.info website and work with the VA DOE. (*Source for the above, July 2015 slide presentation by Daphne Smith to the committee*)

Note from the Committee on Triennial Review of the National Nanotechnology Initiative: Virginia is one of two states (Colorado being the other one) with the nanoscale explicitly included in the K-12 standards of leaning.

There are only two States—Virginia and Colorado—known to have explicitly inserted the requirement for some form of nanoscale science/engineering content into the state K-12 standards of learning; there is no reference to NSE in the Next Generation K-12 Science Standards[18]. Teachers pay particular attention to standards in developing their course content; therefore, it makes sense to focus on those two states to identify models and approaches for addressing the NSE K-12 pipeline. Whereas Colorado has NSE in its standard of learning, there is no known effort at the state level to pursue this requirement. Conversely, in 2010 Virginia launched a series of actions to incorporate nanotechnology into its Science Standards of Learning (implemented in the 2012-2013 school year). Nanoscience appears in "current applications of science" throughout K-12 and explicitly in grade 5, physical science, chemistry, and physics with topics such as size and scale, structure of matter, forces and interactions, quantum

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[17] London Center for Nanotechnology, http://www.london-nano.com/news-and-events/news, accessed August 22, 2016.

[18] See http://www.nextgenscience.org for reference.

effects, size-dependent properties, and models and simulations. The Virginia Math Science and Innovation Center (MSiC) provides teacher training and runs summer camps and teacher forums. See Box 5.1 on Grade 6-12 Nano Education in Virginia. This is a model from which other states could learn. The 2016 NNI annual report[19] states that the NNCO is assisting the Virginia Department of Education and that educational resources and lessons learned will be made available to other states.[20]

> **Finding 5.2:** A variety of approaches to incorporate nanoscale S&E in the K-12 education pipeline are being developed and implemented by entities both inside and outside the NNI. Educators and government education policymakers can learn from these programs and scale-up the more successful ones.
>
> **Recommendation 5.2a: The NNCO, working with the Department of Education and the National Science Foundation, should engage with states that have incorporated nanotechnology into the K-12 curriculum to develop a document outlining the approaches taken and make it widely available, including to individuals or groups seeking to improve K-12 science education in other states.**
>
> **Recommendation 5.2b: The National Science Foundation and the Department of Education should work with states that have incorporated nanotechnology into the K-12 curriculum to identify metrics and track the outcomes of the approach taken by those states to include nanotechnology in the K-12 curriculum.**

RESOURCES AVAILABLE TO ENHANCE NSE EDUCATION

The NNI website hosts information targeted at students and teachers from K-12 to graduate school, supporting classroom teaching as well as extracurricular activities and communities. It provides links to online resources hosted by NNI-funded centers. The education-related webpages on nano.gov list nano-specific programs and materials, as well as more general STEM programs, fellowships, and so on. The NNCO has posed several competitions, such as the Generation Nano competition, that educators can use to teach, challenge, and excite students about nanotechnology. The competitions also can help entice teachers and students to the website where they can see the other information that is there as well.

The following are examples of additional nanotechnology programs intended to enhance education at various levels.

- *Center for Nanotechnology Education Nano-Link*, a program led by Dakota County Technical College, comprising 15 educational institutions throughout the United States. The program is designed to supply NSE competent technicians for industry through 2-year A.A.S. degree programs, deliver modularized educational content for grades K-14, and organize hands-on educator workshops. These programs stress multidisciplinary angles of nanotechnology with major attention being given to nano-electronics, nano-biotechnology, and nano-material science. Nano-Link operates with its affiliates to identity the needs of their

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[19] All budget supplements are able to be found at http://www.nano.gov/node/1071.

[20] In addition to the Virginia material, the NNCO has access to other K-12 teaching aides such as the Nano-Infusion modules from the NanoLink Advanced Technology Education Center, the Materials World Modules from the National Center for Learning and Teaching, NanoTeach from the Mid-Continent Research for Education and Learning; Nano4me from the Nanotechnology Applications and Career Knowledge Network ATE Center and resources from the National Nanotechnology Infrastructure Network Education efforts. See http://www.nano.gov/education-training/teacher-resources (accessed on 2/2/2016) for more detail.

local industries and the available education infrastructure resources to determine how they match up in that particular region.

- *Nanotechnology Applications and Career Knowledge Network* is directed by Pennsylvania State University. The goal of this center is to form partnerships in nanotechnology education among various research universities, 2-year community colleges and technical colleges, and 4-year colleges. These institutions share resources, including courses, programs, laboratory facilities, and staff. The center also gives an opportunity for the student (K-16) to remotely access and control microscopes in order to examine materials at the nanoscale level from classrooms and/or home computers.
- *National Informal Science Education Network* is a national group of researchers and informal science educators dedicated to fostering public awareness, engagement, and understanding of nanoscale science, engineering, and technology.
- *Joint School of Nanoscience and Nano Engineering (JSNN)* is a venture set up between North Carolina A&T State University and the University of North Carolina, Greensboro. Its objective is to train students from various disciplinary backgrounds to perform fundamental and advanced research in nanoscience and nano engineering in industrial, governmental, or academic settings. It offers a master of science in nano engineering and a professional master of science in nanoscience.
- *Colleges of Nanoscale Science and Engineering.* The State University of New York Polytechnic Institute's (SUNY Poly's) College of Nanoscale Science and Engineering (CNSE) is a global education, research, development, and technology deployment resource aimed at nurturing future scientists and researchers in nanotechnology. It is the world's first college to develop comprehensive baccalaureate programs in nanoscale engineering and nanoscale science. SUNY Poly CNSE's cross-disciplinary Ph.D. and M.S. curricula build on the fundamental principles of physics, chemistry, computer science, biology, mathematics, and engineering with the cross-cutting fields of nanoscience, nano engineering, nanotechnology, and nano-economics.
- *Network for Computational Nanotechnology (nanoHUB)* is becoming an increasingly widely used platform for the dissemination of programs and tools for nanoscale computer modeling and simulation. The site also is organized to permit sharing of various educational resources, mostly at the post-secondary level today, but also with materials targeted at K-12 students and teachers. nanoHUB offers online presentations, courses, learning modules, podcasts, animations, videos, and other teaching materials.

Finding 5.3: The NNI has funded the development of a diversity of formal and informal educational materials suitable for various levels and ages. Nanotechnology-focused educational programs at universities around the country, some of which have received substantial state funding, also are developing materials for K-12 students and teachers.

Recommendation 5.3: NNI-funded researchers and others who have developed educational materials should be required to deposit the information content on the nanoHUB.org website and to explore affordable commercial availability for laboratory and classroom demonstration materials.

6

Summary and Conclusion

The NNI comprises the collective activities and investments of the participating agencies, coordinated through the efforts of the interagency Nanoscale Science, Engineering and Technology Subcommittee and with the support of the National Nanotechnology Coordination Office. Since its inception in 2001, the number of participating agencies has grown to include 27 agencies with missions spanning from support for basic research to regulation of commercial products and activities. Today, the NNI participating agencies altogether invest ~$1.5 billion/year. The bulk of spending is in support of fundamental and applied research, including a number of shared use facilities.

As noted by PCAST in 2014, the NNI not only needs to invest in research and discovery, it needs to focus on translating research results into commercial products. This study assesses NNI mechanisms to advance focused areas of nanotechnology towards advanced development and commercialization, with particular attention to advancing nanomanufacturing (Chapters 2 and 3) and the adequacy of the physical and human infrastructure (Chapters 4 and 5) to support not only research but also private sector innovation.

Nanotechnology, which encompasses nanoscale science, engineering and technology, is multidisciplinary and has potential to improve existing products or enable new ones in many sectors, including information and communication technology, energy, and medicine. The innovation process by which the results of NNI research transition into practical application is complex, involving numerous actors from the public and private spheres.

> **Finding 2.1:** The federal government plays a significant role in discovery, applied research, and early-stage development; the private sector plays a dominant role in product development and commercialization. A challenge for nanotechnology, like other emerging technologies, is to bridge from research to practical application. There are federal programs that provide support for advancing ideas to a level that is more likely to attract private investment.
>
> **Recommendation 2.1: The Nanotechnology Innovation and Commercialization Ecosystem Working Group should identify federal programs that assist with transitioning early-stage concepts to more advanced technology readiness. The Nanoscale Science, Engineering, and Technology Subcommittee, with support from the National Nanotechnology Coordination Office, should inform the basic research community about these programs and also communicate to federal program managers about how investment in advancement of nano-enabled technologies can provide opportunities for achieving their program and agency missions.**

The NNI established Nanotechnology Signature Initiatives (NSIs) starting in FY 2013 with the goal of focusing on technology areas of national importance that may be more rapidly advanced through enhanced interagency coordination and collaboration. There are currently five NSIs, including one announced in 2016 Water Sustainability through Nanotechnology. The NSI statements of need and opportunity make clear the potential benefits from advances in nanotechnology in each area. It is not as clear what are the roles and responsibilities of the NNI participating agencies in achieving the stated NSI objectives.

> **Finding 2.2:** Without a plan that has clear targets, goals, and metrics to measure progress, as well as indication of responsible agencies, funding for NSI topics will be more difficult to secure within the NNI agencies and advances will be more serendipitous and less assured.
>
> **Recommendation 2.2. Agencies participating in each Nanotechnology Signature Initiative (NSI) should develop a joint strategic plan with roadmaps and interim and end-result goals. The plans should include goals related to facilitating commercialization of research related to the topic of the NSI.**

Nanotechnology-inspired Grand Challenges are a newer mechanism being employed by the NNI to focus on areas of high impact and technical opportunity. As noted in the announcement of the Grand Challenge for Future Computing, achieving the Grand Challenge will depend on advancements in areas other than nanotechnology and in other government initiatives. Conversely, progress toward the Grand Challenge also supports advances toward the objectives of those other initiatives. This interdependency applies to the NNI as a whole.

> **Finding 2.3:** The NNI is investing in technology areas that are critical to the goals of other federal initiatives and vice versa. The various initiative leaders and managers both inside and outside of the NNI may not have the entire expertise or programmatic influence or control to efficiently achieve their respective initiative goals.
>
> **Recommendation 2.3: The Nanoscale Science, Engineering and Technology Subcommittee should strengthen engagement with the leadership of other high-priority initiatives in order to determine critical nano-enabled technological dependencies. The Subcommittee then should focus NNI efforts to address those dependencies.**

There are additional mechanisms for focusing efforts that are available to the NNI. Innovation incentive prizes are an approach that can draw attention to a technical challenge and tap into a community of innovators who may not currently be participating in addressing problems of interest to the federal government.

> **Finding 2.4:** XPrize, InnoCentive, and other organizations have well developed, proven strategies for managing innovation incentive prize competitions using cash awards and well defined procedures to engage a diverse array of people and organizations, stimulate additional spending, and produce results.
>
> **Recommendation 2.4: NNI agencies should use innovation incentive prizes to engage a broader community to solve technical problems, particularly those underlying Grand Challenges and other national initiatives. NNI agencies can offer prizes directly, or work through existing organizations.**

Transitioning nanotechnology research results into commercial products requires the ability to reliably manufacture with nanoscale precision and control and at an acceptable cost. Since the NNI was established, nanomanufacturing has been recognized as essential to realizing economic benefits from the investment in nanotechnology research and development. Given its importance, the committee felt it was a focus area that warranted closer study.

> **Finding 3.1:** Budget figures in support of nanomanufacturing as reported in the NNI supplements to the President's budget have been inconsistent, and progress made toward recommendations of the 2004 *Manufacturing at the Nanoscale* report is not clear.
>
> **Recommendation 3.1: The Nanoscale Science, Engineering and Technology Subcommittee should prepare a report that provides a self-consistent record of the NNI nanomanufacturing program, the status relative to the recommendations of the 2004 *Manufacturing at the Nanoscale* report, and the NNI plans to move forward.**
>
> **Finding 3.2:** Basic research programs focused on nanomanufacturing have been a strength of the NNI. NSF centers focused on nanomanufacturing have more adequate budgets for facilities and education than do single investigators who have smaller awards. Ending support for nanomanufacturing centers will lead to a decrease in coordinated education and facility efforts.
>
> **Recommendation 3.2: The National Science Foundation should find ways to continue some Nanomanufacturing Center-scale efforts. Such centers might be explicitly tasked to pursue early-stage research in support of advanced manufacturing programs, such as the Manufacturing Innovation Institutes.**

The federal government has launched a substantial effort aimed at stimulating and supporting advanced manufacturing. A number of MIIs focused on various sectors have been established. In addition, the NIST AMTech program is funding planning activities to establish new, or strengthen existing, industry-driven consortia that address high-priority research challenges impeding the growth of advanced manufacturing. The MIIs are focused primarily at bridging the gap between research and commercialization. Connections between the NNI and advanced manufacturing programs such as the MII program and AMTech can accelerate progress toward the goals of those programs.

> **Finding 3.3:** In many cases, progress or success in the MIIs and in implementation of the roadmaps developed under the AMTech program will require advances in nanomanufacturing.
>
> **Recommendation 3.3a: NNI-participating agencies should explicitly support the early-stage (technology readiness level 1-3) nanomanufacturing research needed to enable the roadmaps and goals of current advanced manufacturing programs, in particular the existing Manufacturing Innovation Institutes.**
>
> **Recommendation 3.3b: The Nanoscale Science, Engineering and Technology Subcommittee should form a nanomanufacturing working group to identify nanoscale research needs of advanced manufacturing, coordinate efforts between the NNI and the federal programs focused on advanced manufacture, and foster greater investment by those programs in nano-enabled technologies.**
>
> **Finding 3.4:** Nanomedicine manufacturing is an essential step in realizing the benefits of the considerable investment in nanomedicine research under the NNI. Nanomedicine manufacturing poses a number of specific challenges that are not being met by other NNI manufacturing efforts. Two reports—the NIH NCI "Cancer Nanotechnology Plan 2015" and the PCAST "Report to the President and Congress on the Fifth Assessment of The National Nanotechnology Initiative,

Appendix II - Manufacturing Nanomedicine"— provide a sound basis for NNI focus on this topic.

Recommendation 3.4: The National Institutes of Health should lead the development of a roadmap, in collaboration with the nanomedicine industry, to identify technical barriers to scaling up the manufacture of nanomedicines, as well as areas in which research is needed to overcome those barriers.

Together the NNI agencies have created a geographically distributed set of user facilities that provides the broad nanoscale science and engineering community access to a range of characterization and synthesis tools and facilities. In addition, computational tools for nanoscale modeling and simulation have been developed and are made publicly available, e.g., via nanoHUB. The NNI investment in this physical infrastructure has been a cornerstone of supporting nanotechnology research and development in the United States. While the facilities serve thousands of users annually, there are many who could benefit by are not aware that this infrastructure can help address their needs.

Finding 4.1: The NNI agencies fund a substantial set of facilities that support experimental, computational, and educational activities and users from academia, industry, and government. While information about each facility or center is available on the NNI website, there is little evidence of coordination among the agencies to facilitate access and use by the community at large.

Recommendation 4.1: User facilities should strive to better serve the collective nanoscience research community by (1) sharing—perhaps via a central web-based portal— training materials and simulation and computational tools developed at the individual user facilities, and (2) creating a common proposal form and process that facilitate users moving between facilities to access the more expensive or specialized instrumentation.

The NNI investment in establishing this physical infrastructure has been substantial. However, there does not appear to be planning for sustainment.

Finding 4.2: There is a clear lack of identified funds for the development of new leading-edge instrumentation or recapitalization of commercial tools at NNI-sponsored user facilities, with the exception of CNST. As a result, there is a real risk of obsolescence of the physical and computation infrastructure available to the nanoscience and technology research enterprise, and a corresponding decrease in the user value.

Recommendation 4.2: The National Science Foundation and the Department of Energy, in concert with other NNI agencies with instrumentation programs, should identify funding mechanisms for acquiring and maintaining state-of-the-art equipment and computational resources to sustain leading-edge capabilities at their nanoscale science and engineering user facilities.

Nanotechnology for medicine and other applications that involve contact with the body or the environment are increasing. The refreshed NSF network of user facilities, the National Nanotechnology Coordinated Infrastructure (NNCI), has expanded capabilities in support of nano-biology research. However, there is a growing need for tools and tests to characterize the safety of nanomaterials. The National Cancer Institute (NCI) Nanotechnology Characterization Lab is a successful model for the early assessment of nanomaterials.

Finding 4.3: The Nanotechnology Characterization Lab (NCL) serves as a trusted source of information on the safety of nanomaterials being developed for cancer and has facilitated FDA assessment. However, there is a lack of centralized facilities for addressing other areas of nanomedicine and nanobiotechnology.

Recommendation 4.3a: The National Institutes of Health (NIH) should assess what emerging medical applications, in addition to cancer diagnostics and treatment, rely on engineered nanomaterials. NIH should expand the Nanotechnology Characterization Laboratory to address nanomaterials being developed for those other medical applications.

Recommendation 4.3b: The National Institute for Occupational Safety and Health, the National Institute of Standards and Technology, and the Environmental Protection Agency should join with the Consumer Product Safety Commission and the National Institute of Environmental Health Sciences to support development of centralized nanobiotechnological characterization facilities, at the Nanotechnology Characterization Laboratory or elsewhere, to serve as a trusted source of information on potential environmental, health, and safety implications of nanomaterials.

Increasing the pipeline of undergraduates with STEM education that includes nanoscale science/engineering is also important to the health of the nation's high technology economy and is particularly vital to supporting the defense and government sectors.

Finding 5.1: There are existing programs at many of the NNI-participating agencies that support STEM undergraduate students. The NNI could take better advantage of these programs toward achieving the NNI Goal 3, thereby augmenting nanoscale S&E education without the need for additional resources.

Recommendation 5.1: The Nanoscale Science, Engineering and Technology Subcommittee, working with the National Nanotechnology Coordination Office, should gather from the NNI participating agencies information about their programs that support science, technology, engineering, and mathematics undergraduate students, identify opportunities for increasing the fraction of such program funds going to students engaged in nanotechnology-related activities, and publicize those programs on the NNI website.

As nanotechnology matures and at the same time is incorporated into traditional disciplines, the teaching of nano-related concepts will be incorporated into education at lower levels, including K-12. Development of education materials suited to younger students is the subject of a number of programs within and outside the NNI. In particular, the Commonwealth of Virginia has added nanotechnology to its standard K-12 curriculum.

Finding 5.2: A variety of approaches to incorporate nanoscale S&E in the K-12 education pipeline are being developed and implemented by entities both inside and outside the NNI. Educators and government education policymakers can learn from these programs and scale-up the more successful ones.

Recommendation 5.2a: The NNCO working with the Department of Education and the National Science Foundation, should engage with states that have incorporated

nanotechnology into the K-12 curriculum to develop a document outlining the approaches taken and make it widely available, including to individuals or groups seeking to improve K-12 science education in other states.

Recommendation 5.2b: The National Science Foundation and the Department of Education should work with states that have incorporated nanotechnology into the K-12 curriculum to identify metrics and track the outcomes of the approach taken by those states to include nanotechnology in the K-12 curriculum.

Finding 5.3: The NNI has funded the development of a diversity of formal and informal educational materials suitable for various levels and ages. Nanotechnology-focused educational programs at universities around the country, some of which have received substantial state funding, also are developing materials for K-12 students and teachers.

Recommendation 5.3: NNI-funded researchers and others who have developed educational materials should be required to deposit the information content on the nanoHUB website, and to explore affordable commercial availability for laboratory and classroom demonstration materials.

In summary, the NNI, including the interagency bodies and the NNCO, continues to add value to the portfolio of activities across participating agencies. Looking ahead, the NNI can significantly increase that value by focusing on research that will enable progress and success in other advanced technology areas of priority, especially advanced manufacturing. At the same time, the NNI agencies are called on to sustain investment in and facilitate access to physical infrastructure and to take steps to realize the full value of educational materials and programs. In the course of identifying targeted areas in which to focus, NNI agencies have the opportunity to consider the goals of the initiative and the criteria for continuing to invest resources in its coordination and management.

Appendixes

A

Statement of Task

The National Research Council delivered the first triennial review of the federal National Nanotechnology Initiative (NNI) in 2006 (NRC, 2006), pursuant to the 2lst Century Nanotechnology Research and Development Act, Section 5 of Public Law 108-153. The NRC will appoint a committee to conduct the next triennial NNI review as specified in the law. The overall objective for this NNI review is to make recommendations to the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office that will improve the value of the National Nanotechnology Initiative's (NNI's) strategy and portfolio for basic research, applied research, and applications of nanotechnology to advance the commercialization, manufacturing capability, national economy, and national security interest of the United States. Toward this objective the NNI review will include the tasks listed below.

A. Examine and comment on the mechanisms in use by the National Nanotechnology Initiative (NNI) to advance focused areas of nanotechnology towards advanced development and commercialization, along with the approaches taken to determine those focus areas and to implement the NNI's Signature Initiatives. If warranted, recommend possible improvements.
B. Examine and comment on the physical and human infrastructure needs for successful realization in the United States of the benefits of nanotechnology development. Consider research and development, product design, commercialization, and manufacturing needed both to advance nanoscience and engineering and to grow those portions of the American economy that are spurred by advances in nanotechnologies. If warranted, recommend possible improvements.

B

Acronyms and Abbreviations

AFRL	Air Force Research Laboratory
ALD	Atomic Layer Deposition
AMP	Advanced Manufacturing Partnership
ASU	Arizona State University
BLS	U.S. Bureau of Labor Statistics
CAD	Computer Assisted Design
CEIN	Centers for the Environmental Implications of Nanotechnology
CEMI	Clean Energy Manufacturing Initiative
cGMP	Refers to the Current Good Manufacturing Practice regulations enforced by the U.S. Food and Drug Administration
CMOS	Contract Manufacturing Organizations
CNF	Cornell Nanoscale Science and Technology Facility
CNM	Center for Nanoscale Materials
CNMS	Center for Nanophase Materials Sciences
CNS	Center for Nanoscale Systems at Harvard University
CNSE	Colleges of Nanoscale Science and Engineering
CNST	NIST Center for Nanoscale Science and Technology
CoE	Center of Excellence
CPSC	Consumer Product Safety Commission
DARPA	Defense Advanced Research Projects Agency
DCTC	Dakota County Technical College
DMDII	Digital Manufacturing and Design Innovation Institute
EFRC	Energy Frontier Research Center
EHS	Environmental, Health, and Safety
EMF	Environmental Measurement Facility
EMSL	Environmental Molecular Sciences Laboratory
ERC	Engineering Research Center
FEA	Finite Element Analysis
FEDC	Flexible Electronics and Display Center
FIB	Focused Ion Beam
FNC	Future Naval Capability
GCD	Game Changing Development
GCGH	Grand Challenge in Global Health initiative
GMP	Good Manufacturing Practice
GOALI	Grant Opportunities for Academic Liaison with Industry
HGP	Human Genome Project

ITAR	International Traffic in Arms Regulations
JSNN	Joint School of Nanoscience and Nano Engineering
MAF	Molecular Analysis Facility
MANTH	Mid-Atlantic Nanotechnology Hub for Research, Education and Innovation
MBI	Microproducts Breakthrough Institute
MCCCD	Maricopa County Community College District
MEMS	Microelectro-Mechanical Systems
MIBP	Manufacturing and Industrial Base Policy
MII	Manufacturing Innovation Institute
MINIC	Midwest Nano Infrastructure Corridor
MITS	Manufacturing and Industrial Technologies
MMNIN	Multi-scale Manufacturing and Nano Integration Node
MOEMS	Micro-Opto-Electromechanical Systems
MOSIS	Metal Oxide Semiconductor Implementation Service
MRL	Manufacturing Readiness Levels
MURI	Multidisciplinary University Research Initiative
NACK	Nanotechnology Applications and Career Knowledge Network
NBMC	Nano-Bio Manufacturing Consortium
NCFL	Nanoscale Characterization and Fabrication Laboratory
NCI	National Cancer Institute
NCL	Nanotechnology Characterization Lab
NCN	Network for Computational Nanotechnology
NERC	Nanosystem Engineering Research Center
NICE	Nanotechnology Innovation and Commercialization Ecosystem
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute for Occupational Safety and Health
NISE	National Informal Science Education
NMMB	National Materials and Manufacturing Board
NNCI	National Nanotechnology Coordinated Infrastructure
NNCO	National Nanotechnology Coordination Office
NNF	Nebraska Nanoscale Facility
NNI	National Nanotechnology Initiative
NNIN	National Nanotechnology Infrastructure Network
NNUN	National Nanofabrication User Network
NSCI	National Strategic Computing Initiative
NSEC	Nanoscale Science and Engineering Centers
NSEE	Nanoscale Science and Engineering Education
NSET	Nanoscale Science, Engineering, and Technology
NSI	Nanotechnology Signature Initiative
NSRC	Nanoscale Science Research Centers
NSTC	National Science and Technology Council
NWNI	Northwest Nanotechnology Infrastructure
ONAMI	Oregon Nanoscience and Microtechnologies Institute
OSTP	Office of Science and Technology Policy
PCAST	President's Council of Advisors on Science and Technology

PNNL	Pacific Northwest National Laboratory
QA/QC	Quality Assurance/Quality Control
RET	Research Experience for Teachers
REU	Research Experience for Undergraduates
RFI	Request for Information
RIF	Rapid Innovation Fund
RTNN	Research Triangle Nanotechnology Network
SDNI	San Diego Nanotechnology Infrastructure
SENIC	Southeastern Nanotechnology Infrastructure Corridor
SNF	Stanford Nanofabrication Facility
SNSF	Stanford Nano Shared Facilities
SPL	Solar Power Laboratory
STEM	science, technology, engineering, and mathematics
STRG	Space Technology Research Grant
TDM	Technology Demonstration Mission
TIA	Technology Investment Agreement
TMF	The Molecular Foundry
TONIC	Translation Of Nanotechnology In Cancer
TRL	Technology Readiness Levels
TSCA	Toxic Substances Control Act
UARC	University Affiliated Research Center
ULI	University Leadership Initiative
WNF	Washington Nanofabrication Facility

C

Evolution of the NSET Membership Organizations

Table C.1 shows the broadening and evolving agency participation and the growing involvement of offices focused on technology transition, rather than fundamental research.

TABLE C.1 NSET Agency Representation as Reported in the NNI Supplement to the President's Budget (2001-2016, at 5-year intervals)

		2001	2006	2011	2016
	NNCO				
Science and Engineering Knowledge					
1	**OSTP**				
2	**OMB**				
3	**NSF**	ENG	ENG	ENG	ENG
		DMR	DMR	DMR	DMR
		BIO	BIO	BIO	SBE
			IIP	IIP	IIP
4	**HHS/NIH**	NHGRI	NHGRI	NHGRI	
		NIDCR	NIDCR	NIBIB	NIBIB
			NCI	NCI	NCI
			NHLBI	NHLBI	NHLBI
			NIEHS	NIEHS	NIEHS
				NIGMS	NIGMS
5	**DOD**	DOR	DOR	ODDR&E	ASDR&E
		NRL/ONR	NRL/ONR	NRL/ONR	
		AFOSR	AFOSR	AFOSR	AFOSR
			ARO	ARO	ARO /ARL
					DTRA
6	**DOE**	BES	BES	BES	BES
		EERE	EERE	EERE	EERE
7	**NASA**	HQ	HQ	HQ	STMD
8	**DOC/NIST**	Program Office	Program Office	Program Office	Program Coor
9	**DOT**	Volpe Ctr	Volpe Ctr	RITA	OST-R
			FHWA	FHWA	FHWA
10	**DHS**		TSA	Hughes Ctr	Hughes Ctr
			ORD	ORD	ORD
11	**USDA**		CSREES	NIFA	NIFA
				FS	FS
					ARS
12	**HHS/CDC/NIOSH**		OD	OD	OD
			Taft Lab	NRC	NRC
13	**DOJ/NIJ**		OST	OST	OST
14	**DoTr**		DASEP	BEP	BEP
15	**DOI**			USGS	USGS
16	**DNI**		CIA	CIA	NRO
Regulatory					
17	**EPA**		ORD	ORD	ORD
			Risk Assessment	Risk Assessment	Risk Assessment
18	**HHS/FDA**		OSHC	OCS	OCS
19	**HHS/CDC**				ATSDR
20	**CPSC**		DHS	OHIR	OHIR
21	**NRC**			ONRR	ONRR
22	**DOL/OSHA**				OSHA
Marketplace and Commerce					
23	**DOS**		OSAT	OSAT	OSAT
24	**DOL**			Business Rel Training	
25	**DOC**		OTP		EDA
			BIS	BIS	BIS
			USPTO	USPTO	USPTO
26	**ED**			OPE	STEM Initiatives
27	**USITC**		OoI	OoI	OoI

NOTE: Gray highlight denotes organizations with a focus or mission related to technology transition or commercial activities.
SOURCE: National Nanotechnology Initiative Budget Supplements, accessible at http://www.nano.gov/node/1071.

D

List of International Programs That Promote STEM Repatriation

TABLE D.1 Programs, by Country, that Promote the return of Science, Technology, Engineering, and Mathematics (STEM) Talent Back to Their Home Country

Country	Program	Program Description
Argentina	R@ICES	A program under the Ministry of Science, Technology and Productive Innovation of Argentina. The goals of the program are to strengthen the link between Argentine researchers in the country and abroad, bring Argentines abroad back to Argentina to develop research, and implement retention policies that promote the return of Argentines.
Bavaria	Return to Bavaria	Sponsored by the Bavarian Ministry of Economic Affairs and Media, Energy and Technology, the program was initiated in 2012 to motivate Bavarian and German professions to return home.
Brazil	Science Without Borders "Young Talent Program" (i.e., Jovens Talentos)	A joint effort from Brazil's Ministry of Education and the Ministry of Science and Technology, the program aims to (1) place 100,000 Brazilian students and researchers in top universities worldwide by 2014 and (2) to attract talented young researchers from outside the country, especially Brazilians, to Brazil.
Chile	Start-up Chile	Program started by the Chilean government in 2010 to attract early stage entrepreneurs to build their startup companies in Chile.
China	1000 Talents Program	Launched by the Central Organization Department of the Chinese Communist Party in 2008, the program aims to recruit 1,000 outside Chinese talents to return to China.
Europe	Horizon 2020	Commencing in 2014, Horizon 2020 is an initiative aimed at securing Europe's global competitiveness. There are many different programs (e.g., European Research Council Starting Grants, European Research Council Advanced Grants, Marie Sklodowska-Curie Actions Program, etc.) that facilitate the return of young European scientists back to Europe.
Germany	German Academic International Network (GAIN)	Created by the Deutscher Akademischer Austausch Dienst (i.e., German Academic Exchange Service) in cooperation with the German Research Foundation and the Alexander von Humboldt Foundation, the program provides support, networking opportunities, workshops, and job postings for German scholars and scientists working in North America. GAIN promotes the dissemination of information across the Atlantic and prepares German scientists to return to Germany.
Israel	Gvahim	Initiated in 2006, this non-governmental organization promotes Israel's "Brain Bain" efforts by offering highly-skilled Olim with opportunities and networking in Israel.
Italy	Dulbecco Telethon Institute	Founded in 1999, the institute provides funding to early stage researchers who work on human genetic diseases.
Moldova	Gsorm Gala Studenilor	Moldovan students abroad competed in the competition "Academic Excellence Moldova." The program encourages Moldovan students abroad to return to Moldova.
Portugal	Cienca 2007	An international call for 1000 post-doctoral research positions, both Portuguese and foreign nationals, at Portuguese scientific institutions. The program was launched and closed in 2007.
Russia	Mega Grant (i.e.,	Launched in 2010 by the Government of the Russian Federation, the program

	Resolution No. 220)	provides grants of up to $5 million USD to conduct research in Russia. The program hopes to bring Russian scientists residing abroad as well as foreign scientists to Russian institutions.
South Korea	Brain Return 500	Established by the Institute for Basic Science, the goal of the program is to attract 500 talented young scholars and scientists back to South Korea by 2017.
Spain	Spanish Ramón y Cajal Program	Funded by the Spanish Ministry of Economy and Competitiveness, the program provides financial support to PhD researchers for a period of five years
Sub-Saharan Africa	Homecoming Revolution	Started in 2003, the goal of Homecoming Revolution is to bring highly skilled Africans back to their homelands.
Sweden	Study in Sweden Swedish Institute	The institute is a public agency that provides grants to researchers around the world in order to establish cooperating and lasting relations with other countries. A variety of programs and grants are available depending on the applicant's nationality.
Thailand	Reverse Brain Drain (RBD)	The RBD initiative by Thailand's National Science and Technology Development Agency began in 1990. Initially, the primary goal of the initiative was to promote the permanent return of overseas Thai professionals. In 1997, the RBD's main objective shifted to the promotion of temporary returns of science and technology professionals. As of 2007, RBD promotes the brain circulation of Thai professionals overseas.
Turkey	2232 Repatriation Research Scholarship Program	Enacted by the Scientific and Technological Research Council of Turkey, the program encourages the return of successful Turkish researchers from abroad to continue their work in their home country.

SOURCE: Han, Xueying et al. "Will They Stay or Will They Go? International Graduate Students and Their Decisions to Stay or Leave the U.S. upon Graduation." Ed. Alejandro Raul Hernandez Montoya. PLoS ONE 10.3 (2015): e0118183. PMC. Web. 1 Sept. 2016.

E

Brief Extracts from the Award Synopses of NNCIs

This appendix lists brief extracts from the award synopses of NNCIs. The list is separated into new facilities and legacy facilities.

NEW FACILITIES

- Mid-Atlantic Nanotechnology Hub for Research, Education and Innovation, University of Pennsylvania with partner Community College of Philadelphia, principal investigator (PI): Mark Allen[1]

MANTH will enable access to leading-edge research and development facilities and expertise for academic, government, and industry researchers conducting activities within all disciplines of nanoscale science, engineering, and technology. Examples of its capabilities include: electron-beam, photo-, imprint- and soft-lithographies; material deposition and etching; multiscale 3D printing; laser micromachining; electron and scanning probe microscopy; tip-based nanofabrication; and ion and electron beam milling.

This site will allow users in the mid-Atlantic region, the nation's fifth largest economic area, to access the Singh Center for Nanotechnology, where they can perform nanofabrication and measurement tasks, and interact with nanotechnology experts. The Singh Center is located at the University of Pennsylvania in downtown Philadelphia, and is highly accessible to over 100 regional academic institutions and the industry-rich mid-Atlantic region.

- Montana Nanotechnology Facility, Montana State University with partner Carlton College, PI: David Dickensheets

MONT helps meet the growing need faced by regional and national researchers for access to nanofabrication tools and processes at the interdisciplinary frontiers, with local expertise related to microelectromechanical systems (MEMS) and micro-opto-electromechanical systems (MOEMS), microfluidics, nanostructured materials with unique optical, mechanical or thermal properties, ceramic materials, bio-inspired and bio-derived nanostructures, and bacteria or bacterial biofilms incorporated into micro- or nano-engineered substrates. The MONT site serves both regional users in the northern Rocky Mountains and Great Plains and users from across the U.S. who need the specific expertise and equipment found at Montana State University. Those users are pursuing diverse objectives related to advances in health care diagnostics and surgical solutions, sources of clean energy, remediation strategies for contaminated soils, and technologies related to optical telecommunications, imaging systems and advanced computing.

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[1] Mid-Atlantic Nanotechnology Hub for Research, Education and Innovation, http://www.nsf.gov/awardsearch/showAward?AWD_ID=1542153, accessed August 22, 2016.

- Soft and Hybrid Nanotechnology Experimental Resource, Northwestern University with partner University of Chicago, PI: Vinayak Dravid

SHyNE addresses emerging needs in synthesis/assembly of soft/biological structures and integration of classical clean-room capabilities with soft-biological structures, providing expertise and instrumentation related to the synthesis, purification, and characterization of peptides and peptide-based materials. SHyNE coordinates with Argonne National Lab facilities and leverages existing super-computing and engineering expertise under Center for Hierarchical Materials Design (CHiMaD) and Digital Manufacturing and Design Innovation Institute (DMDII), respectively.

- The Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure, Virginia Polytechnic Institute and State University, PI: Michael Hochella

VT NCE2NI provides an NNCI site to specifically support researchers who work with nanoscience- and nanotechnology-related aspects of the Earth and environmental sciences/engineering at local, regional, and global scales, including the land, atmospheric, water, and biological components of these fields. The national presence of VT NCE2NI is significantly enhanced by a close partnership with the Environmental Molecular Sciences Laboratory (EMSL) at Pacific Northwest National Laboratory (PNNL). NNCI geo- and environmental science/engineering users have access to both the Virginia Tech and EMSL/PNNL sites depending on specific technical needs and geographic considerations. VT NCE2NI consists of (i) the 15,000 sq. ft. Nanoscale Characterization and Fabrication Laboratory (NCFL) that houses a broad array of high-end, state-of-the-art electron-, ion-, and X-ray-based characterization tools, sample preparation laboratories, as well as meeting space and ample office space for visitors; and (ii) the 6,300 sq. ft. Virginia Tech Center for Sustainable Nanotechnology (VT SuN) which contains extensive nanomaterials synthesis facilities and knowhow (in aqueous, soil/solid media, and atmospheric environments), characterization tools, and experimentation/reactor systems.

- North Carolina Research Triangle Nanotechnology Network, North Carolina State University with partners Duke University and University of North Carolina-Chapel Hill, PI: Jacob Jones

The RTNN focuses on pioneering, studying, and refining innovative methods to catalyze both traditional and emerging nanotechnology research areas, including those from Biology, Biomedical Engineering, Textile Engineering, Environmental Engineering, Agriculture, Soil Science, Forest Biomaterials, and Plant & Microbial Biology. RTNN technical capabilities span nanofabrication and nano-characterization of traditional hard, dry materials (i.e., 2D and 3D nanomaterials, metamaterials, photonics, and heterogeneous integration) and emerging soft, wet materials (i.e., tissue, textile, plant, and animal nanomaterials). Specific areas of capability include the environmental assessment of nanotechnology, atomic layer deposition, flexible integrated systems, and fluidic systems. The RTNN will enable emerging research areas by adding additional process flows and tools throughout the project that enable new ways of integrating and interfacing the nano-scale with the human-scale.

- San Diego Nanotechnology Infrastructure, University of California, San Diego, PI: Yu-Hwa Lo

The SDNI site will build upon the existing Nano3 user facility and leverage additional specialized resources and expertise at the University of California at San Diego. The SDNI site is committed to broadening and further diversifying its already substantial user base. The proposed strategic goals include: (i) providing infrastructure that enables transformative research and education through open, affordable access to the nanofabrication and nanocharacterization tools and an expert staff capable of working with users to adapt and develop new capabilities, with emphasis in the areas of NanoBioMedicine, NanoPhotonics, and NanoMagnetism; (ii) accelerating the translation of discoveries and new nanotechnologies to the marketplace; and (iii) coordinating with other NNCI sites to provide uninterrupted service and creative solutions to meet evolving user needs.

- Nebraska Nanoscale Facility, University of Nebraska-Lincoln, PI: David Sellmyer

NNF will build upon the established Central Facilities of the Nebraska Center for Materials and Nanoscience to strongly galvanize research and education in nanotechnology in Nebraska and the region. The Central and Shared Laboratory Facilities include: Nanofabrication Cleanroom, Nanomaterials and Thin-Film Preparation, Nanoengineered Materials and Structures, Electron Microscopy, X-ray Structural Characterization, Scanning Probe and Materials Characterization, Low-Dimensional Nanostructure Synthesis, and Laser Nanofabrication and Characterization. Most of these facilities are housed in the 32,000 sq. ft. Voelte-Keegan Nanoscience Research Center that was completed in 2012 and funded by major grants from the National Institute for Standards and Technology and the University of Nebraska Foundation. The research in NNF is bolstered by strong research groups in nanoscale electronics, magnetism, and materials and structures for energy. NNF in turn will reinforce several centers and focused research programs including the Nebraska NSF-MRSEC: Polarization and Spin Phenomena in Nanoferroic Structures, DOE-EERE Consortium on Magnetic Materials, SRC-NIST Center for Ferroic Devices, NSF-Center for Nanohybrid Materials, and others.

- The Kentucky Multi-scale Manufacturing and Nano Integration Node, University of Louisville with partner University of Kentucky, PI: Kevin Walsh

The MMNIN is to combine micro/nano fabrication processes with the latest in 3D additive manufacturing technology to allow researchers to explore nanotechnology solutions to real-life problems in healthcare, energy, the environment, communication, and security. The MMNIN will be the first open user facility nationwide with a focus on 3D micro/nano fabrication and true multi-scale integration. Users will have access to design, simulation, and fabrication resources that span the nanometer to meter scales, and the expertise to effectively integrate these processes. At the nano-scale, MMNIN will provide rapid prototyping capabilities based on election- and ion-beam induced processes and two-photon polymerization along with the expertise to convert the prototyped structures to functional devices. At the micro-scale, users will have access to a variety of unique fabrication processes including stress engineered thin-film deposition for self-programmed 2D to 3D fabrication, 128 level grayscale lithography for rapid prototyping of complex 3D structures, micro aerosol jet 3D printing using conductive, resistive, dielectric and biological materials, as well as a diversity of traditional semiconductor and MEMS fabrication processes using MMNIN’s new class 100 $30M, 10,000 sq. ft. cleanroom facility. At the meso/macro-scale, MMNIN offers automated roll-to-roll manufacturing processes and the latest in additive manufacturing tools for 3D printing custom structures and enclosures using metals and/or polymers. MMNIN also offers a variety of characterization techniques ranging from transmission electron microscopy to squid magnetometry.

LEGACY FACILITIES

- Texas Nanofabrication Facility, University of Texas at Austin, PI: Sanjay Banerjee[2]

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[2] Texas Nanofabrication Facility, http://www.nsf.gov/awardsearch/showAward?AWD_ID=1542159, accessed August 22, 2016.

The TNF will facilitate breakthroughs in nanoscience and technology, with applications in nanoelectronics/photonics, green energy and healthcare in the Southwest and in the Nation, by providing state-of-the-art capability in nanodevice prototyping, metrology and nanomanufacturing.

Serves one of the 11 largest population areas, large Hispanic population, new med school

- Northwest Nanotechnology Infrastructure, University of Washington with partner Oregon State University, PI: Karl Bohringer

The NWNI serves as a broad-based nanotechnology resource, though three principal research focus areas are highlighted in which the site will provide leadership: (i) Integrated Photonics, which aims at enabling large-scale photonic networks, which are expected to overcome current limits in speed and bandwidth of electronic circuits. Beyond information processing, the miniaturization and integration of photonics in medical devices is facilitating the development of new, minimally invasive health diagnostics; (ii) Advanced Energy Materials and Devices, which aims at providing the scientific and engineering basis for clean energy solutions, including the creation of better batteries or scalable and environmentally benign materials for solar power; and (iii) Bio-Nano Interfaces and Systems, which provides the infrastructure and expertise for inventing and demonstrating new devices for biomedical applications, enabling advances in protein modeling, drug delivery, sensors, bio-scaffolds and bioelectronics. The physical infrastructure consists of the Washington Nanofabrication Facility (WNF, Seattle) and the Microproducts Breakthrough Institute (MBI, Corvallis) for making, the Molecular Analysis Facility (MAF, Seattle) and the Materials Synthesis & Characterization Facility (MaSC, Oregon) for measuring and distributed computational resources for modeling in design and analysis.

- Southeastern Nanotechnology Infrastructure Corridor, Georgia Institute of Technology with partners North Carolina A&T State University and University of North Carolina-Greensboro, PI: Oliver Brand

The Southeastern Nanotechnology Infrastructure Corridor (SENIC) will create a partnership between the Institute for Electronics and Nanotechnology at the Georgia Institute of Technology and the Joint School of Nanoscience and Nanoengineering, an academic collaboration between North Carolina A&T State University (NCA&T) and the University of North Carolina at Greensboro (UNCG). With access to more than 230 nanotechnology fabrication and characterization tools, SENIC's goal is to provide a one-stop-shop approach, covering both top-down approaches using nanoscale patterning, as well as bottom-up approaches based on nanomaterials synthesis and additive processing. A particular strength of the partnership is the ability to connect nanomaterials and devices to full packaged systems. This helps transition nanoscale research achievements more quickly into high-impact applications in biomedical/health, energy, communication, smart transportation, textiles and smart agriculture.

- Midwest Nano Infrastructure Corridor, University of Minnesota Twin Cities with partner North Dakota State University, PI: Stephen Campbell

The Midwest Nano Infrastructure Corridor (MINIC) National Nanotechnology Coordinated Infrastructure (NNCI) site at the University of Minnesota will provide access to leading edge micro and nano fabrication capabilities for the research and development of nanoscience and technology. The MINIC core facilities represent more than $50M in labs and equipment as well as more than 400 man-years of staff expertise. MINIC will support a broad spectrum of nano R&D, however it will target researchers in two new areas: the application of two-dimensional materials and the use of nano in biology and medicine. By partnering with North Dakota State University, MINIC will also enable the packaging of nano devices. This allows researchers to perform reliability testing and to incorporate these devices into complex electronic systems. To better recruit and serve external users, MINIC will add three new process Focus Areas. The first will support the deposition of a broad variety of 2D thin films, beginning with graphene and the transition metal dichalcogenides. Users will be able to build devices on top of their own substrates without the low yield and variability associated with exfoliation. MINIC will also provide new modeling tools to support this area. The second Focus Area will be led by North Dakota State University's Packaging Center, which has long-standing expertise in the area. This will enable researchers in academia and industry to economically package nanoscale devices, including difficult applications such as RF devices, MEMS, power devices, and 3D multichips. MINIC's third Focus Area will support external users working in bio nanotechnology by providing all the facilities and equipment needed to form nanoparticle suspensions, perform sizing and zeta potential measurements, use them to expose cell cultures in a BSL2 environment, and characterize the result with confocal and fluorescence microscopy.

- Stanford Site, Stanford University, PI: Kathryn Moler

Stanford will open the Stanford Nano Shared Facilities (SNSF), the Stanford Nanofabrication Facility (SNF), the Mineral Analysis Facility (MAF), and the Environmental Measurement Facility (EMF) more fully to external users. Open access to these facilities will not only promote the progress of science but also accelerate the commercialization of nanotechnologies that can solve a broad array of societal problems related to energy, communication, water resources, agriculture, computing, clinical medicine, and environmental remediation. Stanford will create and assemble a comprehensive online library of just-in-time educational materials that will enable users of shared nanofacilities at Stanford and elsewhere to acquire foundational knowledge independently and expeditiously before they receive personalized training from an expert staff member. The Stanford Site's shared nanofacilities will offer a comprehensive array of advanced nanofabrication and nanocharacterization tools, including resources that are not routinely available, such as an MOCVD laboratory that can deposit films of GaAs or GaN, a JEOL e-beam lithography tool that can inscribe 8-nm features on 200-mm wafers, a NanoSIMS, and a unique scanning SQUID microscope that detects magnetic fields with greater sensitivity than any other instrument. The facilities occupy ~30,000 ft2 of space, including 16,000 ft2 of cleanrooms, 6,000 ft2 of which meet stringent specifications on the control of vibration, acoustics, light, cleanliness, and electromagnetic interference. The staff members who will support external users have acquired specialized expertise in fabricating photonic crystals, lasers, photodetectors, optical MEMS, inertial sensors, optical biosensors, electronic biosensors, cantilever probles, nano-FETs, new memories, batteries, and photovoltaics.

- Cornell Nanoscale Science and Technology Facility, Cornell University, PI: Daniel Ralph

The unique nanofabrication capabilities that the CNF will make available to the nation's researchers include world-leading electron-beam lithography, advanced optical lithography, dedicated facilities for soft lithography, and direct-write tools for rapid prototype development, along with the flexibility to accommodate diverse projects through the ability to deposit and etch a very wide variety of materials. Under this National Nanotechnology Coordinated Infrastructure (NNCI) site award, hundreds of engineers and scientists nationwide, from throughout academia, industry, and government, will utilize CNF's unique toolset and technical staff. The new research and technology development that the CNF makes possible will transform many fields of engineering and science, spanning sensor and actuator arrays for probing how the brain works; improved photovoltaics, batteries, and fuel cells for economical renewable energy; new types of electronic devices that surmount limitations of silicon; fabrication of living tissues and organs; distributed measurement networks for geosciences; microbiome characterization and manipulation; on-chip signal processing with light; precision agriculture using new sensors; low-cost medical diagnoses; and improved quantum devices for utilizing entanglement.

- Nanotechnology Collaborative Infrastructure Southwest, Arizona State University with partners Maricopa County Community College District and Science Foundation Arizona, PI: Trevor Thornton

The goals of the NCI-SW are to build a southwest regional infrastructure for nanotechnology discovery and innovation, to address societal needs through education and entrepreneurship, and to serve as a model site of the NNCI. The NCI-SW site will encompass six collaborative research facilities: the ASU NanoFab, the LeRoy Eyring Center for Solid State Science, the Flexible Electronics and Display Center (FEDC), the Peptide Array Core Facility, the Solar Power Laboratory (SPL), and the User Facility for the Social and Ethical Implications of Nanotechnology. The NCI-SW site will open the FEDC and SPL to the broader research community for the first time. The site will provide particular intellectual and infrastructural strengths in the life sciences, flexible electronics, renewable energy and the societal impact of nanotechnology. ASU will collaborate with Maricopa County Community College District (MCCCD) and Science Foundation Arizona (SFAz) to develop STEM materials with a nanotechnology focus for A.S. and A.A.S students in communities throughout metropolitan Phoenix and rural Arizona. NCI-SW will provide entrepreneurship training for users who wish to commercialize nanotechnology in order to benefit society. To facilitate the commercialization of research breakthroughs, the NCI-SW will support prototyping facilities and low-volume manufacturing pilot lines for solar cells, flexible electronics and biomolecular arrays.

- The Center for Nanoscale Systems at Harvard University, Harvard University, PI: Robert Westervelt

CNS provides a collaborative, multi-disciplinary research environment that allows researchers from academia and industry to study and develop new structures, devices, systems, and technologies in fields ranging from biomedicine to nanoscale electronics and photonics. CNS offers tools for nanofabrication, electron microscopy, and characterization of nanoscale systems, with technical expertise and assistance provided by its staff. CNS is one of the most active nanofabrication and imaging facilities in the world with more than 1500 users, and it is an important part of the high-technology boom in the Northeast. As part of the previous NNIN, CNS developed diverse and versatile facilities including multi-length-scale optical and electron-beam lithography, focused ion beam (FIB) and reactive ion etch (RIE) systems to shape structures, and soft lithography expertise to enable fabrication of a wide variety of microfluidic systems. These tools allow users to push the frontiers of nanoscale electronics and photonics using nontraditional materials, and they enable the development of sensor systems for biomedicine. CNS researchers pursue advanced topics including plasmonics, diamond photonics, nanoscale sensors, and atomic-layer devices. CNS has an outstanding suite of imaging and characterization tools including an aberration-corrected STEM, a high resolution TEM, a CryoTEM, and an Atom Probe for 3D tomography, as well as scanned probe microscopes, and linear and non-linear optical microscopes. Its characterization tools permit detailed analysis and assessment of materials, components, and systems, providing researchers with a comprehensive platform for nanotechnology research.

F

Committee Biographies

CELIA I. MERZBACHER, *Chair***,** is the vice president of Innovative Partnerships at Semiconductor Research Corporation (SRC). Dr. Merzbacher is primarily responsible for developing novel partnerships with stakeholders in government and the private sector in support of SRC's research and education goals. Before joining SRC, Dr. Merzbacher was assistant director for technology R&D in the White House Office of Science and Technology Policy (OSTP), where she coordinated and advised on a range of issues, including nanotechnology, technology transfer, technical standards, and intellectual property. At OSTP she oversaw the National Nanotechnology Initiative (NNI), the multiagency federal program for nanotechnology research and development. She also served as executive director of the President's Council of Advisors on Science and Technology, which is composed of leaders from academia, industry, and other research organizations, and advises the president on technology, scientific research priorities, and math and science education. Previously, Dr. Merzbacher was on the staff of the Naval Research Laboratory (NRL) in Washington, D.C. As a research scientist at NRL, she developed advanced optical materials, for which she received a number of patents. She also worked in the NRL Technology Transfer Office, where she was responsible for managing NRL intellectual property. Dr. Merzbacher served on the board of directors of the American National Standards Institute and led the U.S. delegation to the Organisation for Economic Cooperation and Development, Working Party on Nanotechnology. Dr. Merzbacher received her B.S. in geology from Brown University and M.S. and Ph.D. in geochemistry and mineralogy from the Pennsylvania State University.

JAMES S. MURDAY, *Vice Chair***,** is the director of physical sciences at the University of Southern California's (USC's) Washington, D.C., Office of Research Advancement. He received a B.S. in physics from Case Institute of Technology in 1964 and a Ph.D. in solid state physics from Cornell in 1970. Before joining USC's Office of Research Advancement in the fall of 2006, he was at the NRL, where he served as bench scientist from 1970 to 1974, led the surface chemistry effort from 1975 to 1987, and was superintendent of the Chemistry Division from 1988 to 2006, when he retired from federal service. Additional responsibilities include these: from May to August 1997 he served as acting director of research for the Department of Defense DOD) Research and Engineering; from January 2003 to July 2004, he served as chief scientist, Office of Naval Research (ONR); from January 2001 to April 2003 he served as director of the National Nanotechnology Coordination Office; and from January 2001 to November 2006, he served as executive secretary of the U.S. National Science and Technology Council's Subcommittee on Nanometer Science Engineering and Technology (NSET). He is a member of the American Physical Society (APS), the American Chemical Society ACS, and the Materials Research Society; and he is a fellow of the American Vacuum Society's (AVS's) Science and Technology Society and the United Kingdom's Institute of Physics. His research interests in nanoscience began in 1983 as an ONR program officer and continued through his work at the NRL Nanoscience Institute. Under his direction, both the AVS and the International Union for Vacuum Science, Technology and Applications created a nanometer science/technology Division.

ROBERT H. AUSTIN is a professor of physics at Princeton University. He received his B.A. in physics from Hope College at Holland, Michigan, and his Ph.D. in physics from the University of Illinois at Urbana-Champaign in 1976. He held a postdoctoral position at the Max Planck Institute for Biophysical Chemistry from 1976 to 1979 and has been at Princeton University in the department of physics from 1979 to the present, achieving the rank of Professor of Physics in 1989. He is a fellow of the APS, a fellow of the American Association for the Advancement of Science (AAAS), and a member of the U.S. National Academies of Sciences, Engineering, and Medicine. He has served as a president of the Division of Biological Physics at APS, and of the present chair of the U.S. Liaison Committee of the International Union of Pure and Applied Physics. He has served as the biological physics editor for *Physical Review Letters*, serves on numerous review panels for NIH, NSF, the Burroughs Welcome Fund, and NIST, and is the editor of *Virtual Journal of Biological Physics*. He won the 2005 Edgar Lilienfeld Prize of the APS.

ANITA GOEL is the chairman and CEO at Nanobiosym. Dr. Goel is a world-renowned expert and pioneer in the emerging field of nanobiophysics, a new science at the convergence of physics, nanotechnology, and biomedicine. Dr. Goel was named by MIT's *Technology Review Magazine* as one of the world's "Top 35 Science and Technology Innovators." Her pioneering contributions to nanotechnology and nanobiophysics have been recognized globally by prestigious honors and awards, including multiple awards from U.S. government agencies such as the Defense Advanced Research Projects Agency (DARPA), DOD, DOE, AFOSR, NSF, USAID, and HHS. Dr. Goel holds a Ph.D. and an M.A. in physics from Harvard University, an M.D. from the Harvard-MIT Joint Division of Health Sciences and Technology (HST) at Harvard Medical School and a B.S. in physics with honors and distinction from Stanford University. As chairman and CEO of Nanobiosym and Nanobiosym Diagnostics, Dr. Goel has harnessed these fundamental insights to invent, incubate, and start commercializing next-generation nanotechnology platforms like Gene-RADAR® for mobile and personalized health, energy harvesting and quantum computing with molecular nanomachines that read and write information in DNA. She served on the Committee on Manufacturing, Design, and Innovation of the National Academy of Engineering (NAE) to look at the future of manufacturing in the U.S. Dr. Goel also serves on the Canadian Institute for Advanced Research (CIFAR) research council to advise their president on the development of advanced research roadmaps for Canada Dr. Goel is a fellow of the World Technology Network, a fellow-at-large of the Santa Fe Institute, an adjunct professor at the Beyond Institute for Fundamental Concepts in physics, and an associate of the Harvard Physics Department. She also serves on the Nanotechnology Advisory Board of Lockheed Martin Corporation and the Scientific Advisory Board of Pepsico. Dr. Goel was recently awarded the XPRIZE in the 2013 Nokia Sensing XCHALLENGE.

DOUGLAS W. JAMISON is the chairman and chief executive officer at Harris & Harris Group, Inc., a publicly traded venture capital company listed on the Nasdaq Global Market (NASDAQ: TINY). Harris & Harris Group builds transformative companies enabled by disruptive science. He has previously held the positions of president, chief operating officer, and chief financial officer of Harris & Harris Group, Inc. He is also currently chairman and chief executive officer of H&H Ventures Management, Inc., a wholly owned subsidiary of Harris & Harris Group. He is chairman of the board of Directors of HZO, Inc., and ProMuc, Inc., as well as a member of the Board of Directors of Produced Water Absorbents, Inc., and a Board observer in ABS Materials, Inc., and Metabolon, Inc., privately held portfolio companies of Harris & Harris Group. He was responsible for Harris & Harris Group's investment in Solazyme, Inc. (Nasdaq: SZYM) prior to it going public in May 2011. He was also a member of the Board of Directors of Innovalight, Inc., prior to its acquisition by E.I. du Pont de Nemours and Company. He is co-editor-in-chief of "Nanotechnology Law & Business." He was a member of the University of Pennsylvania Nano-Bio Interface Ethics Advisory Board. Prior to joining Harris & Harris Group, he was a Senior Technology Manager at the University of Utah Technology Transfer Office, where he managed intellectual property in physics, chemistry and the engineering sciences. He is a graduate of Dartmouth College (B.A., 1992) and the University of Utah (M.S., 1999).

GERHARD KLIMECK is the director of the Network for Computational Nanotechnology and the Reilly Director of the Center for Predictive Materials and Devices and Professor of Electrical and Computer Engineering at Purdue University. He is a fellow of the Institute of Physics (IOP), a fellow of the APS, a fellow of the Institute of Electrical and Electronics Engineers (IEEE), and member of the Eta Kappa Nu

(HKN) and Tau Beta Pi (TBP) honor societies.. He guides the technical developments and strategies of nanoHUB.org, which annually serves over 320,000 users worldwide with online simulation, tutorials, and seminars. Professor Klimeck's research interests are the modeling of nanoelectronic devices, parallel cluster computing, and genetic algorithms. He headed the development of the Nanoelectronic Modeling Tool—NEMO5. Dr. Klimeck was the supervisor of the High-Performance Computing Group and a principal scientist at the NASA Jet Propulsion Laboratory, California Institute of Technology. Previously he was a member of technical staff at the Central Research Lab of Texas Instruments, where he served as manager and principal architect of the Nanoelectronic Modeling (NEMO 1-D) program. At JPL and Purdue, Dr. Klimeck developed the Nanoelectronic Modeling tool (NEMO 3-D) for multimillion atom simulations. He received his Ph.D. in 1994 on quantum transport from Purdue University and his German electrical engineering degree in experimental studies of laser noise propagation in 1990 from Ruhr-University Bochum. Dr. Klimeck's work is documented in more than 220 peer-reviewed jounal articles and 180 papers in proceedings publications and more than 220 invited and 410 contributed presentations to conferences. His h-index is 37 on the Web of Science and 47 on Google Scholar.

MARTIN A. PHILBERT is a professor of toxicology and dean at the University of Michigan. He became dean of the University of Michigan School of Public Health on January 1, 2011, having previously served as senior associate dean for research at the school since 2004. He arrived at UM in 1995 from Rutgers' Neurotoxicology Laboratories, where he was a research assistant professor. He has maintained a continuously federally funded portfolio of basic research activities throughout his career. Most recently his work has been funded by the National Institutes of Health, the Department of Air Force, and the National Cancer Institute. At the national level, he is recognized for his expertise in neurotoxicology and experimental neuropathology. He is the author of numerous research publications in top peer-reviewed journals and one book. Active research activities include experimental neuropathology, nitrocompound-induced encephalopathies, mitochondrial mechanisms in non-neuronal cell death, the development of nano-optical chemical systems for in vivo physiology, and nanostructure-based imaging and treatment of tumors of malignant gliomas.

NELLY M. RODRIGUEZ is the president of Catalytic Materials LLC. She has a Ph.D. from the University of Newcastle upon Tyne. As an associate professor of chemistry at Northeastern University she cofounded Catalytic Materials in 1995 and became the president in 2001. Her early career included a position as assistant professor at Universidad Industrial de Santander, Bucaramanga, Colombia. Part of her early industrial career includes a position as internal researcher at Airco Carbon and as researcher at the corporate research laboratories of Exxon Research & Engineering Co. Additional international experience was gained at Hokkaido University in Sapporo, Japan, during 1986. During her time at Pennsylvania State University in the materials research laboratory, she spent 1992-1994 as an assistant professor of materials and research and 1994-1996 as an associate professor. She has 110 publications; 28 patents; and one book edited. During her whole career, key research areas have always included aspects of carbon nanotechnology, heterogeneous catalysis, work with in situ transmission electron microscopy of materials and nanoparticles, as well as controlled atmosphere studies of carbon gasification by atomic oxygen and catalyzed carbon deposition processes.

BRIDGET R. ROGERS is associate professor of chemical and biomolecular engineering at Vanderbilt University. She obtained her Ph.D. and M.S. from Arizona State University in 1998 and 1990, respectively, and a B.S. from the University of Colorado Boulder, in 1984. Dr. Rogers completed her M.S. and Ph.D. work while holding a full-time engineering position with Motorola. From 1984 through 1998 she was an engineer in Motorola's Semiconductor Products Division, starting as a rotational engineer and rising to the level of technical staff scientist. Through her years at Motorola, she held positions as manufacturing process engineer in the areas of photolithography and etch, process development engineer in plasma and RIE etching, and technical staff scientist in materials characterization and development. Her specialty was electron spectroscopies, and her last project at

Motorola was diffusion barrier development for copper metallization. Dr. Rogers joined Vanderbilt as an assistant professor in the Chemical Engineering Department in 1998. Her research has focused on the relationships of processing, properties, and performance of technically important materials. In 2001 she won an NSF Career Award for development of alumina/zirconia alloys for high-k gate dielectrics. She was awarded a DoD Presidential Early Career Award for Scientist and Engineers (PECASE))for "contributions to fundamental studies of thin film growth mechanisms, and for being the first to prove experimentally that the composition of multi-component films deposited into microelectronic device features varied with depth into the feature." Dr. Rogers was a key contributor to the development of the cleanroom facilities for the Vanderbilt Institute of Nanoscale Science and Engineering. She is a fellow of AVS. Her recent activities with the AVS have been focused on nanomanufacturing. She led the Nanomanufacturing Focus Topic at the 2011-2013 AVS International Symposia and is currently the chair of the AVS Manufacturing Science and Technology Group. Dr. Rogers has also served on proposal review panels for the NSF Nanomanufacturing program.

LOURDES SALAMANCA-RIBA is a professor at the University of Maryland. Her research is in the areas of self-assembly of semiconductor nanowires and liquid crystal nanocomposites for hybrid photovoltaic applications, DNA-based biosensors and radiation sensors on GaAs, and materials called covetics that have high C content in the form of nanocarbon. Dr. Salamanca-Riba's research involves the use of transmission electron microscopes and the atomic force microscope at the Nanoscale Imaging, Spectroscopy, and Properties (NISP) Laboratory. Her project on covetics involves understanding the effects of nanocarbon on the structure and properties of metals. The incorporation of carbon enhances several properties of the host metal, such as its thermal and electrical conductivity, oxidation and corrosion resistance, and yield strength. Her project on DNA attached to GaAs aims at understanding the anchoring mechanism between thiolated DNA and GaAs that gives rise to arrays of single-stranded DNA molecules oriented normal to the surface of GaAs. These structures could be used for the fabrication of biosensors and radiation sensors. Her third project is in the growth and characterization of semiconductor nanowire arrays of ZnO for the fabrication of light-emitting devices. The nanowires are combined with liquid crystals for applications as hybrid photovoltaics in which the liquid crystal is the hole conductor and the ZnO the electron conductor. These solar cells are expected to have higher efficiencies than organic solar cells and to be less expensive to produce than inorganic solar cells.

BRENT M. SEGAL is the director of Advanced Research Programs at Lockheed Martin. He is also chief technologist for Lockheed Martin Nanosystems, following the acquisition of the Nantero government business in 2008. In his role at Lockheed Martin, Dr. Segal has a broad charter to integrate nanotechnology throughout the Lockheed Martin product portfolio. In addition he is active in the Healthcare, Energy, and Cleantech spaces, acting as a technology scout to bring small companies and university projects to Lockheed Martin. He assists with government program management for projects involving sensors, nanoelectronics, and materials science with DOD, DOE, and other customers. Dr. Segal received a B.S. in biochemistry from Reed College and a Ph.D. in chemistry from Harvard University. Before joining Lockheed Martin, he cofounded and served as the chief operating officer of Nantero, a leading nanotechnology company, where he generated more than 100 patents and applications. Nantero raised $31.5 million in three private equity rounds (DFJ, CRV, and Globespan) and secured government programs totaling in excess of $50 million. Dr. Segal's interest in energy issues has led him to explore deals involving reduction of global CO_2 levels through the use of renewable energy sources such as biofuels, photovoltaics, wind power, and fuel cells.

SUBHASH C. SINGHAL, a member of the NAE**,** is a Battelle fellow emeritus at Pacific Northwest National Laboratory (PNNL). He joined the Energy and Environment Directorate at PNNL in April 2000 after having worked at Siemens Power Generation (formerly Westinghouse Electric Corporation) for more than 29 years. At PNNL, Dr. Singhal provided senior technical, managerial, and commercialization leadership to the laboratory's extensive fuel cell and clean energy programs. At Siemens/Westinghouse, he conducted and/or managed major research, development, and demonstration programs in the field of advanced materials for various energy conversion systems, including steam and gas turbines, coal gasification, and fuel cells. He has authored more than100 scientific publications, edited 18 books, received 13 patents, and given more than 325 plenary, keynote, and other invited presentations worldwide. Dr. Singhal is also an adjunct professor in the Department of Materials Science and Engineering at the University of Utah and a visiting professor at the China University of Mining and Technology-Beijing. He serves on the advisory boards of the Department of Materials Science and Engineering at the University of Florida, of the Florida Institute for Sustainable Energy, of the Division of Materials Science and Engineering at Boston University, and of the Center on Nanostructuring for Efficient Energy Conversion at Stanford University. Dr. Singhal is a member of the the Washington State Academy of Sciences. He has also served on many national and international advisory panels, including those of the National Materials Advisory Board of the National Research Council; the National Science Foundation; Materials Properties Council; U.S. Department of Energy; NATO Advanced Study Institutes and NATO Science for Peace Programs; the United Nations Development Program (UNDP), the United Nations Industrial Development Organization (UNIDO), the International Energy Agency (IEA); and the European Commission. Dr. Singhal holds a Ph.D. in materials science and engineering from the University of Pennsylvania and an M.B.A. from the University of Pittsburgh.

RHONDA STROUD is the head of the Nanoscale Materials Section at the NRL. In her current position she oversees DOD's most advanced electron microscope facility for nanoscale materials characterization. She is an expert in the application of transmission electron microscopy to advancing nanoscale materials development through establishing structure-composition-properties relationships, including understanding the life cycle of nanoscale materials in space environments. Her research interests span many classes of materials, from quasicrystals and oxide electronics to aerogel nanocomposites and nanoparticles formed in supernovas. She received her B.A. in physics from Cornell University in 1991 and her Ph.D. in physics from Washington University in St. Louis in 1996. After 2 years as an NRL-NRC postdoctoral fellow, she became an NRL research physicist in 1998 and was promoted to section head in 2007. Her publications include more than 250 journal articles and conference proceedings, with more than 5,000 citations and an h-index of 39. She holds five patents. She has served as an external reviewer for the Materials Division at Argonne National Laboratory and on DOE's external review committee for the electron microscopy user facilities at Oak Ridge National Laboratory and the National Center for Electron Microscopy at Lawrence Berkley National Laboratory. She was a director of the Microanalysis Society of America (MAS) (2011-2013) and now serves as the MAS Strategic Planning Chair (2015-2018). She has received many awards for her work, including election to fellowship in the APS and the Meteoritical Society, the NRL Sigma Xi Young Investigator Award, and the naming of an asteroid in her honor by the International Astronomical Union.

MICHAEL S. TOMCZYK is the Innovator in Residence at Villanova University, where he is engaged in a variety of innovation activities through the Center for Innovation, Creativity, and Entrepreneurship (ICE) in Villanova's School of Business. He joined Villanova after retiring from the Wharton School at the University of Pennsylvania (1995-2014), where he served as managing director of the Emerging Technologies Management Research Program, the Mack Center for Technological Innovation, and the Mack Institute for Innovation Management. Mr. Tomczyk is an authority on radical/disruptive innovation and an avid innovation champion dedicated to helping to develop, guide, and promote emerging technologies and applications. He is a frequent speaker on innovation topics at insight-building workshops and conferences for industry, academic, and government organizations. His research and writing currently focus on innovations in nanotechnology. Mr. Tomczyk is the author of *NanoInnovation: What Every Manager Needs to Know* (Wiley, 2014). As part of his research for this book he interviewed more than 150 leaders in nanotechnology science, engineering, and business. He is a senior member of the IEEE/IEC committee developing standards for the use of nanotechnology in electronics and a founding strategic advisor of the Nanotechnology Research Foundation. He has also contributed thought leadership in bioscience and medical innovation. For 10 years he served on the translational medicine committee at the Perelman School of Medicine, University of Pennsylvania. His numerous publications include a book chapter entitled "Applying the Marketing Mix (5 P's) to Bionanotechnology" in *Biomedical Nanotechnology* (Springer, 2011) and a coauthored research report *The Future of BioSciences: Four Scenarios for 2020 and Their Implications for Human Healthcare* (Wharton, 2006). During his career he has been involved in a wide range of high tech innovations, as a corporate executive and business consultant. As a technology pioneer, he is best known for managing the development and launch of the first full-featured home computer (the Commodore VIC-20, 1980) which was the first microcomputer to sell one million units. His Commodore experiences are described in his 1984 book *The Home Computer Wars*. He earned an M.A. in environmental studies from the University of Pennsylvania, an M.B.A. from the University of California, Los Angeles (UCLA), and a B.A. from the University of Wisconsin Oshkosh.