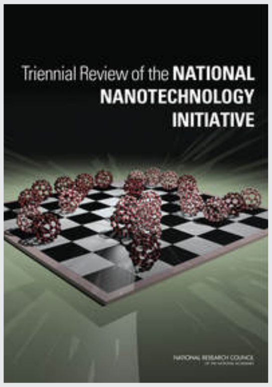

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DETAILS

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Triennial Review of the NATIONAL NANOTECHNOLOGY INITIATIVE

Committee on Triennial Review of the National Nanotechnology Initiative: Phase II

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

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[1] NAE, National Academy of Engineering.

Preface

The National Research Council was asked by the National Nanotechnology Coordination Office (NNCO) to review the National Nanotechnology Initiative (NNI) pursuant to the 21st Century Nanotechnology Research and Development Act, Section 5 of Public Law 108-153.[1] A cross-disciplinary, complex system with a diverse stakeholder base, the NNI coordinates nanotechnology-related R&D of 26 federal agencies. Owing to the complex and extensive nature of its review, the committee prepared an interim report on one of the three tasks within the statement of task (Appendix A)[2]—specifically, Task 2, assessment of progress and metrics. The main text of the interim report, which substantially informed this final report, is reprinted in Appendix E.

As the United States faces grave financial challenges, the ability of a program like the NNI to become economically effective in facilitating the creation of technology, products, and jobs in almost all sectors of the economy is a bright beacon. As co-chairs we are honored to work on evaluating a program that has such potential to benefit science and society.

We thank the committee members for their exceptional efforts in preparing this report. In executing its charge, the committee met five times from January 11 to

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[1] The first review by the National Research Council was published as *A Matter of Size: Triennial Review of the National Nanotechnology Initiative,* The National Academies Press, Washington, D.C., 2006.

[2] National Research Council, *Interim Report for the Triennial Review of the National Nanotechnology Initiative, Phase II,* The National Academies Press, Washington, D.C., 2012 (reprinted in Appendix E).

September 13, 2012. The committee also heard from a broad spectrum of speakers from government, industry, consultant organizations, nonprofit trade organizations, and academe. In particular, the committee thanks the following for their contributions to this study and for their participation in the committee's meetings: Robert Celotta, Hongda Chen, Hilary Flynn, Lynn E. Foster, Chuck Geraci, Piotr Grodzinski, Barbara Herr Harthorn, Bruce Kisliuk, Harriet Kung, Julia Lane, Robert Langer, Matthew Laudon, Minh Le, Alex Liddle, Carlos Peña, Tom Picraux, Robert Pohanka, Mihail C. Roco, Jonathan M. Samet, Maxine Savitz, Brent Segal, Neal D. Shinn, Phillip Singerman, Lewis E. Sloter II, Jerry Thursby, Sally Tinkle, Michael S. Tomczyk, and Bob Welch. We also thank the following National Cancer Institute staff for their participation in a conference call: Dorothy Farrell, George Hinkal, Nora Miralieva, and Stephanie Morris.

We and the committee also thank the interim director of the National Materials and Manufacturing Board, Dennis Chamot, and the study director, Erik Svedberg, for their help and guidance in performing this triennial review. And we express special appreciation to staff members Laura Toth, Linda Williams, Ricky D. Washington, and Ann Larrow for assistance with meeting arrangements and all the daily tasks.

Carol A. Handwerker, Co-Chair
Michael N. Helmus, Co-Chair
Committee on Triennial Review of the
National Nanotechnology Initiative: Phase II

Acknowledgment of Reviewers

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. 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 thank the following for their review of the report:

Harold G. Craighead, NAE,[1] Cornell University,
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Axel Scherer, California Institute of Technology.

[1] NAE, National Academy of Engineering.
[2] NAS, National Academy of Sciences.

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 Carl Lineberger, NAS, University of Colorado, Boulder, and Major General Richard Paul, U.S. Air Force, retired. Appointed by the National Research Council, they were 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.

Contents

Summary

The National Nanotechnology Initiative (NNI) is a multiagency, multidisciplinary federal initiative comprising a collection of research programs and other activities funded by the participating agencies and linked by the vision of "a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society."[1] As first stated in the 2004 NNI strategic plan, the participating agencies intend to make progress in realizing that vision by working toward four goals (Box S.1).

Planning, coordination, and management of the NNI are carried out by the interagency Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC) Committee on Technology (CoT) with support from the National Nanotechnology Coordination Office (NNCO). The NSET Subcommittee has established four topical working groups, which, along with the relationships of the above interagency bodies, are indicated in Figure S.1.

The NNI itself is described as follows on the nano.gov webpage:

> NNI today consists of the individual and cooperative nanotechnology-related activities of 26 Federal agencies with a range of research and regulatory roles and responsibilities. Fifteen of the participating agencies have research and development (R&D) budgets that relate to nanotechnology, with the reported NNI budget representing the collective sum of these investments. Funding support for nanotechnology R&D stems directly from NNI

[1] See National Nanotechnology Initiative, "NNI Vision Goals and Objectives," available at http://www.nano.gov/about-nni/what/vision-goals, accessed on January 9, 2013.

member agencies, not the NNI. As an interagency effort, the NNI informs and influences the Federal budget and planning processes through its member agencies and through the National Science and Technology Council (NSTC). The NNI brings together the expertise needed to advance this broad and complex field—creating a framework for shared goals, priorities, and strategies that helps each participating Federal agency leverage the resources of all participating agencies. With the support of the NNI, nanotechnology R&D is taking place in academic, government, and industry laboratories across the United States.

BOX S.1
The Four National Nanotechnology Initiative Goals

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

SOURCE: See http://www.nano.gov/about-nni/what/vision-goals, accessed on January 9, 2013.

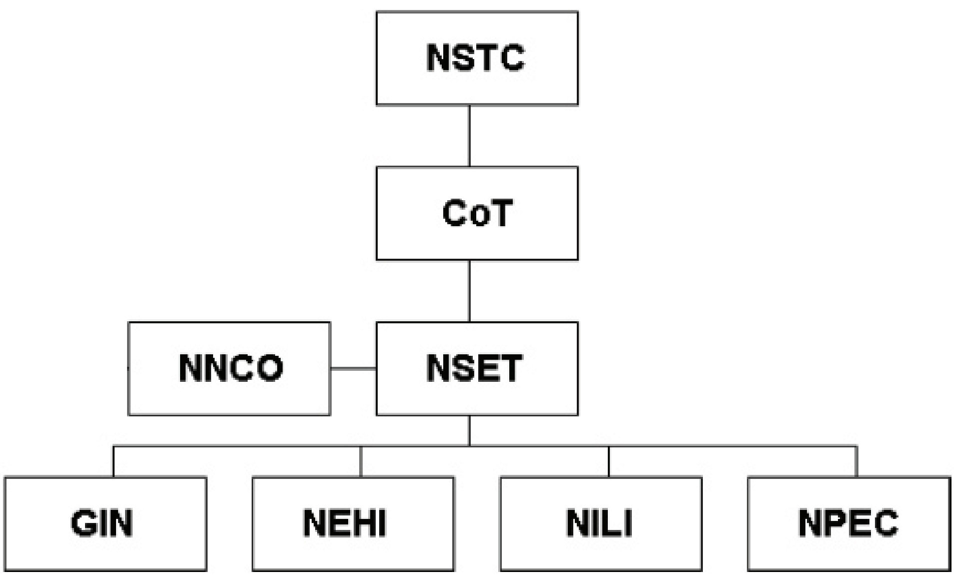

FIGURE S.1 Structure of the interagency bodies that coordinate and manage the NNI. The four working groups are GIN, Global Issues in Nanotechnology; NEHI, Nanotechnology Environmental and Health Implications; NILI, Nanotechnology Innovation and Liaison with Industry; and NPEC, Nanotechnology Public Engagement and Communication.

This report is the latest National Research Council review of the NNI, an assessment called for by the 21st Century Nanotechnology Research and Development Act of 2003. The overall objective of the review is to make recommendations to the NSET Subcommittee and the NNCO that will improve the NNI's value for basic and applied research and for development of applications in nanotechnology that will provide economic, societal, and national security benefits to the United States. (Box S.2 gives the abbreviated task in the charge for the Committee on Triennial Review of the National Nanotechnology Initiative.) In its assessment, the committee found it important to understand in some detail—and to describe in its report—the NNI's structure and organization (Chapter 1); how the NNI fits within the larger federal research enterprise, as well as how it can and should be organized for management purposes (Chapter 2); and the initiative's various stakeholders and their roles with respect to research (Chapter 3). Because technology transfer, one of the four NNI goals (see Box S.1), is dependent on management and coordination, the committee chose to address the topic of technology transfer last (Chapter 6), following its discussion of definitions of success and metrics for assessing progress toward achieving the four goals (Chapter 4) and management and coordination (Chapter 5). Addressing its tasks in this order would, the committee hoped, better reflect the logic of its approach to review of the NNI. Concluding remarks are provided in Chapter 7.

BOX S.2
Tasks in the Charge to the Committee

The charge to the committee, and the sections in which each topic is addressed, are as follows:

1. Examine the role of the NNI in maximizing opportunities to transfer selected technologies to the private sector, provide an assessment of how well the NNI is carrying out this role, and suggest new mechanisms to foster transfer of technologies and improvements to NNI operations in this area where warranted. (Chapter 6)
2. Assess the suitability of current procedures and criteria for determining progress towards NNI goals, suggest definitions of success and associated metrics, and provide advice on those organizations (government or non-government) that could perform evaluations of progress. (Chapter 4 and the committee's interim report,[1] reprinted in Appendix E)
3. Review NNI's management and coordination of nanotechnology research across both civilian and military federal agencies. (Chapter 5)

[1] National Research Council, *Interim Report for the Triennial Review of the National Nanotechnology Initiative, Phase II,* The National Academies Press, Washington, D.C., 2012 (reprinted in Appendix E).

In addressing the three tasks, the committee found a number of topics that were crosscutting and that are reflected in its recommendations with strong overlap and similarity (e.g., the importance of collecting and making certain information available on the Web). The committee considered that these crosscutting topics and the aspects of its recommendations that are overlapping represent the areas and actions that are of highest priority for the success of the NNI going forward. Below the committee distills these five topics and summarizes elements that its recommendations have in common. (The related full recommendations are presented later in this Summary and also in the report chapters in which they are developed.) The recommendations highlighted here are those the committee considered the most important. Additional recommendations are offered in the main text of the report.

The five crosscutting topics identified by the committee in addressing its statement of task are as follows:

- First, the lack of information at the project level on who is performing research, where, and on what has many implications. The nanotechnology community is not as cohesive as it could be, leading to a loss of potential benefits and value of the NNI investment. Researchers do not necessarily know they are part of the NNI, what its goals are, and who else it supports. As a result, they may not know of related research activity that could be of use to their own research and may not be fully aware of NNI-funded user facilities, networks, and other programs that are available. In addition, program managers do not necessarily know what other agencies are funding and, therefore, are not able to benefit from other government spending. Businesses do not have a central place where they can find researchers who are working in fields of interest.
- Second, planning, management, and coordination can be enhanced by developing and implementing interagency plans for focused areas, i.e., the signature initiatives and the working groups. Effective plans usually have clearly laid out goals, desired outcomes, and models and actions linking investment, outputs, and short-term outcomes to long-term outcomes. Effective plans also clearly identify roles and responsibilities, milestones and metrics, and reasonable time frames.
- Third, a website (such as nano.gov) has to effectively serve all the various stakeholder groups, including researchers, small and large businesses, investors, educators and students, and the media.
- Fourth, current advances in technology and methods—for example, for data collection and social network analysis—can be used effectively to develop and test metrics for assessing progress toward goals and for informing program leadership.

- Fifth, there are benefits from identifying, sharing, and implementing best practices, such as those described in this report, especially relating to technology transfer and commercialization. Too great a diversity of processes and agreements, and in some cases an associated lack of flexibility, can be a barrier to transitioning research results to commercial use. In addition to more conventional pathways for transitioning research from universities and government laboratories to businesses, partnerships with industry consortia, e.g., under the proposed AMTech or National Network for Manufacturing Innovation, can add new pathways.

The committee recognizes that a broad interagency initiative such as the NNI is managed differently from a program within a single agency. Critically, the NNI does not have a separate program budget, and the NSET Subcommittee and NNCO do not have budgetary authority—instead the funding for NNI research is part of the budgeting and program management within the agencies participating in the NNI. Funding allocations are made within the participating agencies according to their respective missions and how they see nanotechnology fitting within their agency. The NNCO budget is approved by the NSET Subcommittee and funded by agency contributions that are prorated according to the agencies' respective NNI budgets. The challenge, then, is for the NNI to develop, implement, and track targeted goals, metrics, and processes that allow participating agencies to maximize the return on their individual investments, while also maximizing the collective return to U.S. taxpayers and the nation.

Many aspects of the NNI and the activities of the federal agencies involved are to be commended and are even exemplary among federal initiatives. The NNI has successfully engaged agencies from across the government, including not only research agencies but also those with regulatory and other responsibilities (e.g., the U.S. Patent and Trademark Office, the National Institute for Occupational Safety and Health, and the Consumer Product Safety Commission) that are relevant to maximizing benefits from advances in nanotechnology while managing risks.

Equally noteworthy is the NNI's impact beyond the federal government. The NNI has sparked investment by states, universities, businesses, venture capital, and other nations worldwide.[2] Examples of state-funded university-based initiatives include those of the College of Nanoscale Science and Engineering in Albany, New York (http://cnse.albany.edu/Home.aspx), and the Joint School of Nanoscience and Nanoengineering, a collaboration between North Carolina A&T State University and the University of North Carolina at Greensboro (http://www.gatewayurp.com/

[2] For a listing of the many state-led efforts, see National Nanotechnology Initiative, "Regional, State, and Local (RSL) Nanotechnology Initiatives and Resources," available at http://www.nano.gov/initiatives/commercial/state-local, accessed September 25, 2012.

JSNN.html). Although private-sector investment and activity are difficult to quantify, there exists today a diverse and growing nanotechnology ecosystem comprising many stakeholder groups beyond the federal government and the researchers supported by NNI funding. Nevertheless, there are opportunities to substantially strengthen the initiative and increase its impact.

DEFINITIONS OF SUCCESS AND METRICS OF PROGRESS TOWARD ACHIEVING NNI GOALS

Key to determining progress in any initiative is having an explicit framework that links desired goals and specific long-term outcomes (e.g., the definitions of success) to investment (funding and other resources), implementation plans, actions, outputs, and short-term outcomes that can be measured and evaluated (metrics). The current practice of periodic strategic planning and reporting represents only some of the framework elements. That is, the NNI reports annually on budgets and expenditures by agency and subject-based program component areas and obtains anecdotal evidence of activity and accomplishments, some of them interagency, related to each of the four NNI goals (see Box S.1). The general lack of quantifiable targets or detail in these reports or from other NNI-wide sources (e.g., the NNI website) made it difficult for the committee to link what is reported to measurable progress toward realizing the NNI goals.

The interim report prepared by the committee for this study provided suggestions for definitions of success in meeting the current NNI goals.[3] Some examples from the 24 definitions in that report are as follows:

- The frontiers of knowledge are being substantially advanced, commensurate with the scale of funding.
- An appropriate scientific and technical workforce is being trained and educated in the United States.
- Vibrant, competitive, and sustainable industry sectors are being developed in the United States that use nanotechnology to enable the creation of new products, skilled employment, and economic growth.
- Rates of use are high for infrastructure that meets users' technical needs.
- Businesses of all sizes are aware of potential risks of nanomaterials and know where to obtain current information about the properties of and best practices for handling such materials.

[3] National Research Council, *Interim Report for the Triennial Review of the National Nanotechnology Initiative, Phase II,* The National Academies Press, Washington, D.C., 2012 (reprinted in Appendix E).

Despite their appropriateness, the definitions suggested in the committee's interim report are not all equally suited as targets against which progress can be measured, nor are the data for quantifying progress toward each equally easy to gather.

In addition to definitions of success, the committee's interim report included more than 20 possible metrics of progress toward achieving the four NNI goals, including, for example, "number of publications based on NNI-funded R&D, with analysis of authorship to assess the share that is multidisciplinary, multi-departmental, multiuniversity, multinational, and multisectoral (for example, academe-industry or academe-government)" (p. 162 in Appendix E) and "use of current infrastructure, according to numbers and types of users, and the outcomes of use of the infrastructure" (p. 167).

Yet lists of definitions of success and metrics of progress are not sufficient. The NNI needs a framework that links the high-level goals with specific actions, outputs, and outcomes that are measurable.

Recommendation S-1 (2-1): An overarching definition of success for the NNI as a federal initiative should be evidence that NNI agencies are establishing and implementing an effective, explicit framework for planning, managing, and coordinating publicly identified NNI interagency programs, such as the signature initiatives. Such a framework should be based on essential performance-management concepts, and plans for and progress toward specific outcomes should be reported annually in the NNI supplement to the President's budget.

Having a framework is only a first step in developing and implementing metrics; data are also required. With the NNI goals and proposed definitions of success in mind, the committee identified specific data sets to which various metrics reflecting national-level priorities could be applied.

Recommendation S-2 (4-1): Nine searchable data sets (listed in abbreviated form below) should be collected annually and made available on the NNI website to allow the NNI's impacts and successes to be assessed by internal and external interested parties and used for resource allocation and planning.

1. NNI-funded projects, including such information as researcher name and affiliation, funding agency and amount, and abstract.
2. Published documents arising from NNI activities.
3. Data related to impact, including frequently cited and downloaded papers and patents, invited presentations, special sessions at conferences, and reports in the mass media.
4. Number of students supported.

5. User facility and network use.
6. Data related to technology transfer, including details of meetings, workshops, conferences, and sessions in conferences.
7. Data related to education and outreach, including workshops, activities aimed at K-12 students, and museum exhibits.
8. U.S.-based nanotechnology job advertisements.
9. NNI-related communications about environmental, health, safety, and societal implications of nanotechnology, such as guidance from the National Institute for Occupational Safety and Health (NIOSH) regarding nanomaterials in the workplace.

For a full description of each data set, see Chapter 4.

Of these data sets, the first is the most critical and has the highest priority: knowing nanotechnology R&D projects, people, and organizations funded within the NNI will allow connections to be tracked over time from science to commercialization. Collecting and analyzing the data sets will require expertise and resources. To go from the data sets to metrics of progress toward selected definitions of success will require careful analysis and the development of proper models. Recognizing the variable and potentially significant cost associated with collecting the proposed data sets, the committee believes that the NSET Subcommittee and the NNI agencies are in the best position to identify an efficient and workable manner in which to collect the data, with priority given to the first data set. In addition, although it is beyond the committee's task and expertise to address the details of how this recommendation can be carried out and funded, it is understood that the task is quite substantial.

Recommendation S-3 (4-2): The NSET Subcommittee and the NNCO should obtain data-mining expertise to undertake the collection and collation of essential data sets, develop tools to analyze the data in accordance with the management and reporting needs of the NNCO and the agencies, and manage the process of making the data sets publicly available.

The committee notes that creating perfect data sets for assessing and managing the NNI is neither reasonable nor possible. The NNI is a large organization, and the data sets will probably be incomplete, although it can be expected that they will improve with time. Any commentary based on the data, metrics, and interpretations should acknowledge the known limitations.

Research on metrics is evolving quickly with the development and application of "big data" tools. It will be important to link databases; one useful way to do that is by unambiguously identifying the scientists involved and associating them with research results and outcomes.

Recommendation S-4 (4-4): NNI agencies should record NNI participants and link them to their work products and organizations by individual grants, using Open Researcher and Contributor ID (ORCID), and link these data to published paper and patent databases, which over time may be linked to social and economic outcomes.

MANAGEMENT AND COORDINATION

Management and coordination of the NNI have emphasized the sharing of information among participating agencies, development of strategic plans with broad goals, annual reports that include agency spending (planned and actual), and joint support of the NNI website, workshops, and other activities aimed primarily at nonresearch goals (such as support of regional, state, and local nanotechnology efforts) through the NNCO. Recently, the NNI created signature initiatives to promote coordination in targeted fields. Those management and coordination activities, some of which are required by law, are driven by the NSET Subcommittee and its working groups. The committee recommends steps that can increase interagency collaboration and progress toward the NNI goals.

Updating Interagency Management at All Levels

The four working groups (see Figure S.1) cover subjects that could benefit from greater interagency focus and coordination. Regarding the task of bringing together appropriate agency experts on such topics as global issues and environment and health implications, the effectiveness of the groups appears uneven. Although a description of the overarching purpose of each group is available on the NNI website, except in the case of Nanotechnology Environmental and Health Implications the committee was not able to determine what specific needs are addressed, what their priorities are, and what each group is planning and has accomplished.

The NNI and the global nanotechnology landscape have evolved since the working groups were established, and it is now both timely and important for the NSET Subcommittee to re-evaluate and, if appropriate, rebalance the working-group portfolio. There appears to be substantial opportunity to revise the roles of existing working groups or to create new working groups on user facility oversight and coordination, on education and workforce development, and perhaps in the future on other topics as well.

Recommendation S-5 (5-3): The NSET Subcommittee should regularly assess the working groups to ensure that each is serving a useful management and coordination role related to the goals and objectives of the NNI strategic plan. Working groups that are no longer useful should be redefined or eliminated, and new working groups should be formed as needed. In particular, the NSET Subcommittee should consider creating new groups in the areas of user facility oversight and coordination and education and workforce development.

Recommendation S-6 (5-4): Each working group should address specific goals and objectives and should develop and annually update plans for outputs and short-term outcomes that are related to longer-term outcomes. Ties to signature initiatives should be highlighted. The NNI annual report should include working group plans, such as information about annual objectives, activities, management, and accomplishments.

The human resources committed by the participating agencies are substantial, but there are concerns that interagency involvement does not extend to sufficiently high levels of the administration to inform budget decision making. The committee recognizes that there may be a trade-off between authority in the agencies and the ability to devote time and effort to the many NNI coordinating activities.

Recommendation S-7 (5-5): To improve engagement by senior NNI participating-agency officials and decision makers, the NSET Subcommittee should inform and obtain input from the NSTC Committee on Technology on NNI objectives and plans at least annually.

Strengthening Information Management and Communication

Acquisition and sharing of information are vital to the success of any enterprise as diverse, interdisciplinary, and complex as the NNI, but they also pose a challenge. Communications could increase the impact of the NNI by increasing general awareness of emerging nanotechnologies, by encouraging students to enter science, technology, engineering, and mathematics fields related to nanotechnology so that an educated workforce can be developed, and by educating the public on environmental, health, and safety issues and other issues related to nanotechnology. Those activities necessarily cover a wide set of audiences, from K-12 students and teachers through academic and business circles to the general population. The communication tools need to be appropriate for the intended audience.

The NNI website is a primary vehicle for managing and sharing a variety of information. It provides introductory material on nanotechnology aimed at all ages and contains links to NNI reports, workshop announcements, research centers and user facilities, and funding opportunities. However, the committee believes that the NSET Subcommittee and the NNCO can and should make two important improvements. First, organizing the website to provide portals and paths designed to guide specific groups of stakeholders (such as educators, small businesses, local governments, and nongovernment organizations) to resources would improve NNI communication substantially. Second, the website could offer a highly interactive and easily searchable dashboard that integrates information across agency-centric content. For example, it could serve as a central resource for all the relevant centers and facilities that would enable potential users to identify the instruments, capabilities, and expertise in each facility and center and would provide links for accessing them. It also could host the project-related data called for by the present report. Such a searchable database would allow all stakeholders to identify projects of interest, the participants involved, and the agencies funding the work. It would also aid agency program managers in becoming cognizant of related programs and investments by other agencies and thereby enhance the NNI's management and coordination capabilities.

> **Recommendation S-8 (5-7):** The NNI website (www.nano.gov) should be redesigned and its content organized to provide portals and guidance directed to the NNI stakeholder communities (industry, facilities, users, educators, mass media, and so on). The information should be appropriately integrated across the participating NNI agencies.

Advancing Signature Initiatives

In the annual report that accompanied the 2011 budget, the NNI announced signature initiatives aimed at developing technology in key fields in which focused and closely coordinated research and development (R&D) among agencies could lead to rapid advances. Whereas the breadth of NNI R&D and the diversity of agency missions and needs make it impractical and in some cases unhelpful for the NSET Subcommittee to manage and coordinate the entire portfolio of activities in support of NNI goals, the signature initiatives offer clear opportunities and pathways for accelerating progress in targeted subjects. The current signature initiatives are as follows:

- Nanotechnology for Solar Energy Collection and Conversion: Contributing to Energy Solutions for the Future;
- Sustainable Nanomanufacturing: Creating the Industries of the Future;
- Nanoelectronics for 2020 and Beyond;
- Nanotechnology Knowledge Infrastructure (NKI): Enabling National Leadership in Sustainable Design; and
- Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment.

For each signature initiative, a white paper outlines the need that is addressed, the focus topics in which research is needed, expected outcomes, and relevant agency expertise. In some cases, there are quantifiable technical targets, but the white papers include no plans for making or assessing joint progress toward the expected, and presumably desired, outcomes.

Recommendation S-9 (5-1): Each signature initiative team should develop a strategic plan. The NSET Subcommittee and the signature initiative teams should expand the associated white papers to include specific goals (outcomes) with quantifiable technical targets where possible, milestones for reaching them, expected outputs and short-term outcomes, and roles and responsibilities of the (two or more) participating agencies, the NSET Subcommittee, and the NNCO. Planned actions and outputs and short-term outcomes to document progress should be reported online and in the annual report.

Roadmapping

Each signature initiative, if successful, has the potential for considerable economic impact. Translating efficiently from research to technology solutions can be expedited by engaging with industry to identify goals and pathways for reaching them. An example of such direction setting is the International Technology Roadmap for Semiconductors. The fundamental elements of a roadmap need not be specific to a particular technology but should reflect recognition that the entities in the relevant industries need to come together and share information—something that not all industries have experienced in the past. The federal government can encourage industry members to collaborate on developing a roadmap.

The proposed Advanced Manufacturing Technology Consortium program (AMTech) is intended to stimulate early-stage technology development based on industry needs by incentivizing industry-led consortia (new or existing) that would support long-term basic and applied research on enabling technologies. AMTech also provides grants to consortia to develop roadmaps of critical long-term industry research needs. The NSET Subcommittee could expand efforts that encourage industry consortia to plan and fund long-term research, using programs similar to AMTech.

Recommendation S-10 (5-6): The NSET Subcommittee should incentivize groups in nanotechnology-enabled industries to participate in developing roadmaps and in partnering to address long-term research needs. Roadmapping would be especially helpful in realizing progress in the signature initiatives.

Exemplary models of management and coordination with robust planning and strong engagement among participants include the National Institutes of

Health cancer nanotechnology research program and the Nanoelectronics Research Initiative. The former is led and managed by the National Cancer Institute and the latter by a consortium of semiconductor companies in partnership with the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST).

TECHNOLOGY TRANSFER

The path from NNI-related funded research to practical application and commercialization can be long and complex. It involves actors in the private sector that use the results of NNI-related research but might not be integrated into the initiative. The NNI can help by removing barriers to private-sector access to and use of research results and infrastructure.

Current NNI activities aimed at technology transfer include holding workshops focused on regional nanotechnology economic development efforts and tracking and reporting Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) spending levels. Relevant NNI agencies—such as NIST, the Environmental Protection Agency, and the Food and Drug Administration—are involved in standards development at the national and international level. NNI reports include anecdotal evidence of research that has been incorporated into products, but little is known about where students go after graduation or about whether and what kinds of barriers stand in the way of nanotechnology commercialization. The data sets called for in the present report include information related to workforce and technology-transfer activities.

One reason that the NNI does not focus more resources on technology transfer may be that, aside from its novelty and the fact that there is little in the way of standards and regulatory certainty, nanotechnologies are not unusual in the challenges and obstacles faced in the movement of discoveries from the laboratory into application and use. Therefore, agencies rely on existing technology-transfer tools and processes—for example, cooperative research and development agreements between nongovernment and government entities, SBIR and STTR programs, and newer programs, such as NSF's I-Corps.

Ways in which the NNI can provide support for technology transfer include

- Easing access by businesses, especially small businesses, to user facilities and other resources by promoting widespread adoption of uniform best practices and intellectual-property terms and conditions;
- Continuing support of sound standards development, especially at the international level; and
- Revising the website to improve access to information related to commercialization, such as NIOSH guidance and relevant regulations.

Recommendation S-11 (6-4): Each NNI agency should identify best practices in intellectual property management and transfer those practices that were developed by it or by other institutions and then share among all agencies the recommended templates and guidelines for such best practices.

CONCLUDING COMMENTS

The NSET Subcommittee, NNI agencies, and the NNCO are to be commended for their work and progress to date in coordinating such a diverse multiagency program. The NNI has been a leader among interagency initiatives in many ways. Now it has an opportunity to make the initiative more effective and as a result more valuable to the nanotechnology community and the nation. Taking action to implement the recommendations in this report will be a measurable next step, which the committee believes will help the initiative to better fulfill its goals and facilitate progress toward its vision. It is noted that the recommendations in this Summary are considered key recommendations but are only a subset of all the recommendations the committee made. For the full set of recommendations see Chapters 2 through 6 in this report.

1

Introduction

OVERVIEW OF THE NATIONAL NANOTECHNOLOGY INITIATIVE

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. According to the 2011 NNI strategic plan,[1]

> The Vision of the NNI is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society. The NNI expedites the discovery, development, and deployment of nanoscale science, engineering, and technology to serve the public good, through a program of coordinated research and development aligned with the missions of the participating agencies.

Established in 2001 by President Clinton, and strongly supported by Presidents Bush and Obama and by six Congresses, the NNI strives not only to advance the frontiers of nanoscience and nanotechnology (see Box 1.1) but also to serve the public good through technology transfer, assessing and mitigating the risks associated with nanotechnology, educating students at all levels, reaching out to and informing the public about nanotechnology, developing a nanotechnology

[1] National Science and Technology Council (NSTC), *National Nanotechnology Initiative Strategic Plan,* Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf, accessed December 19, 2012.

BOX 1.1
Why Nanomaterials Are Special

Nanoscale particles are not new in either nature or science. However, the recent leaps in such fields as microscopy have given scientists new tools for understanding and taking advantage of phenomena that occur naturally when matter is organized at the nanoscale. In essence, these phenomena are based on “quantum effects” and other simple physical effects, such as expanded surface area. In addition, the fact that most biologic processes occur at the nanoscale gives scientists models and templates for imagining and constructing new processes that can enhance their work in medicine, imaging, computing, printing, chemical catalysis, materials synthesis, and many other fields. Nanotechnology is not simply working at ever smaller dimensions; rather, working at the nanoscale enables scientists to use the unique physical, chemical, mechanical, and optical properties of materials that naturally occur at that scale.

SOURCE: http://www.nano.gov/nanotech-101/special, accessed January 10, 2013.

workforce, and supporting the prominence of the United States in commercial applications and economic value and benefit.

The NNI sprang from advances in the ability to see, measure, and manipulate matter at the nanoscale, from the new properties that emerged from nanoscale materials and structures, and from the recognized potential for nanotechnology to provide benefits and solutions in response to national needs. It grew from the 8 federal agencies that came together in the late 1990s to form the Interagency Working Group on Nanotechnology to 26 participating agencies today with a corresponding increase in the federal budget for nanotechnology research from about $500 million in 2001 to nearly $1.8 billion in the President’s 2013 budget request. The cumulative investment in the NNI since 2001 (including the estimated spending in 2012) is about $16 billion. Of the 26 participating agencies, 15 have budgets for R&D. Nearly 95 percent of the total comes from five of the NNI charter agencies: the National Science Foundation (NSF), the Department of Defense (DOD), the National Institutes of Health (NIH), the Department of Energy (DOE), and the National Institute of Standards and Technology (NIST).

It should be noted that the nanotechnology investment is not controlled by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC) Committee on Technology. As described in the NNI implementation plan,[2] each agency invests in projects that

[2] NSTC, *NNI: Leading to the Next Industrial Revolution. The Initiative and Its Implementation Plan*, July 2000, pp. 38-40, available at http://www.wtec.org/loyola/nano/IWGN.Implementation.Plan/nni.implementation.plan.pdf, accessed January 8, 2013.

support its own mission and retains control over how it will allocate resources in light of its NNI proposals on the basis of the availability of funding; the substantial investment over the last decade has yielded progress in all aspects of nanoscale science and technology. Several thousand research projects in all 50 states and the District of Columbia have advanced the foundational knowledge and enabled unprecedented understanding and control of matter at the nanoscale. That has occurred through a system of new university research centers; nanotechnology networks involving academe and industry; national user facilities, such as those in DOE, NIST, and NIH; and many smaller infrastructure investments. There have been technological breakthroughs in such diverse arenas as biomedicine, electronics, communication, pharmaceuticals, energy and water resources, agriculture, and forestry.[3] New fields and materials—such as spintronics, plasmonics, metamaterials, graphene, and nanomanufacturing—have emerged and blossomed. Attention to and ability to address the environmental health and safety (EHS) challenges associated with nanotechnology have also advanced markedly.

Nanotechnology is not a single technology: It is the application of control and manipulation of matter at the nanoscale to create technology solutions—for example, for improving human health, optimizing available energy and water resources, supporting a vibrant economy, increasing the standard of living, and increasing national security. The successful discovery, development, and use of nanotechnology depend also on facilities, education, an educated workforce, technology transfer, risk assessment, and risk management.

With the NNI established through consensus and cooperation among the founding agencies, it quickly flourished and grew at the time of the enactment in 2003, with bipartisan support, of the 21st Century Nanotechnology Research and Development Act (Public Law 108-153).[4] That law made statutory many of the structures and activities that were already in place and required periodic planning, reviewing, and annual reporting to Congress of NNI progress toward its goals—a process needed for sound management and oversight.

The management and oversight structure of the NNI and the relationships among the various federal stakeholders are shown in a simplified form in Figure S.1 and in a more complete form in Figure 1.1. Central to NNI management and oversight is the interagency NSET Subcommittee, which is made up of representatives of the participating agencies and is cochaired by an agency representative (the position rotates among the agencies) and a representative of the White House

[3] National Nanotechnology Initiative, "Benefits and Applications," available at http://www.nano.gov/you/nanotechnology-benefits, accessed January 10, 2013.

[4] Public Law 108-153, 21st Century Nanotechnology Research and Development Act, available at http://www.gpo.gov/fdsys/pkg/PLAW-108publ153/html/PLAW-108publ153.htm, accessed November 13, 2012.

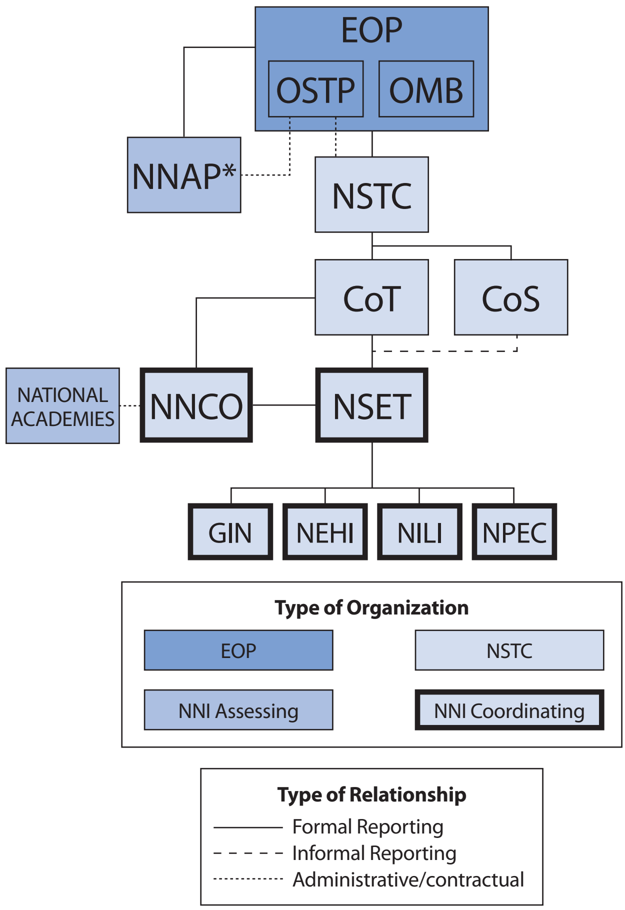

FIGURE 1.1 Coordination and assessment of the NNI. For definitions of acronyms, see Appendix B. NOTE: Executive Order 13349 designates the President's Council of Advisors on Science and Technology (PCAST) as the National Nanotechnology Advisory Panel (NNAP). SOURCE: National Science and Technology Council 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. Accessed December 12, 2012.

Office of Science and Technology Policy (OSTP). The NSET Subcommittee meets at least once a month to share projects, plans, strategies, and results.

The NSET Subcommittee has four working groups to enable enhanced focus on specific crosscutting issues that are important to the NNI. Three working groups were originally chartered in the 2004 NNI strategic plan: on Nanotechnology Environmental and Health Implications (NEHI), on Nanomanufacturing, and on Industry Liaison. By the time of the 2007 NNI strategic plan, the NSET Subcommittee had formed four working groups: NEHI remained, a merged Nanomanufacturing and Industry Liaison working group was renamed Nanomanufacturing, Industry Liaison, and Innovation (NILI), a new Global Issues in Nanotechnology (GIN) group, and a new Nanotechnology Public Engagement and Communications (NPEC) group. Membership in the working groups is open to all NNI member agencies.

As required by statute, the NSET Subcommittee develops and publishes a triennial strategic plan. The first, released in 2004, created the vision, goals, and categories of investment, or program component areas (PCAs), that are still in place with only minor adjustment. The PCA that comprised environmental, health, and safety (EHS), education, and societal implications was divided earlier to report EHS as a separate category. The four NNI goals are listed below:

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

Later strategic plans have retained the original vision and four goals, but there have been changes and additions. These successive strategic plans do not seem to be updated with respect to progress made since previous plans. In the 2008 strategic plan, the single PCA on societal dimensions was split into two: one containing EHS and one containing education and societal dimensions. Also in 2008, high-impact application opportunities and examples of critical research needs were added. The 2011 strategic plan included more detailed objectives for each goal, some of which are quantitative. Also new was an emphasis on collaborative agency activities, most notably the signature initiatives, "areas ripe for significant advances through close and targeted program-level interagency collaboration to enable the rapid advancement of science and technology in the service of national economic, security, and environmental goals by focusing resources on critical challenges and R&D gaps."[5]

Today, there are five signature initiatives:

- Nanotechnology for Solar Energy Collection and Conversion: Contributing to Energy Solutions for the Future.
- Sustainable Nanomanufacturing: Creating the Industries of the Future.
- Nanoelectronics for 2020 and Beyond.

[5] NSTC, *National Nanotechnology Initiative Strategic Plan, 2011, p. 39.*

- Nanotechnology Knowledge Infrastructure: Enabling National Leadership in Sustainable Design.
- Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment.

The breadth of the NNI goals shows that the scope of the NNI goes beyond a mere collection of research projects and programs on nanotechnology in the federal government. It also seeks to ensure that technology transfer, education, workforce development, support for research infrastructure, and appropriate responsibility and oversight are addressed.

As required by statute, the NSET Subcommittee develops and publishes an annual report and budget request in the form of the NNI supplement to the President's fiscal year budget. The annual reports detail progress toward each of the NNI's goals from an agency-by-agency perspective and highlight specific interagency activities, changes in the balance of investments by NNI member agencies among the PCAs, information on use of the Small Business Innovation Research and Small Business Technology Transfer programs in support of nanotechnology development, and responses to external NNI reviews.

The National Nanotechnology Coordination Office (NNCO), which was made statutory by the act, provides technical and administrative support to the initiative and the NSET Subcommittee. The NNCO budget is set by the NNI agencies that actually have their own budgets for nanotechnology research and funded by prorated contributions from the agencies. The NNCO budget is about $3 million per year, which represents 0.12 percent of the total NNI budget.

The 2003 legislation that authorized the NNI also set up procedures for regular review and oversight. A National Nanotechnology Advisory Panel (NNAP) was established to evaluate the NNI every 2 years and report the results of the evaluation to the President. The NNAP assesses the trends and developments in nanotechnology overall and the strategic direction of the NNI, particularly as it is related to maintaining U.S. leadership in nanotechnology research; comments on NNI program activities, management, coordination, and implementation; determines whether the program is adequately addressing societal, ethical, legal, environmental, and workforce issues; and makes recommendations on how to improve the NNI. President Bush designated the Council of Advisors on Science and Technology (PCAST) as the NNAP in 2004, and President Obama has elected to continue this appointment. On submission of the report to the President, the director of OSTP transmits a copy of it to Congress. The most recent NNI assessment by PCAST was released in April 2012.

In addition to review by the NNAP, the act calls for the National Research Council to conduct triennial reviews of the NNI that cover diverse topics (see Appendix A). Pursuant to Section 5 of Public Law 108-153, the director of the

NNCO requested that the National Research Council conduct the third triennial review of the NNI, and this review is the subject of the present report.

CHARGE TO THE COMMITTEE

The overall objective of the National Research Council's triennial reviews of the NNI is to make recommendations to the NSET Subcommittee and the NNCO that will improve the value of the NNI 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. In keeping with that objective, the present review addresses the tasks listed below:

1. Examine the role of the NNI in maximizing opportunities to transfer selected technologies to the private sector, provide an assessment of how well the NNI is carrying out this role, and suggest new mechanisms to foster transfer of technologies and improvements to NNI operations in this area where warranted;
2. Assess the suitability of current procedures and criteria for determining progress toward NNI goals, suggest definitions of success and associated metrics, and provide advice on those organizations (government or non-government) that could perform evaluations of progress; and
3. Review NNI's management and coordination of nanotechnology research across both civilian and military federal agencies.

Those tasks represent a recognition that more than a decade after inception the NNI—like nanoscale science and engineering—has evolved and matured. The NNI has established a distinguished record of federal investment and scientific accomplishments in nanotechnology research. Through activities and coordination of the NSET Subcommittee and the NNCO, the NNI has helped agencies to meet their individual and collective needs and has developed best practices in interagency planning and coordination in connection with it.

The question is how to move the NNI to the next level in meeting its long-term goals. In the interim report,[6] the committee began to examine Task 2. In the present report, the committee

- Discusses the origins of the current procedures and criteria for determining progress toward NNI goals and assesses their suitability. (Interim report: Chapter 2)

[6] National Research Council, *Interim Report for the Triennial Review of the National Nanotechnology Initiative, Phase II,* The National Academies Press, Washington, D.C., 2012 (reprinted in Appendix E).

- Suggests new definitions of success and their associated metrics and recommends how the procedures and criteria could be changed if the new definitions of success for the NNI were adopted. (Chapter 4)
- Identifies the federal government stakeholders and other stakeholders across the nation that have benefited and could benefit more from the NNI if such definitions of success were adopted. (Chapter 3)
- Describes management and coordination roles of OSTP, the agencies, the NSET Subcommittee, and the NNCO from the point of view of the nongovernment stakeholders. (Chapter 5)
- Examines the role of metrics in evaluating progress toward planned outcomes of the NNI. (Chapter 4)
- Recommends definitions of success and associated metrics for NNI goals. (Chapter 4 and the interim report)
- Suggests organizations that could evaluate progress on the basis of these definitions. (Chapter 4)
- Examines the current role and assesses the performance of the NNI in maximizing opportunities to transfer selected technologies to the private sector. (Chapter 6)
- Recommends changes in the NSET Subcommittee and the NNCO regarding management, planning, and coordination on the basis of the recommended definitions of success and expands on these recommendations with respect to technology transfer and commercialization. (Chapter 6)

The committee believed that this order of discussion of the elements in its statement of task best reflected the logic of its approach to review of the NNI. The committee recognizes that—as a broad interagency initiative based on a shared vision of a crosscutting technology, that is, nanotechnology—the NNI operates differently from a mission-centric program in a single agency. The committee believes that the synergy added by the NNI to the substantial strengths residing in the 26 NNI participating agencies has proved to be a result of a wise and fruitful investment by the United States. The challenge is to develop a framework that supports targeted NNI goals, planned outcomes, metrics, and processes and that allows participating agencies to meet their missions while maximizing the collective benefit of nanotechnology R&D to taxpayers and the nation.

2

Measuring Progress and Defining Success in the Context of Federal Research Initiatives

The National Nanotechnology Initiative (NNI) is a component of the overall federal investment in science and technology (S&T), and the NNI goals fit within the broad S&T goals and priorities of the federal government as a whole. To assess the NNI and progress toward its goals, it is important to understand the framework within which it operates and how the definitions of success of federal initiatives are established.

The federal research and development (R&D) enterprise comprises programs in individual agencies focused on specific needs and missions and activities, such as the NNI, that involve a number of agencies and address national goals and priorities. The highest-level goals of federal S&T investment appear in various budget documents, such as the June 2012 memorandum on S&T priorities for the FY 2014 budget from Jeffrey Zients, acting director of the Office of Management and Budget (OMB), and John Holdren, director of the Office of Science and Technology Policy (OSTP):

> Scientific discovery, technological breakthroughs, and innovation are the primary engines for expanding the frontiers of human knowledge and are vital for responding to the challenges and opportunities of the 21st century. We look to scientific innovation to
>
> - Promote sustainable economic growth and job creation,
> - Improve the health of the population,
> - Move toward a clean energy future,
> - Address global climate change,
> - Manage competing demands on environmental resources, and
> - Ensure the security of the Nation.

That memorandum[1] and its predecessors[2] articulated the continuing role of S&T in providing benefit to the nation and identified specific outcomes that the U.S. government and taxpayers expect from federal investment in S&T (Box 2.1).

The priorities memorandums also identified S&T priorities that required investment by and cooperation among multiple federal agencies and departments for success. In responding to those priorities, the heads of the executive departments and agencies were instructed to

> Balance priorities to ensure resources are adequately allocated for agency-specific, mission-driven research while focusing resources, where appropriate, on addressing the (following) multi-agency research activities that cannot be addressed effectively by a single agency.

The 2014 R&D priorities document[3] lists nine multiagency R&D priorities: advanced manufacturing; clean energy; global climate change; R&D for informed policy making and management; information technology R&D; nanotechnology (the NNI); biologic innovation; science, technology, and mathematics education; and innovation and commercialization.

Nanotechnology has been highlighted as a multiagency R&D priority in the annual priorities memorandums almost since the NNI was created. The memorandums call for agencies to "strengthen interagency coordination," to find "novel approaches to collaboration," and to support "joint programs using shared resources." Whereas the NNI is emphasized as a priority of the current and past administrations, it also has been described as "a governmental initiative, representing a priority area for investment and activity, but not a distinct funding program with separate budget authority or central management." The direction from OSTP and OMB for the agencies to focus resources in the NNI "where appropriate" and the lack of a clear management or budget authority for the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council Committee on Technology has led to an agency-mission focus

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[1] Memorandum for the Heads of Executive Departments and Agencies, "Science and Technology Priorities for the FY 2014 Budget," M-12-15, June 6, 2012, available at http://www.whitehouse.gov/sites/default/files/m-12-15.pdf, accessed November 13, 2012.

[2] For a summary, see R.M. Jones, "Making hard choices: OMB and OSTP issue guidance to agencies on formulation of FY 2014 budget requests," *FYI: The AIP Bulletin of Science Policy News*, Number 88, June 19, 2012, available at http://www.aip.org/fyi/2012/088.html, accessed November 13, 2012; and Memorandum for the Heads of Executive Departments and Agencies, "FY 2009 Administration Research and Development Budget Priorities," M-07-22, August 14, 2007, available at http://m.whitehouse.gov/sites/default/files/omb/assets/omb/memoranda/ fy2007/m07-22.pdf, accessed November 13, 2012.

[3] Memorandum for the Heads of Executive Departments and Agencies, "Science and Technology Priorities for the FY 2014 Budget," M-12-15, June 6, 2012, available at http://www.whitehouse.gov/sites/default/files/m-12-15.pdf, accessed November 13, 2012.

BOX 2.1
Nanotechnology-Specific Excerpts from Representative OSTP-OMB Priorities Memoranda

2005 Priorities Document[1]

Nanoscale R&D priority areas continue to include material science and research relevant to medical care and homeland security. Though research at the nanoscale offers natural bridges to interdisciplinary collaboration, especially at the intersection of the life and physical sciences, the administration encourages novel approaches to accelerating interdisciplinary and interagency collaborations. Activities such as joint programs utilizing shared resources, as well as support for interdisciplinary activities at centers and user facilities, are encouraged.

2009 Priorities Document[2]

Robust federal investment in the agency programs that make up the NNI will expedite realization of the potential of nanotechnology to address national priorities in areas such as energy, security, health care, and the environment and will maintain U.S. scientific and technological leadership in this field.

Agencies should strengthen interagency coordination and support research on potential risks to human health and the environment, consistent with the National Science and Technology Council's 2006 report, *Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials*.[3]

More broadly, the NNI should support both basic and applied R&D in nanoscience, develop instrumentation and methods for nanoscale characterization and metrology, and disseminate new technical capabilities to help industry advance nanofabrication and nanomanufacturing. Nanoscale research offers a natural bridge to collaboration between the life and physical sciences; therefore, agencies are encouraged to use approaches that accelerate interdisciplinary and interagency collaboration. Agencies are encouraged to participate in activities such as joint programs utilizing shared resources or leveraging complementary assets, as well as support for interdisciplinary activities at centers and user facilities.

2014 Priorities Document[4]

Within the interagency NNI, agencies should give priority to implementation of the 2011 Environmental, Health, and Safety Research Strategy,[5] presenting an approach to ensuring the safe, effective, and responsible development and use of nanotechnology; and support for the Nanotechnology signature initiatives, which spotlight topical areas that represent key opportunities and can be more rapidly advanced through focused interagency R&D efforts.

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[1] FY 2005 Interagency Research and Development Priorities, available at http://www.whitehouse.gov/sites/ default/files/omb/assets/omb/memoranda/m03-15.pdf, accessed November 13, 2012.

[2] Memorandum for the Heads of Executive Departments and Agencies, August 14, 2007, available at http://m.whitehouse.gov/sites/default/files/omb/assets/omb/memoranda/fy2007/m07-22.pdf.

[3] National Science and Technology Council (NSTC), *Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials,* Nanoscale Science, Engineering, and Technology Subcommittee, Committee on Technology, Executive Office of the President, September 2006, http://www.whitehouse.gov/files/documents/ostp/NSTC%20Reports/NNI_EHS_research_needs%202006.pdf, accessed October 1, 2013.

[4] Memorandum for the Heads of Executive Departments and Agencies, June 6, 2012, available at http://www.whitehouse.gov/sites/default/files/m-12-15.pdf, accessed November 13, 2012.

[5] NSTC, *Environmental, Health, and Safety Research Strategy,* Subcommittee on Nanoscale Science, Engineering, and Technology, Committee on Technology, Executive Office of the President, October 2011, available at http://www.nano.gov/sites/default/files/pub_resource/nni_2011_ehs_research_strategy.pdf, accessed October 1, 2013.

within the NNI for many agencies. All the member agencies see nanotechnology as enabling and the NNI as an important means of nurturing nanotechnology in the agencies, throughout federal R&D, and in R&D throughout the nation, but the agencies have used the NNI and its interagency bodies (the NSET Subcommittee and the National Nanotechnology Coordination Office [NNCO]) primarily as a vehicle for information-sharing and coordination of nanotechnology R&D activities. Program coordination and joint programs with shared resources have been planned and implemented by agencies "as appropriate" only when they support the primary missions of the agencies involved.

The conflict between the guidance from OSTP and OMB to the agencies to strengthen collaboration to meet the NNI goals and the agencies' interpretation of "as appropriate" is a continuing source of tension between the NNI and those who review it. Entities that support oversight activities, such as the President's Council of Advisors on Science and Technology (PCAST), which currently serves as the National Nanotechnology Advisory Panel called for by law, the Government Accountability Office (GAO), and the NRC panels that have advised and reviewed the NNI, have called upon the NNI agencies, through the NSET Subcommittee and the NNCO, to create long-term collaborations with a shared vision, supported by joint planning, coordination, and management. This sentiment dates back to the 2002 report of the NRC entitled *Small Wonders, Endless Frontiers*, which made recommendations for the initial organization and management of the NNI. That report included recommendations for the NSET Subcommittee to increase multiagency investments in research, in particular at the intersection of nanoscale technology and biology. This report recognizes the challenges to interagency programming and therefore calls for a special fund for Presidential grants, under OSTP management, to support interagency research programs relevant to nanoscale science and technology. The expectation of interagency collaboration also is reflected, for example, in the 2012 PCAST evaluation of NNI strategic planning: "While the NSET Subcommittee in 2011 produced a 'National Nanotechnology Initiative Strategic Plan,' individual agency contributions lack the cohesion of an overarching framework, and there is no clear connection between the goals and objectives of the NNI strategic plan with those of individual agencies." That observation led the PCAST to recommend, as a first step, clarifying how the NNI fits into agency priorities and programs: "NNCO in partnership with OSTP should work with the agencies to develop implementation plans for achieving the goals and objectives outlined in the 2011 NNI strategic plan."

The conflict is also reflected in the 2012 GAO report *Nanotechnology: Improved Performance Information Needed for Environmental, Health, and Safety Research*, in which GAO evaluated NNI environmental, health, and safety (EHS) documents according to its six desirable characteristics for a national strategy, as seen in Table 2.1. The report stated:

TABLE 2.1 Summary of Desirable Characteristics of a National Strategy

Desirable Characteristic	Brief Description
Purpose, scope, and methods	Addresses why the strategy was produced, the scope of its coverage, and the process by which it was developed.
Problem definition and risk assessment	Addresses the particular national problems and threats at which the strategy is directed.
Goals, subordinate objectives, activities, and performance measures	Addresses what the strategy is trying to achieve, steps to achieve the results, and priorities, milestones, and performance measures for gauging results.
Resources, investments, and risk management	Addresses what the strategy will cost, the sources and types of resources and investments needed, and where resources and investments should be targeted by balancing risk reductions and costs.
Organizational roles, responsibilities, and coordination	Addresses who will be implementing the strategy, what their and others' roles will be, and mechanisms for them to coordinate their efforts.
Integration and implementation	Addresses how a national strategy is related to other strategies' goals, objectives, and activities and to subordinate levels of government and their plans for implementing the strategy.

SOURCE: GAO, Report to the Chairman, Committee on Environment and Public Works, U.S. Senate, Nanotechnology Improved Performance Information Needed for Environmental, Health, and Safety Research, Appendix I, accessed August 8, 2012.

> NNI strategy documents for EHS research issued by the NSTC address two and partially address the other four of the six desirable characteristics of national strategies identified by GAO that offer a management tool to help ensure accountability and more effective results. For example, the NNI strategy documents provide a clear statement of purpose, define key terms, and discuss the quality of currently available data, among others. However, they do not include performance information—such as performance measures, targets, and time frames for meeting those measures—that would allow stakeholders to evaluate progress towards the goals and research needs of the NNI. In addition, the documents do not include, or sufficiently describe, estimates of the costs and resources needed for the strategy. Without this information, it may be difficult for agencies and stakeholders to implement the strategy and report on progress toward achieving the research needs and assess if investments are commensurate with costs of the identified needs.[4]

The concerns raised by the GAO report with respect to NNI EHS documents apply in general to the initiative as a whole. When NNI agencies do not share long-term goals as evidenced by joint planning, resource allocation, coordination, and

[4] Government Accountability Office, *Nanotechnology: Improved Performance Information Needed for Environmental, Health, and Safety Research,* GAO-12-427, 2012, p. 1, available at http://www.gao.gov/assets/600/ 591007.pdf, accessed August 8, 2012.

management to reach the goals, it becomes difficult at best to define meaningful "performance measures, targets, and time frames for meeting those measures" or to assess "if investments are commensurate with costs of the identified needs." As noted in Table 2.1, performance measures ("metrics") follow directly from defining "what the strategy is trying to achieve, steps to achieve the results, and priorities, milestones, and performance measurers for gauging results." The question is then to what extent the NNI agencies and the interagency NSET Subcommittee should be expected to create, implement, and assess a formal, long-term, interagency national strategy for the NNI that is based on the GAO model.

The present committee's interim report assessed the suitability of current procedures and criteria for determining progress toward NNI goals and laid out possible definitions of success and associated metrics for the NNI on the basis of its four stated goals. (The interim report is Appendix E.) The committee found that the current procedures and criteria that the NSET Subcommittee and OSTP use for assessing progress toward NNI goals are embodied in annual supplements to the President's budgets and the NNI strategic plans. As noted above, the annual supplements describe current and proposed investments in nanotechnology by agency; quantify investment by agency, program component area, and Small Business Innovation Research and Small Business Technology Transfer programs; and provide examples of specific accomplishments by individual agencies and by groups with respect to the four broad NNI goals[5] and the objectives in the strategic plan. The NNI strategic plan provides "the framework that underpins the nanotechnology work of the NNI member agencies," describes the interests of the individual agencies in nanotechnology R&D and the NNI, and identifies objectives and actions to reach the four goals.[6] The implicit criteria for progress toward the NNI goals that the NSET Subcommittee and OSTP formally use are thus based on the quality of the specific examples of research or activities that meet the four goals in the programs of the individual agencies or in collaboration with other groups and on whether objectives in the strategic plan have been met.

> **Finding:** The committee found that although the four NNI goals establish the scope of the NNI and the annual supplements are useful for communicating the breadth of NNI activities in the agencies, they are insufficient for measuring progress and guiding the management and coordination of the NNI.

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[5] See Box S.1 in the Summary.

[6] National Science and Technology Council (NSTC), *National Nanotechnology Initiative Strategic Plan,* Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf, accessed December 19, 2012, p. 23.

In its interim report, the committee stated the need for an explicit framework for managing and coordinating the NNI that links investment, outputs, and short-term outcomes to specific long-term goals and links outcomes in the individual agencies and of interagency collaborations. Such a framework would include essential performance-management concepts, such as having a vision, goals, clearly articulated desired outcomes (long-term, medium-term, and short-term), accurate data on the resources and funding available and how they are allocated, agreed-on milestones and timelines, and models that link all these with specific agreed-on performance measures (metrics) chosen to relate short-term and medium-term outcomes and outputs to specific longer-term goals and outcomes.

That stated need is in line with the PCAST and GAO findings and recommendations. As an interim step, PCAST recommended that all the individual NNI agencies develop NNI implementation plans and articulate how their plans are related to the NNI strategic plan. Some of the participating agencies, such as the National Science Foundation and the National Institutes of Health, already have publicly articulated strategic plans or implementation strategies for nanotechnology, but most do not; see Box 2.2. Without goals that are more specific than the four general NNI goals, a public commitment to specific outcomes, and a publicly articulated performance-management framework, it is not possible to measure NNI progress toward its four goals. The committee's interim report also noted that the suggestion for a framework is especially timely in light of the rapid development of computational tools and methods for collecting and analyzing data that may be useful for tracking and measuring the progress of the NNI and guiding its management.

> **Recommendation 2-1:** An overarching definition of success for the NNI as a federal initiative should be evidence that NNI agencies are establishing and implementing an effective, explicit framework for planning, managing, and coordinating publicly identified NNI interagency programs, such as the signature initiatives. Such a framework should be based on essential performance-management concepts, and plans for and progress toward specific outcomes should be reported annually in the NNI supplement to the President's budget.

In the following chapter, Chapter 3, the committee lays out some of the key factors to consider when developing a framework for planning, management, and coordination of NNI programs:

- Who benefits, and how? The NNI stakeholders are discussed in light of how they benefit from the NNI and what their definitions of success would be.
- What financial resources are available within the NNI, and for what purpose? The funding for NNI, which is all provided by the agencies, is

BOX 2.2
Current Processes and Procedures for Evaluating Progress Toward NNI Goals

Each year in the annual NNI Supplements to the President's budget, the NSET and the NNCO report lists (1) budget and expenditures data allocated to the program component areas (PCAs) from each agency's budget, (2) highlights from each agency programs, and (3) areas in which multiple agencies or external organizations have been active. Progress of the NNI against its four stated goals is reported in largely anecdotal form and is generally agency-centric. Several agencies have reported examples of successful nanotechnology-relevant programs and projects; some provide numerical data, and some have presented short summaries without many details. Interagency activities are reported in the same manner. This clearly reflects the priorities of the NNI agencies: NNI agencies manage their overall portfolios to focus on their primary missions, with nanotechnology being secondary.

For example, according to agency websites, the mission of the Department of Energy is to "ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions;"[1] the mission of the Department of Agriculture is to "provide leadership on food, agriculture, natural resources, rural development, nutrition, and related issues based on sound public policy, the best available science, and efficient management";[2] and the mission of the Department of Defense is to "provide the military forces needed to deter war and to protect the security of our country."[3]

Programs and individual projects are monitored and evaluated within each agency with respect to its agreed-on mission-based deliverables by using processes and metrics developed by the agencies. But the evaluations typically are program-specific and agency-specific, and the deliverables and outcomes are generally reported in forms that cannot be easily aggregated and analyzed for their nanotechnology-related content. The committee found that no method or system is common to the NNI agencies for measuring and tracking progress toward NNI goals. Broad generalizations can be made, but there is little granularity except for specific examples of successful projects, discoveries, and products related to the agencies' missions, which are mapped onto the four goals.

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[1] U.S. Department of Energy, About Us, available at http://energy.gov/about-us, accessed October 1, 2013.

[2] U.S. Department of Agriculture, Mission Statement, available at http://www.usda.gov/fundinglapse.htm?navid=MISSION_STATEMENT, accessed October 1, 2013.

[3] U.S. Department of Defense, About the Department of Defense (DOD), available at http://www.defense.gov/about/, accessed October 1, 2013.

analyzed in terms of the primary goals of the funding and the level of interagency interaction.

- What subjects in the NNI could benefit most from the framework? The NNI signature initiatives and the NSET Subcommittee working groups are examined in some detail.

3

National Nanotechnology Initiative Stakeholders

In moving toward its goals and addressing national needs, the National Nanotechnology Initiative (NNI) involves, affects, and interacts with many stakeholder groups in and outside the federal government. The interconnections between NNI stakeholders are many and complex and are essential for the success of the President's *Strategy for American Innovation*[1] in creating jobs and industries of the future that are based on scientific breakthroughs, innovation-based economic growth, and a world-class workforce. Each stakeholder group plays a role in the nanotechnology "innovation ecosystem," and the success of each is important for the realization of benefits from nanotechnology in general and the success of the NNI in particular. The participating NNI federal agencies support many nonfederal stakeholders, but the support is not unidirectional. Advances can be greatly expedited through public-private collaborations and by planning for long-term outcomes from the beginning. Moreover, the NNI can help to connect nonfederal stakeholders with federal stakeholders and to each other—for example, connecting NNI centers with regional, state, and local centers and with teachers and students around the country and connecting entrepreneurs with those seeking new ideas and solutions.

[1] See National Economic Council, Council of Economic Advisers, and Office of Science and Technology Policy, *A Strategy for American Innovation—Securing Our Economic Growth and Prosperity,* February 2011, available at http://www.whitehouse.gov/sites/default/files/uploads/InnovationStrategy.pdf, accessed November 14, 2012.

FOSTERING INTERACTION AND ENGAGEMENT

The text below describes the roles and responsibilities of various federal and nonfederal stakeholders and emphasizes where partnerships and collaborations can (and sometimes do) take place.

The stakeholders in the NNI include

- Individual researchers,
- Research teams, institutes, and centers,
- Small businesses,
- Large businesses,
- Contract laboratories,
- Universities,
- Students,
- Educators,
- Nonprofit organizations,
- Investors,
- Office of Science and Technology Policy,
- Federal departments and agencies,
- User facilities,
- State, local, and regional governments,
- State, local, and regional science centers,
- Labor organizations,
- Trade and professional organizations,
- Policy centers,
- News organizations,
- Regulators,
- Congress,
- Law firms,
- Consumers, and
- U.S. taxpayers.

Specific examples drawn from a 2010 NNI-sponsored workshop are given in Appendix C.

Nanotechnology research takes place worldwide. An idea of the international stakeholders interested in the economic benefits of nanotechnology to their countries can be obtained from a list of the organizations that participated in the recent International Symposium on Assessing the Economic Impact of Nanotechnology. The symposium—which was organized by the NNI, the American Association for the Advancement of Science (AAAS), and the Organisation for Economic Co-operation and Development (OECD) and was held in March 2012 in Washington, D.C.—had an objective that was central to the tasks given to the present committee: "to systematically explore the need for and development of a methodology to assess the economic impact of nanotechnology across whole economies, factoring in many sectors and types of impact, including new and replacement products and materials, markets for raw materials, intermediate and final goods, and employment and other economic impacts."[2] The broad interest of nations around the world in the symposium indicates the level of importance paid not only to nanotechnology but also to maximizing national and regional return on investment in research in general.

The National Research Council report *Rising to the Challenge: U.S. Innovation Policy for Global Economy* looks at innovation policies in other areas of the world and how, for example, science and technology (S&T) parks have affected technology transfer in such fields as nanotechnology.[3]

The NNI has created structures that enhance interaction among stakeholder groups. An example is the creation and diffusion of knowledge and ideas through formal connections between and among authors of scientific publications and their organizations in the 19 National Science Foundation (NSF) nanoscience and engineering centers.[4]

Other NNI structures that foster stakeholder engagement and interaction are the NSF Network for Computational Nanotechnology (NCN) and the NSF Nanoscale Informal Science Education Network (NISE). Those networks are designed to serve diverse research and education user groups, from world-leading

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[2] See Organisation for Economic Co-operation and Development, "International Symposium on Assessing the Economic Impact of Nanotechnology," 2012, available at http://www.oecd.org/sti/nano/, accessed December 12, 2012.

[3] National Research Council, *Rising to the Challenge: U.S. Innovation Policy for Global Economy*, The National Academies Press, Washington, D.C., 2012. See especially the following pages: France, p. 113; China, p. 236; and India, p. 245.

[4] Center for Nanotechnology in Society, Arizona State University; Center for Electron Transport in Molecular Nanostructures, Columbia University; Center for Nanoscale Systems, Cornell University; Center for Environmental Implications of Nanotechnology, Duke University; Science of Nanoscale Systems and Their Device Applications, Harvard University; Center for High Rate Nanomanufacturing, Northeastern University; Center for Integrated Nanopatterning and Detection Technologies, Northwestern University; Center for Affordable Nanoengineering of Polymeric Biomedical Devices, Ohio State University; Center for Directed Assembly of Nanostructures, Rensselaer Polytechnic Institute; Center for Biological and Environmental Nanotechnology, Rice University; Center for Probing the Nanoscale, Stanford University; Center of Integrated Nanomechanical Systems, University of California, Berkeley; Center for Scalable and Integrated Nanomanufacturing, University of California, Berkeley; Center for Environmental Implications of Nanotechnology, University of California, Los Angeles; Center for Nanotechnology in Society, University of California, Santa Barbara; Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, University of Illinois, Urbana-Champaign; Center for Hierarchical Manufacturing, University of Massachusetts Amherst; Nano/Bio Interface Center, University of Pennsylvania; and Center in Templated Synthesis and Assembly at the Nanoscale, University of Wisconsin, Madison.

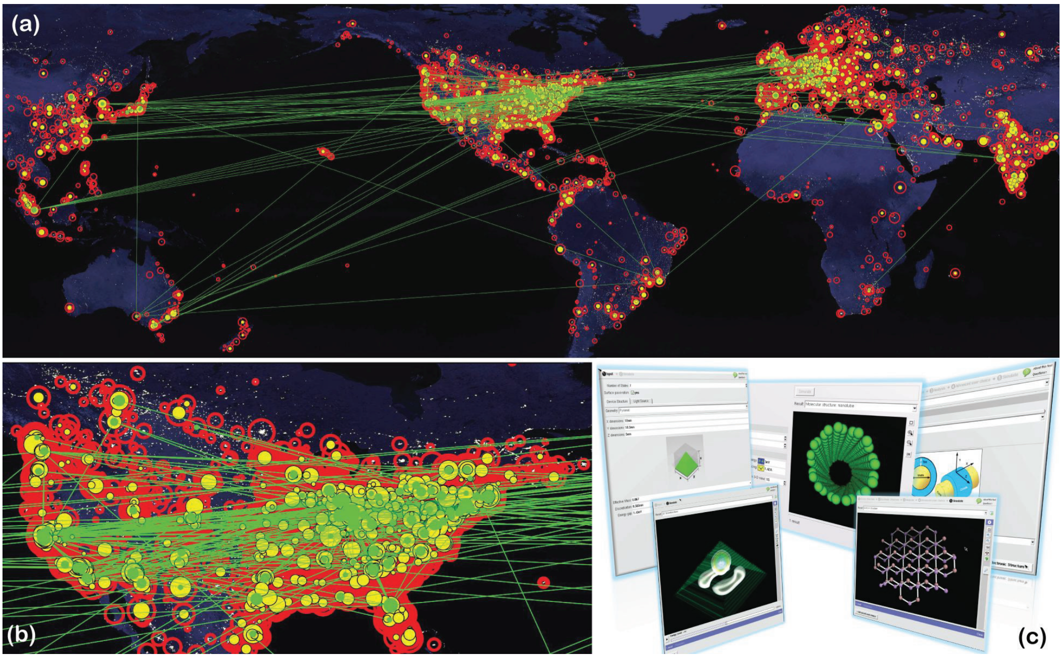

FIGURE 3.1 (a) nanoHUB user map in the year 2011 superposed on the National Aeronautics and Space Administration's world at night. Red circles designate users viewing lectures, tutorials, or homework assignments; yellow dots, users of simulations; and green dots, authors of over 720 scientific publications that cite nanoHUB. Dot size corresponds to the number of users, and lines show author-author connections indicative of the existence of intense research collaboration networks. (b) United States enlarged. (c) Collage of typical nanoHUB interactive tool sessions and three-dimensional-rendered interactively explorable results (quantum dots, carbon nanotubes, and nanowires). SOURCE: Courtesy of Gerhard Klimeck, nanoHUB, Purdue University.

nanotechnology researchers to K-12 educators, their students, and the public. The nanoHUB.org website is NCN's primary dissemination mechanism for providing a wide array of tools and simulation software and is designed and managed to measure and improve its effectiveness in research and education. Not just an Internet repository of software for computational nanotechnology, nanoHUB allows researchers and educators to contribute, access, and run nanoscience and nanotechnology simulation tools from a web browser. Use and dissemination tracking software for these tools, as illustrated in the usage map in Figure 3.1, provides critical information on who is using the tools, where and how they are using them, and how effective specific NCN strategies are for making the tools more useful, increasing the number of available tools, and propagating their use. From innovation ecosystem maps to the evolution of networks within the nano-

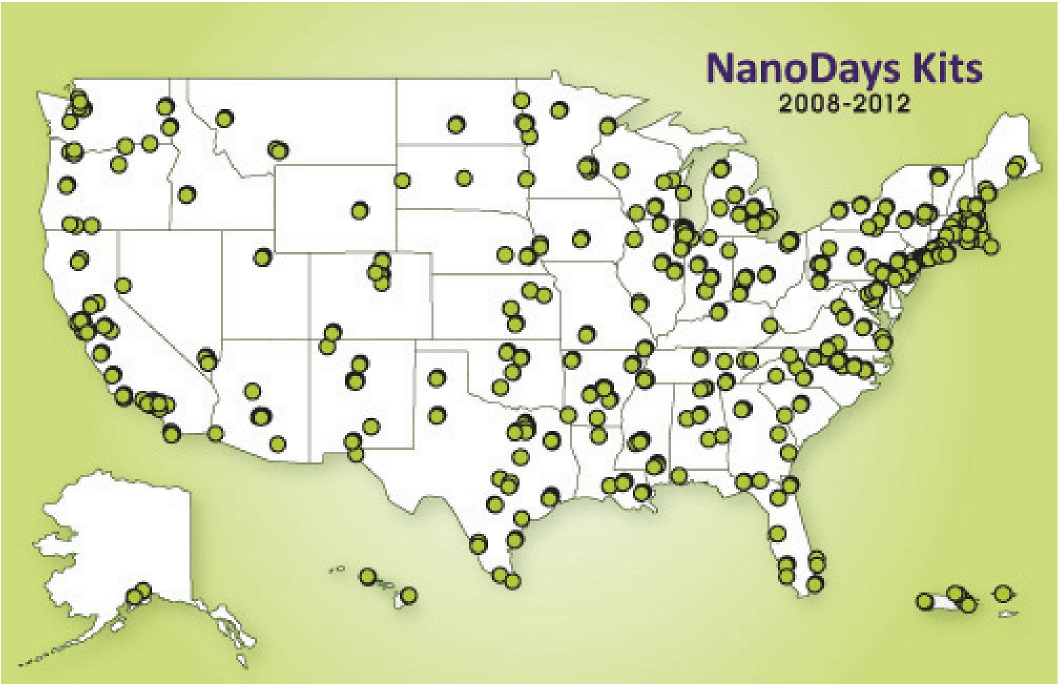

FIGURE 3.2 Map of organization participants in Nanodays, 2008-2012. SOURCE: Nanoscale Informal Science Education website at http://www.nisenet.org/nanodays.

technology community, such types of analyses help to measure the effectiveness in meeting the needs of NNI stakeholder groups and in improving connections necessary to make the NNI vision a reality.

The outreach and educational activities of NISE are aimed at general audiences and focus on informal education. The annual Nanodays sponsored and strongly supported by NISE constitute a nationwide educational "festival" at museums, research centers, and universities focused on engaging and informing the public about nanoscale science, engineering, and technology. Through its website, NISE provides teaching and media kits to event organizers in both physical and digital forms. The number of annual events has grown from about 100 in 2008 to over 200 across the United States in 2011.[5] Figure 3.2 provides a visual indication of Nanodays

[5] C. McCarthy, R. Ostman, M. Kortenaar, A. Stein, C. Akers, K.C. Miller, V. Olney, and S. Pattison, *NanoDays 2011 Report and Survey,* National Science Foundation Award Numbers ESI-0532536 and 0940143, May 25, 2011, available at http://www.nisenet.org/sites/default/files/catalog/eval/uploads/2011/09/703/nd2011_report_ 25may11.pdf, accessed November 19, 2012.

events held in the United States in 2008-2012. Another education example is the NNI program involving the Pennsylvania State University Nanotechnology Applications and Career Knowledge (NACK) Network (www.nano4me.org). The NACK Network "provides national coordination of workforce development programs and activities on behalf of the NSF ATE (Advanced Technological Education) program in an effort to meet industry needs for skilled micro-nanotechnology workers. The NACK Network is a partnership of 2-year community and technical colleges and 4-yr universities that provide resources for educators and students to create and sustain economically viable nanotechnology education across the U.S."[6] The NACK Network is partially funded by NSF.

Another key group is the professional societies—such as the Optical Society of America, SPIE, the American Physical Society, the Materials Research Society, the American Vacuum Society, the Institute of Electrical and Electronics Engineers, AAAS, and the American Chemical Society—which have contributed substantially to nanotechnology knowledge dissemination and technology transfer. Numerous meetings and symposia on nanotechnology have been organized by professional societies. They provide a forum for networking among academic, industrial, and government scientists. In addition, research presented at the meetings is occasionally highlighted in the popular press, and this exposes the general population to nanotechnology advances. Much of the research presented at the meetings has been sponsored by the NNI; highlights can be found on the nano.gov website.

Professional societies also hold educational workshops, which are attended by many in industry for their own professional development. Much of the research sponsored by the NNI is published in journals of professional societies.

The above examples illustrate a number of excellent NNI programs and infrastructure for outreach, education, and connection of various stakeholder groups. It is hoped that implementing a framework for planning, management, and collaboration will make it easier to identify the stakeholders who are expected to benefit from the NNI in the short term, the intermediate term, and the long term and to assess the benefits at each timescale on the basis of the goals of the program and the resources that are made available.

NATIONAL NANOTECHNOLOGY INITIATIVE PLANNING, COORDINATION, AND MANAGEMENT BY FEDERAL STAKEHOLDERS

This section reviews the current roles, responsibilities, and actions of federal stakeholders involved in planning, coordination, and management of the NNI.

[6] Nanotechnology Applications and Career Knowledge Network, "About Us," available at http://nano4me.org/ aboutus.php, accessed January 11, 2013.

Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) has as part of its mission to "ensure that the scientific and technical work of the Executive Branch is properly coordinated so as to provide the greatest benefit to society."[7] Moreover, OSTP seeks to "energize and nurture the processes by which government programs in science and technology are resourced, evaluated, and coordinated" and to "sustain the core professional and scientific relationships with government officials, academics, and industry representatives that are required to understand the depth and breadth of the nation's scientific and technical enterprise, evaluate scientific advances, and identify potential policy proposals."

OSTP provides guidance and oversight for the NNI. Those roles are apparent in the Government Accountability Office (GAO) report released in 2012 titled *Nanotechnology—Improved Performance Information Needed for Environmental, Health, and Safety Research*.[8] The report states that in 2008 GAO had "recommended that the Director of OSTP, in consultation with the Directors of NNCO [the National Nanotechnology Coordination Office] and OMB [the Office of Management and Budget], provide better guidance to agencies on how to report nanotechnology EHS [environmental, health, and safety] research" (p. 6). In its 2008 report,[9] the agency had "found that neither NSET [the Nanoscale Science, Engineering, and Technology Subcommittee of the National Science and Technology Council Committee on Technology (NSTC)] nor OMB had provided guidance on whether or how to apportion funding for a single research project to more than one program component area [PCA], if appropriate" (p. 21). In the 2012 report, "GAO recommends that the Director of the Office of Science and Technology Policy (OSTP), which administers the NSTC, (1) coordinate development of performance information for NNI EHS research needs and publicly report this information; and (2) estimate the costs and resources necessary to meet the research needs" (Highlights page).

NNI Participating Agencies

In contrast with most large federal programs, the NNI is funded through requests in the individual agencies' annual budgets. The NNI agencies establish goals that are based on their missions, identify research that is needed to accomplish

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[7] Office of Science and Technology Policy, "About OSTP," available at http://www.whitehouse.gov/administration/eop/ostp/about, accessed December 7, 2012.

[8] Government Accountability Office (GAO), *Nanotechnology: Improved Performance Information Needed for Environmental, Health, and Safety Research*, GAO-12-427, May 2012, available at http://www.gao.gov/products/GAO-12-427, accessed August 8, 2012.

[9] GAO, *Better Guidance Is Needed to Ensure Accurate Reporting of Federal Research Focused on Environmental, Health, and Safety Risks*, GAO-08-402, March 31, 2008.

those goals, allocate and distribute federal resources, monitor progress, and take action to maximize return on federal investments while ensuring that the primary agency goals are met. Agencies report their nanotechnology-related funding in the supplement to the President's annual budget as required by statute. When agencies fund programs in which nanotechnology is explicitly identified among agency priorities, agency advisory bodies often are called on to provide input, review, or make recommendations. However, a substantial fraction of the support reported as NNI funding is within research and development (R&D) programs designed to meet mission needs. In such cases, the role of nanotechnology is subordinate to mission needs, and relevance to the NNI is determined after the funding is committed.

Despite the "bottom-up" mechanism by which NNI funding is developed, participating agencies realize added value through their involvement in the NNI and the NSET Subcommittee (Box 3.1), assigning representatives to the various interagency bodies (Box 3.2) and committing resources to the interagency effort.

Interagency Bodies

> The NSTC was established in 1993 as the principal means within the executive branch to coordinate science and technology policy across the diverse entities that make up the Federal research and development enterprise. Chaired by the President, the membership of the NSTC is made up of the Vice President, the Director of the Office of Science and Technology Policy, Cabinet Secretaries and Agency Heads with significant science and technology responsibilities, and other White House officials. A primary objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in a broad array of areas spanning virtually all the mission areas of the executive branch. . . . The work of the NSTC is organized under five primary committees: Environment, Natural Resources and Sustainability; Homeland and National Security; Science, Technology, Engineering, and Math (STEM) Education; Science; and Technology.[10]

As stated in the 2003 supplement to the President's budget, "the NNI is managed within the framework of the National Science and Technology Council (NSTC) Committee on Technology (CoT). The committee, composed of senior-level representatives from the federal government's research and development departments and agencies, provides policy leadership and budget guidance for the NNI and other multiagency technology programs."[11]

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[10] National Science and Technology Council (NSTC), "About NSTC," available at http://www.whitehouse.gov/administration/eop/ostp/nstc/about, accessed December 19, 2012.

[11] NSTC, "Strengthening National, Homeland, and Economic Security—Networking and Information Technology Research and Development: Supplement to the President's Budget, July 2002," available at http://www.nitrd.gov/open/PDF/FY_2003_Supplement_to_the_President%27s_Budget.pdf, accessed November 10, 2012.

BOX 3.1
Examples of Agency Involvement in the NNI

The NNI, through regular Nanoscale Science, Engineering, and Technology (NSET) Subcommittee meetings and activities within the NSET working groups, provides mechanisms for the U.S. Geological Survey to share information on nanotechnology research and to collaborate with other agencies.

The U.S. Patent and Trademark Office has contributed substantially to the NNI by providing advice on patent and other intellectual-property matters and has contributed a variety of nanotechnology-related patent data, which have been used as a benchmark to analyze nanotechnology development and to perform trend analysis of nanotechnology patenting activity in the United States and globally.

National Institute of Standards and Technology (NIST) staff members participate widely in nanotechnology-related standards development and international cooperation activities to promote transfer of NIST research, technology, and measurement services and to advance NNI objectives that are in the Department of Commerce mission.

The National Institute for Occupational Safety and Health (NIOSH) will continue to work with the NNI and a broad array of national and international partners to develop research-based information and guidance to protect workers involved with nanomaterials. The results being produced by NIOSH will continue to serve as the foundation for meeting the critical NNI research needs related to human exposure assessment, exposure mitigation, risk-assessment techniques, risk-management practices, and human medical surveillance and epidemiology.

The Department of State actively participates in the NNI to identify and promote multilateral and bilateral scientific activities that support U.S. foreign-policy objectives, protect national security interests, advance economic interests, and foster environmental protection. International scientific collaboration enhances existing U.S. research, development, and innovation programs.

The 2011 NNI strategic plan clearly defines the roles of the NSET Subcommittee, its responsibilities, and actions that its roles and responsibilities imply:

> Coordinated under the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC's Committee on Technology (CoT), the NNI provides a framework for a comprehensive nanotechnology R&D program by establishing shared goals, priorities, and strategies complementing agency-specific missions and activities and providing avenues for individual agencies to leverage the resources of all participating agencies. Further, the NNI provides a central interface with academia and industry as well as regional/state organizations and international counterparts in the process of innovating nanotechnology.[12]
>
> The NSET Subcommittee leads the interagency coordination of the Federal Government's nanotechnology R&D enterprise by cooperatively coordinating the research, development, communication, and funding functions of the NNI. The NSET Subcommittee develops the

[12] NSTC, *National Nanotechnology Initiative Strategic Plan,* Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf, accessed December 19, 2012, p. 1.

BOX 3.2
Examples of the Benefits Enjoyed by Agencies That Participate in the NNI

The interagency coordination provided by the NNI enables the Bureau of Industry and Security of the Department of Commerce (DOC) to stay apprised of nanotechnology advances that may present national security challenges and that may provide opportunities for companies in the national defense industrial base.

The Consumer Product Safety Commission (CPSC), in cooperation with federal partners, analyzes the use and safety of nanotechnology in consumer products. To meet identified data needs, the CPSC staff has met and collaborated with staff at a number of federal agencies on subjects of mutual interest when collaboration would be beneficial and support the missions of the individual agencies.

The Department of Defense (DOD) was among the initial participating agencies in the NNI and the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee. It continues to consider the initiative and its formal coordination to be valuable as a means of facilitating technology planning, coordination, and communication among the federal agencies. The meetings and workshops hosted or facilitated by the NNI participants help to identify and define options and opportunities that contribute materially to DOD planning activities and program formulation. The reviews and collegial meetings, working groups, and task forces established under the auspices of the NSET Subcommittee are valuable means of formal and informal coordination at the federal level and form a solid basis for exploring collaborative activities, addressing mutual or pervasive issues, and identifying instances in which interagency assistance is needed or would be productive. DOD has continuously contributed to the NNI through participation in the above-noted activities and through numerous outreach and programmatic efforts in which nanotechnology has been a principal aspect of the program or planning. The transparency that is enabled by the NNI is viewed as symmetrically beneficial to DOD, the other agencies, and the many private-sector stakeholders in the broad arena of nanoscience, nanotechnology, and nanotechnology-enabled applications.

The Department of Energy (DOE) has participated in the NNI since its inception and maintains a strong commitment to the initiative, which has served as an effective and valuable way of spotlighting needs and targeting resources in this critical emerging field of science and technology. The NNI continues to provide a focus for overall investment in physical sciences, a crucial locus for inter-

> NNI Strategic Plan, prepares the annual NNI supplement to the President's Budget, and sponsors workshops or other interagency activities that inform the Federal Government's nanotechnology-related decision-making processes. The high level framework provided by the NNI Strategic Plan establishes goals, objectives, and priorities. It guides and informs the participating agencies in developing their nanotechnology R&D implementation plans. The subcommittee promotes balanced investment across all of the agencies to address the critical elements needed to support the development and utilization of nanotechnology. Further, the subcommittee interacts with pertinent academic, industry, state, and local government groups, and with international organizations.[13]

In other words the responsibilities of the NSET Subcommittee as stated in the 2011 NNI strategic plan are as follows:

[13] Ibid., p. 33.

agency communication and collaboration, and an impetus for coordinated planning. The research and infrastructure successes spurred by the NNI have made the United States a world leader in the field, with substantial national benefit.[1]

To help nanotechnology to create maximum societal benefits and to minimize its potential environmental effects, the Environmental Protection Agency (EPA) works with its federal partners on the NSET Subcommittee to ensure that research gaps are covered, critical issues are addressed, and information is communicated to all interested stakeholders.

Through the NNI interagency efforts, the Occupational Safety and Health Administration (OSHA) accomplishes its mission by collaborating and sharing information with other federal agencies. As part of that effort, OSHA's goal is to educate employers on their responsibility to protect workers and educate them in safe practices in handling nanomaterials. OSHA is developing guidance and educational materials promoting worker safety and health that will be shared with the public and through the NNI.

The Department of State actively participates in the NNI to identify and promote multilateral and bilateral scientific activities that support U.S. foreign-policy objectives, protect national security interests, advance economic interests, and foster environmental protection. International scientific collaboration enhances existing U.S. research, development, and innovation programs.

Through participation in the NNI and representation on the NSET Subcommittee, the research and development arm of the U.S. Department of Agriculture (USDA) Forest Service has begun to partner with other federal entities—such as the National Institute of Standards and Technology (NIST), NSF, DOE, and DOD—industry, and academe to develop the precompetitive science and techology critical for the economic and sustainable production and use of new high-value, nanotechnology-enabled forest-based products. Participation in the NNI and the NSET Subcommittee has helped to create a favorable environment for increased Forest Service investment in nanotechnology research and development.

[1] NSTC, *National Nanotechnology Initiative Strategic Plan,* Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf, accessed December 19, 2012.

- Sharing information between NNI participating agencies.
- Making sure that other agencies know of research results that affect their ability to fulfill their missions.
- Avoiding duplication among agencies.
- Setting strategic directions and formulating strategic plans for the NNI.
- Coordinating interagency planning, budgeting, and review of the NNI.
- Coordinating and maintaining interactions between OSTP, OMB, and Congress, including annual reporting.
- Developing and coordinating signature initiatives.
- Interacting with and enabling partnerships with regional, state, and local government organizations, academe, industry, and other nonfederal government stakeholders and organizations, including international organizations, researchers, and governments.

- Coordinating the response to and the implementation of specific recommendations by the President's Council of Advisors on Science and Technology (PCAST) and other advisory bodies.
- Communicating and interacting with federal and nonfederal stakeholders, including communication via the NNI website.

The goals of the individual agencies determine the level of involvement of their NSET Subcommittee representatives in NNI roles, responsibilities, and activities.

The NSET Subcommittee has formed four working groups (see Figure 1.1): Global Issues in Nanotechnology (GIN); Nanotechnology Environmental and Health Implications (NEHI); Nanomanufacturing, Industry Liaison, and Innovation (NILI); and Nanotechnology Public Engagement and Communications (NPEC).[14] The working groups have goals that are in synergy with the four main goals of the NNI as described in Box S.2.

The GIN working group goals are these:

> Monitoring foreign nanotechnology programs and development; broadening international cooperation and communications regarding nanotechnology research and development (R&D) including activities related to safeguarding environmental and human health; and promoting the United States' commercial and trade interests in nanotechnology in the global marketplace. The GIN working group will seek to identify areas for international cooperation and anticipate and address areas of potential international concern in order to facilitate the responsible and beneficial development of nanotechnology.[15]

The NEHI working group has goals of protecting public health and the environment. It promotes communication of EHS information and provides information exchange among agencies regarding nanotechnology research, regulation, and guidelines related to nanomaterials and products containing nanomaterials. NEHI supports development of tools and methods to identify, set priorities among, and manage strategies to enable risk analysis and regulatory decision making for nanomaterials and products incorporating nanomaterials. It also supports development of consensus-based nanotechnology standards, including nomenclature and terminology, by working with international organizations and governments and shares its findings and EHS best practices with international organizations. NEHI takes responsibility for managing, coordinating, reviewing, and revising the interagency EHS research strategy.[16]

NILI's stated goals are to develop interactions with U.S. industry and state

[14] National Nanotechnology Initiative (NNI), "Working Groups," available at http://www.nano.gov/about-nni/working-groups, accessed September 25, 2012.

[15] NNI, "Global Issues in Nanotechnology (GIN)," available at http://www.nano.gov/gin, accessed September 25, 2012.

[16] NNI, "Nanotechnology Environmental and Health Implications (NEHI)," available at http://www.nano.gov/nehi, accessed September 25, 2012.

organizations to support nanotechnology development and technology transfer. The overall purpose is

> to advance and accelerate the creation of new products and manufacturing processes derived from discovery at the nanoscale. This includes stimulating nanotechnology innovation in and by Federal Government agencies, for their use and in transferring technology among industry, academe, and State and local organizations. The NILI Working Group serves to coordinate nanomanufacturing R&D and translation activities among the participating agencies, which also involves liaison and close coordination with the private sector, where nanomanufacturing innovations will be implemented. It also facilitates interagency cooperation, and cooperation with industry, in the development of standards and nomenclature.[17]

The purposes of the NPEC working group are "to encourage, coordinate, and support NNI member agencies and interagency efforts toward educating and engaging the public, policy makers, and stakeholder groups regarding nanotechnology, its applications and implications, and the work of the NNI."[18] NPEC provides public input and outreach by convening regular and continuing public discussions on nanotechnology. It helps to plan public engagement activities and assess the need for continuing NNI-related public participation.

National Nanotechnology Coordination Office

The NNCO provides technical and administrative support to the NSET Subcommittee and its working groups and is critical for the success and effectiveness of the NNI. It organizes NNI workshops and facilitates the production of various reports, strategic plans, and so on, that represent efforts at the interagency level. The NNCO develops and maintains the NNI website (nano.gov), which serves as a portal for information and questions about federal nanotechnology programs and activities ranging from research to regulation.

The NNCO model is embodied in a memorandum of agreement among NNI participating agencies.[19] In effect, the NSET Subcommittee is the equivalent of the NNCO board of directors, approving activities and providing direction to the NNCO. OSTP, which cochairs the NSET Subcommittee and to which the NNCO director reports, also has input on the roles and responsibilities of the NNCO. Additional tasks for the NNCO that require resources are ultimately paid for, and must be agreed to,

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[17] NNI, "Nanomanufacturing, Industry Liaison, and Innovation (NILI)," available at http://www.nano.gov/nili, accessed September 25, 2012.

[18] NNI, "Nanotechnology Public Engagement and Communications (NPEC)," available at http://www.nano.gov/npec, accessed September 25, 2012.

[19] This and the preceding paragraph are paraphrased from NNI, "National Nanotechnology Coordination Office (NNCO)," available at http://www.nano.gov/about-nni/nnco, accessed September 25, 2012.

by the contributing agencies. The NNCO currently coordinates activities, including interactions with regional, state, and local governments and the signature initiatives.

STAKEHOLDERS RECEIVING NATIONAL NANOTECHNOLOGY INITIATIVE–RELATED FEDERAL FUNDING

The funding related to the NNI in 2012 was reported to be $1.85 billion among the participating agencies. (NNI-related federal funding is defined as participating agency funding associated with nanotechnology projects and initiatives that fall under the NNI umbrella.) Because their research is identified by the agencies as part of the NNI (and reported as such annually by the agencies in the supplement to the President's annual budget), people and organizations receiving NNI-related federal funding are expected by organizations that review the NNI (OSTP, PCAST, GAO, and the National Research Council) to be active in working toward the four NNI goals.[20] The NSET Subcommittee, the NNCO, and the funding agencies provide support for and expect them to meet agency priorities while in some cases helping to achieve national-level NNI outcomes. Each year, the participating NNI agencies provide the NNCO with funding data by program component area and as part of the Small Business Innovation Research and Small Business Technology Transfer programs, but in general they do not indicate what people, organizations, or projects are funded, how they are connected to the NNI, or what their roles are in meeting NNI goals. In the discussion that follows, the committee has categorized NNI funding in three types of federal research investment in nanotechnology. Dividing the investment into three types helps to clarify the relationship between the people and organizations whose research is identified as being part of the federal NNI investment, the NNI agencies, the NSET Subcommittee, and the NNCO.

Type 1: Agency Mission Needs Are Primary, Nanotechnology Secondary

Type 1 funding reflects the identification of nanotechnology-based approaches to agency R&D needs for which nanotechnology is not a required component. In Type 1 funding, people and organizations receive federal funding for nanotechnology-related research through many mechanisms. For example, federal and nonfederal stakeholders respond to requests for proposals from federal agencies, develop nanotechnology research approaches within a larger program, or identify nanotechnology as a key responsibility of a federal R&D laboratory. The agencies have specific agency mission–based definitions of success for this research or for these technologies, and the agencies have mechanisms and metrics in place for evaluating them. Examples of Type 1 funding include part of the 30 NSF materials research science and engineering

[20] See Box S.2 in the Summary.

centers, Advanced Research Projects Agency-Energy, Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, and Defense Advanced Research Projects Agency funding. For these agencies, there were no nanotechnology-specific calls for proposals. As described by Department of Defense (DOD) and DOE representatives on the NSET Subcommittee, most NNI funding from DOD and DOE is Type 1 funding. The total Type 1 investment is determined by agency after funding is allocated and is reported to the NNCO as part of the agency total for the supplement to the President's annual budget. The total Type 1 investment and the scope of the projects that it represents are indications of the diffusion of nanoscience and nanotechnology among federal R&D programs and of the potential for future commercialization and the need for a nanotechnology workforce.

Supporting and organizing workshops to bring groups of researchers together to share mission-agency-oriented approaches to the application of nanotechnology constitute one example of the NSET Subcommittee's strategy for supporting short-term agency-centric goals and promoting information sharing among NNI agencies and stakeholders. Periodic conferences, such as Nanotechnology for Defense, fit that model. A substantial fraction of research for the NNI signature initiatives appears to be Type 1 funding.

Although Type 1 funding is included in the total NNI budget, the people and organizations being funded do not necessarily know that they are considered by their funding agencies to be related to the NNI. Furthermore, the agencies do not share information with each other on what is being funded except broadly by PCA. With respect to appropriate definitions of success for the NNI, that raises two questions: What roles and responsibilities should the NSET Subcommittee and the NNCO have in assisting NNI stakeholders, including the agencies, and the people, organizations, and projects receiving Type 1 funding, to achieve NNI goals and support national priorities? What roles and responsibilities should those receiving Type 1 funding have in meeting long-term NNI goals?

Type 2: Nanotechnology-Driven Within a Single Agency

In Type 2 funding, nanotechnology is identified in a mission agency as offering a possible solution of a problem or class of problems. Nanoscience-based and nanotechnology-based programs are created in the agencies and, for extramural funding (outside the agencies), proposals are solicited and people and organizations are funded to perform nanotechnology-specific research. Examples of centers that receive Type 2 funding are NSF nanoscale science and engineering centers and nanosystems engineering research centers, the National Institutes of Health's (NIH's) National Cancer Institute (NCI) centers of cancer nanotechnology excellence, the NIST Center for Nanoscale Science and Technology, the USDA Forest Service cellulose nanomaterials pilot facilities, and the five DOE nanoscale science research centers. People and organizations that receive funding generally know that they are part of the NNI, and their project goals and milestones are aligned with agency goals and at least some of the NNI goals.

Type 3: Nanotechnology-Driven in Multiple Agencies

For people and organizations that receive Type 3 funding, at least two agencies have jointly planned and implemented a collaborative nanotechnology program to meet those agencies' shared goals. Examples of institutions that receive Type 3 funding include the Nanotechnology Characterization Laboratory of NCI, the Food and Drug Administration (FDA), and NIST; the Nanoelectronics Research Initiative of NSF and NIST in collaboration with the Semiconductor Research Corporation; and the centers for the environmental implications of nanotechnology of NSF and EPA. The people and organizations that receive Type 3 funding generally understand the goals of the collaborating agencies and the relationship between those goals and their project goals.

BUILDING A STRONGER COMMUNITY OF FEDERALLY FUNDED NATIONAL NANOTECHNOLOGY INITIATIVE STAKEHOLDERS

Defining the three types of NNI investment helped the committee to clarify the importance of NNI projects in meeting the agencies' goals and the NSET Subcommittee's and the NNCO's roles in information sharing, planning, management, and coordination. A key finding is that most projects that receive Type 1 funding and some that receive Type 2 funding are not identified publicly as part of the NNI; people, organizations, and projects are being counted in the NNI federal investment budget, but the people and organizations do not generally know that they are part of the NNI. The NNI does not report where federal funding is going, for what purpose, or how the activities and research are connected in the short term or the long term. Accordingly, it is not known how much NNI activity is performed by different stakeholder groups—for example, federal-agency researchers; researchers using agency user facilities and national nanotechnology networks; researchers in universities, small companies, large companies, or nonprofit research organizations; or partnerships made up of all or some of the above.

There are, however, some excellent examples in which NNI researchers working in a common area are clearly and publicly identified; projects, long-term goals, and national strategies are clearly and publicly connected; and NNI resources and activities for moving from innovative concepts to commercialization are developed and promulgated throughout the community. One outstanding model of the planning, coordination, and management involving nanotechnology stakeholders working toward common goals is the NIH cancer nanotechnology research program, shown

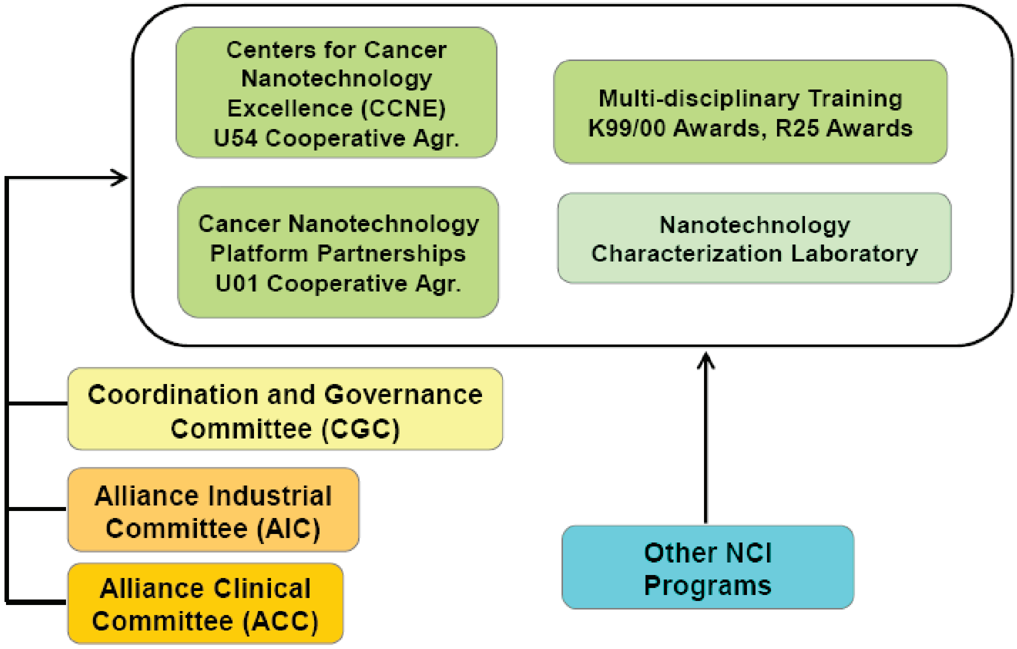

FIGURE 3.3 NIC Alliance for Nanotechnology in Cancer—organizational structure. SOURCE: Piotr Grodzinski, Office of Cancer Nanotechnology Research, National Cancer Institute, "Cancer Nanotechnology—Opportunities and Challenges—View from the NCI Alliance for Nanotechnology in Cancer," Alliance Overview Presentation, updated January 21, 2011, available at http://nano.cancer.gov/ about/presentation/, accessed August 14, 2012.

in Figure 3.3. With its strategic plan articulated by the NCI Office of Cancer Nanotechnology Research, the program's objective is to "discover and develop innovative nanotechnologies for application(s) ranging from discovery through translation and delivery of innovative clinically relevant technologies for cancer prevention, diagnosis, and treatment by developing and implementing programs with and for the external research community."[21] Key components of the program (described in Box 3.3) align with the characteristics of successful national strategies as identified by GAO (shown in Table 2.1). Of special note in the context of the NNI are

- The NIH Reporter, a comprehensive public database of all funded nanotechnology projects throughout NIH.

[21] National Cancer Institute, *NCI Center for Strategic Scientific Initiatives,* July 27, 2010, NIH Publication No. 11-7776, Bethesda, Md., p. 27.

BOX 3.3
Alliance for Nanotechnology in Cancer

Before the establishment of the NNI, the National Cancer Institute (NCI) had determined that nanotechnology-based materials and devices could substantially benefit cancer research and clinical oncology. The NCI Alliance for Nanotechnology in Cancer (ANC) is the formal structure created to make the nanotechnology-enabled strategies for prevention, detection, and treatment a reality. The ANC, an NNI best practice in planning and implementing a vision of nanotechnology, is planned and implemented across the cancer-research enterprise through the NCI Office of Cancer Nanotechnology Research (OCNR) in the NCI Center for Strategic Scientific Initiatives (CSSI). The ANC has a well-defined mission, common goals, a strategic plan with short-term and long-term outcomes, a well-defined organizational structure with articulated roles and responsibilities, integrated funding platforms, and demonstrations of progress at different stages from concept through commercialization.[1, 2]

The ANC website (www.cancer.gov) provides access to the cancer nanotechnology plan and descriptions of the ANC structure and how researchers and clinicians can apply for funding and connect with the existing regional centers. The ANC participates in cross-agency initiatives, such as the NCI-NIST-FDA Nanotechnology Characterization Laboratory (NCL), which facilitates interdisciplinary collaboration with improved scientific and technologic outcomes. That leverages National Institute of Standards and Technology (NIST) expertise in characterization, with the Food and Drug Administration (FDA) providing regulatory perspective. A key outcome is that techniques developed in the NCL are incorporated into regulatory requirements.

The ANC and the NCI Center for Biomedical Informatics and Information Technology have established the Cancer Nanotechnology Characterization Portal, a database of results of the NCL's and the ANC's studies that makes them more accessible to the research community."[3]

The process for ANC management occurs in 5-year increments; it is currently in the second phase through 2015. Programs are initiated by obtaining input from the scientific community for compelling research needs. The resulting priorities are then communicated to the NCI Executive Committee and advisory boards.

Of special note are the best-practices documents that the ANC provides to NCI grantees on how to operate their centers. These include best practices operations manuals for the following:

- The planning and coordination responsibility for nanotechnology initiatives in the NCI Center for Strategic Scientific Initiatives (CSSI).
- The NCI multicenter, multistakeholder Alliance for Nanotechnology in Cancer (ANC), which includes all the initiatives.
- The Nanotechnology Characterization Laboratory (of NIH NCI, NIST, and FDA), which is responsible for developing and performing "standardized characterization of nanoscale materials developed by researchers from academia, government, and industry."
- The NCI information clearinghouse and communication portal (http://nano.cancer.gov/).

- Centers of cancer nanotechnology excellence.
- Cancer nanotechnology platform partnerships.
- Cancer nanotechnology training centers.

There is also a strong emphasis on developing metrics to determine productivity and outcomes, including network collaboration "density" and how that correlates with degree of interdisciplinarity and innovation rates. Efforts will include an attempt to get at the impact of centers relative to individual-investigator awards. There is close attention to student tracking. The information-technology aspects of metrics are described in the nanotechnology informatics white paper prepared for NCI by the Integrative Cancer Research Nanotechnology Working Group.

NCI provides funding for preclinical work on diagnostics, devices, and pharmaceutical therapies although other National Institutes of Health funding can be leveraged for clinical evaluation. Principal investigators are encouraged to identify alternative funding for clinical and commercialization efforts. Clinical trials started on nano-enabled technologies are being tracked, but it is too early for them to have reached the commercialization stage. Early commercialized nanotechnologies from NCI are described in the footnote.

Many researchers funded by the ANC have received funding from other NNI agencies. A number of researchers had not received NIH funding before. The ANC has created connections between engineering, materials science, and biomedical researchers.

In the current environment, funding is flat. There is a continuing need to position programs to be able to leverage funding from other sources, such as Translation of Nanotechnology in Cancer (TONIC), a public–private partnership that seeks to evaluate promising nanotechnology platforms and facilitate their successful translation from academic research to the clinic.

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[1] For more information, go to http://nano.cancer.gov/about/mission/, accessed November 12, 2012.

[2] For more information, go to http://nano.cancer.gov/action/recent/, accessed November 12, 2012.

[3] National Cancer Institute, "Alliance Program Office Activities," available at http://www.nano.cancer.gov/about/activities/, accessed November 12, 2012.

Although the ANC has been established primarily in one agency, the potential value added to the NNI by similarly identifying and more formally linking people, organizations, and projects to long-term goals, particularly for the signature initiatives, could be enormous. A first step would be informing the community of NNI federally funded researchers that they are part of the NNI. A second step would be to make available information about all NNI-funded researchers and projects (see details in Chapter 4) so that individual researchers can identify those doing related research. Improvements in communication and interaction with and between federally funded researchers and within the NNI agencies, the NSET Subcommittee, and the NNCO should increase the use of federal facilities and resources, build and strengthen the nanotechnology community, and accelerate progress toward national goals.

Finding: Most projects that receive funding are not identified publicly as part of the NNI; they are counted in the NNI federal investment budget, but researchers generally do not know that they are part of the NNI and that their research is considered integral in achieving the NNI goals. Accordingly, managers, policy makers, and other interested parties do not know how much NNI activity is performed by different stakeholder groups. Those who review the NNI do not know the level of or goals of reported federal investments in nanotechnology. NNI researchers may not be aware of broader NNI resources, such as agency user facilities and national nanotechnology networks.

Recommendation 3-1: The NSET Subcommittee and the NNCO should create and maintain a publicly accessible database of NNI projects, people, and organizations funded by the U.S. federal government, including project title, grant number, principal investigators and senior personnel, participating organizations, funding agency and amounts, abstract, technology readiness level, performer types (such as university, corporations, small businesses, and national laboratory), signature initiative participation, and interagency collaboration. The data set will provide a more accurate picture of the NNI investment and of collaboration between agencies and organizational boundaries. It will also allow an assessment of the spectrum of nanotechnology activities that are supported by the federal government—from fundamental to applied studies—and their relevance to specific programs, such as NNI signature initiatives.

Recommendation 3-2: The NNI agencies should inform researchers and their organizations that their research is part of the NNI and the signature initiatives (where applicable) at the earliest possible date, and there should be a database of project-level information that stakeholders across the NNI can use to identify relevant activity.

For researchers outside the agencies, the latter information should be part of initial notification that proposals have been selected for award. The notification to awardees should include a summary of the broad goals of the NNI and available NNI resources, including infrastructure networks, user facilities and centers, and technology-transfer and commercialization programs. Agency management should provide the same notification to staff members who are performing research that they are part of the NNI and, when applicable, its signature initiatives.

Notification may also extend to other national initiatives, such as the Materials Genome Initiative. It is possible, for example, that an NNI-related project that is part of the Nanotechnology Knowledge Infrastructure signature initiative will also be part of the Materials Genome Initiative. (An NNI-related project is defined as a project belonging to a participating agency associated with nanotechnology projects and initiatives that fall under the NNI umbrella.) Notification of NNI-related funded researchers is a critical component of building a stronger nanoscale science and engineering community in combination with the database of research projects and investigators called for above.

The next two chapters describe and recommend definitions of success, relevant metrics, and changes in NSET Subcommittee and NNCO planning, management, and coordination to support the participating NNI agencies and departments, federally funded NNI researchers and organizations, and the broader NNI stakeholder community.

4

Metrics, Definitions of Success, and Data

The National Nanotechnology Initiative (NNI) aims to understand and control matter at the nanoscale so that industries can be revolutionized and society will benefit. That vision provides a high-level, generalized "definition of success" for the NNI. The substantial complexity, federal investment, and importance of this enterprise, on the basis of its four goals, require careful and regular assessment of its effectiveness. Because it can be argued that federal investments in nanotechnology by many of the participating agencies would have occurred even without the formal establishment of the NNI, a key challenge for the NNI is to identify and possibly quantify the extra value added by its establishment and operation and to determine whether it is meeting its goals.

The NNI is working to accomplish four primary goals:[1]

1. To advance world-class nanotechnology research and development.
2. To foster the transfer of new technologies into products for commercial and public benefit.
3. To develop and sustain educational resources, a skilled workforce and the supporting infrastructure and tools to advance nanotechnology.
4. To support the responsible development of nanotechnology.

[1] See National Nanotechnology Initiative, "NNI Vision, Goals, and Objectives," available at http://www.nano.gov/about-nni/what/vision-goals, accessed January 23, 2013.

The challenge raises issues that go well beyond the usual assessments of an individual agency or mission. Each agency already has in place processes for relating inputs to outcomes. There appear to be data that, although not routinely cast in this form, would permit each agency to evaluate the effectiveness and efficiency of its individual NNI investments. One example is the NSF website, detailing grants funded by the agency; another is the NIH Reporter, giving details of grants, albeit slightly different.[2] The committee found that those computer-based assessment tools are not adequate for assessing the overall effectiveness of the NNI as a major national multiagency initiative. In particular, the kinds and formats of data collected by the participating agencies are neither mutually compatible nor readily shared among the agencies.

However, progress toward achieving the four NNI goals is currently reported by NNI in largely anecdotal form in the annual NNI supplements to the President's budget. There, several agencies provide examples of successful projects; some provide numerical data, and some present short summaries without many details. Interagency activities are reported in the same manner. Clearly this makes it difficult to link what is reported to specific progress toward achieving each of the four goals.

The result is lost opportunities to evolve best practices; to measure the value added by interagency cooperation, planning, and collaboration; to identify and rectify programmatic gaps or redundancies; or to determine whether the levels of investment are adequate to meet the goals. The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council's (NSTC's) Committee on Technology and the National Nanotechnology Coordination Office (NNCO) could gather and aggregate such information from the agencies and bring the data and associated metrics to bear toward NNI goals in ways that are accessible to the various NNI stakeholders.

In this chapter, the committee identifies some of the shortcomings of the current processes and offers recommendations for improvement. It describes in general terms the role of data and metrics in assessment, identifies some aspects of particular relevance to the NNI, and then briefly reviews other studies of metrics for federal research and development (R&D) programs and suggestions for specific types of data and models appropriate for the NNI. It also discusses some new tools and methods that are becoming available owing to research in the field of metrics and assessment and concludes with a proposed implementation process.

[2] See, for example, the NSF and NIH webpages on current funding at http://www.nsf.gov/award-search/ or http://projectreporter.nih.gov/reporter.cfm, accessed January 24, 2013.

ASSESSING PROGRESS

The key for determining progress toward successful outcomes is to have explicit models for the NNI that link desired goals and specific long-term outcomes to investment (funding and resources), implementation plans, actions throughout the NNI, outputs, and short-term outcomes that can be measured and evaluated. The purpose of measurement and evaluation can be thought of as threefold: to determine whether the plans are being followed, to determine whether the investments and plans should be changed on the basis of outputs and short-term outcomes, and to determine whether the plans are producing the desired outcomes.

The methods, techniques, and potential of nanotechnology pervade the programs of the participating agencies. In many cases—such as the Department of Energy (DOE) Nanoscale Science Research Centers (NSRCs), the National Science Foundation (NSF) Nanotechnology Undergraduate Education (NUE) program and similar programs, and the multiple agency investments in the environmental, health, safety, and societal effects of nanotechnology—the mapping of investments to specific NNI goals is clear and direct. In other cases, however, such mapping is substantially less straightforward. Most often, the nanotechnology funding accounted for under the NNI is not defined by explicit nano-directed programs but is ascribed to nano-related projects in the broad portfolio of existing agency programs (the Type 1 funding described in Chapter 2). That makes it difficult to assess the true effect of NNI investment on outcomes of agency research or to distinguish when nanotechnology has been the driver in the outputs of the agency programs from when it has played a supporting, yet enabling, role. The committee believes that improving how individual agencies determine their share of NNI funding and making this publicly known would substantially enhance the ability to relate NNI-derived funding of projects directly to the overall output and outcomes of the agency research portfolios.

Finding: Data appear to exist that would permit evaluation of the effectiveness and efficiency of each agency's individual NNI investment. However, at present the kinds and formats of data collected by the participating agencies are neither mutually compatible nor readily shared among the agencies.

Finding: The NSET Subcommittee and the NNCO could gather and aggregate such already existing information across agencies and bring the data and associated metrics to bear to assess progress toward NNI goals.

ESTABLISHING METRICS FOR QUALITY IMPROVEMENT

In its interim report, the committee examined the role of metrics in managing such programs as the NNI.[3] It is most important that measurements be made only if actions will be taken as a result. With a materials-manufacturing analogy, the information in Box 4.1 sheds light on the general relationship between making measurements and taking action as a result.

The following excerpts from the interim report highlight some additional thoughts that guided the committee through the process of writing this chapter and defining its recommendations. For the full text of the committee's interim report, see Appendix E.

> This report reflects the committee's view that measuring something just because it can be measured is not good enough: metrics must be indicators of desired outcomes. There must be a model that accurately relates what is measured to a desired outcome and an equally accurate system to perform the measurement. Having both constitutes a metric. Without both, measurements have little value for program assessment and management. (p. 141)
>
> . . . progress toward achieving the four NNI goals is reported in largely anecdotal form. Several agencies provide examples of successful projects, some provide numerical data, and some present short summaries without many details. Interagency activities are reported in the same manner. That approach is consistent with how the NNI agencies manage their overall portfolios, how they gather information to report to the president, and what is included in the NNI supplement to the president's budget. (pp. 152 and 153)
>
> A good metric for output should be an accurate measure of whether the desired outcomes of an activity have been achieved—outcomes that represent the value that the activity was intended to generate. In fact, however, many accepted quantitative metrics are used to measure what can be easily measured, rather than the value created in the course of the activity. (p. 154)
>
> Additional characteristics of a good metric are that the information supporting it are reliably and relatively easily obtainable and that, at the very least, the benefits contributed by the metric to evaluation, strategy, and priority setting justify the cost of obtaining the information. (p. 155)

The definitions of success and associated metrics that have been applied to NNI-funded programs are set by the agencies, and are, therefore, predominantly agency-mission-based, with nanotechnology being secondary. More is needed for assessing the success of the NNI as a whole beyond the success of the individual agencies in fulfilling their missions. As noted in a 2012 Government Accountability

[3] National Research Council, *Interim Report for the Triennial Review of the National Nanotechnology Initiative, Phase II,* The National Academies Press, Washington, D.C., 2012 (reprinted in Appendix E).

BOX 4.1
Metrics in Industry and in Academia

The relationship between output metrics and desired outcomes for the NNI can be illustrated by analogy with manufacturing—which is predicated on a market, i.e., "customer need." In manufacturing, a material or product is measured for three reasons: quality control, quality improvement, and establishing that a legal requirement specified in a contract between a supplier and a customer has been met. In the first case, all that is needed is a simple, reliable measurement to identify when it is no longer producing acceptable outcomes; the measurement produces as simple a result as "acceptable/unacceptable," and the information it provides stays local to provide quality control. In the second case, the measurement is more quantitative, guiding changes to produce better outcomes than previously obtained. In the third case, a supplier agrees to provide the customer a material that has specific properties as measured with specific agreed-on, standardized techniques. In each of those cases, there is an established model that relates a measurement to a desired outcome, and the measurement may be different in each case.

Academia's answer is to evaluate an individual based on a model of academic success using a set of subjective, qualitative metrics supported by quantitative data on output and subjective evaluation of that data. This combination of subjective evaluations and quantitative output metrics has evolved to support a model of academic success for faculty at different career stages and performance levels, from assistant to full professor.

Dependence on the subjective evaluation of a group of experts chosen for some mix of technical expertise, judgment, and breadth of knowledge of the field is key to this approach. Although the results of the application of qualitative metrics are subjective, such metrics have been demonstrated both to be reasonably reproducible and to successfully encourage desired outcomes.

Office (GAO) report,[4] neither input data nor output data can be readily compared among agencies. The measurement systems are not the same; each agency uses different metrics and processes for quality control of its programs that are based on the agency, its mission, and its historical way of doing things.

Establishing metrics for quality improvement—in which the process being improved is the NNI and its R&D system for addressing the four goals (listed on the first page of this chapter) and contractual obligations between the agencies and the societal customer—would be a reasonable next step. For these cases, an effective model would be one that connects what is being measured and evaluated (funding and resources) to the intermediate-term and long-term outcomes for which the customer is paying. Without the establishment of this connection, even accurate metrics will likely provide an incomplete and inaccurate assessment of whether desired outcomes are being met. As noted in the interim report, having

[4] GAO, *Nanotechnology: Improved Performance Information Needed for Environmental, Health, and Safety Research*, GAO-12-427, 2012, available at http://www.gao.gov/assets/600/591007.pdf, accessed October 11, 2012.

both a model and a valid measurement system constitutes a "metric." Without both, measurements have little value for program assessment and management.

An important characteristic of a good metric is that the necessary supporting information is reliable, rigorously definable, and relatively easily obtainable. Also the information generated by the metric should inform decisions that guide the program quality. The quest for good metrics is often confined to quantitative metrics. That can lead to collection of output data that are peripheral to the goals and outcomes of the activity. Furthermore, there is general awareness that reliance on quantitative metrics alone may change the behavior of participants in ways that are not necessarily beneficial or helpful in achieving successful outcomes.

The committee believes that effective evaluation must couple judiciously chosen quantitative measures with appropriate qualitative methods. In particular, subjective evaluation by a group of domain experts is key to any overall analysis of the NNI's effectiveness. It is an accepted component of the agencies' review panels and reports that serve as input to program management.

Similarly, quantitative and qualitative metrics can and must be applied to assessing the effects of NNI-related activity. The committee recognizes the great difficulty in defining robust models and metrics for a field as diffuse as nanotechnology and for agencies as diverse as the NNI member agencies. Nevertheless, the models and metrics applied must be rigorous and have clearly and publicly defined assumptions, sources, methods, and means for testing whether the models and data are accurate. If the data or analysis methods are inaccurate, incomplete, or not rigorously defined, the resulting evaluation, decision making, and allocation of resources will be compromised.

Although it is exciting, as discussed below, that new methods for gathering, analyzing, and interpreting data are being examined in the scientific community, the committee urges caution in their adoption before thorough evaluation. For example, although the NSF Star Metrics project[5] has many promising characteristics, it also presents grounds for concern. Directly accessing institutional human-resources databases to automate data collection on personnel, for example, seems excellent, but the software algorithms used to parse project summaries to identify emerging fields of research may not be ready for application. Implementation of the Star Metrics approach to define fields and current funding levels without independent validation could thus lead to erroneous conclusions.

[5] See Department of Health and Human Services, "What Is STAR METRICS?," available at https://www.starmetrics.nih.gov/, and Federal Demonstration Partnership, "STAR METRICS," available at http://nrc59.nas.edu/star_info2.cfm, as well as J. Lane and S. Bertuzzi, "The STAR METRICS Project: Current and Future Uses for S&E Workforce Data," available at http://www.nsf.gov/sbe/sosp/workforce/lane.pdf; all accessed February 1, 2013.

In summary, the committee suggests that strictly quantitative output metrics are not themselves definitive in evaluating the success of the NNI mission. Well-crafted qualitative and semiquantitative metrics and their review, supported by rigorously documented quantitative metrics, are more likely to be useful in producing evaluations that measure success and in setting NNI goals and policy.

DEFINITIONS OF SUCCESS AND METRICS FOR THE NNI: BUILT ON DATA AND SCIENCE

In the interim report (see Appendix E), the committee developed definitions of success for the NNI based on the four NNI goals (Box 4.2).

The committee believes that these are appropriate definitions of success for the NNI. The challenge for NNI is now to develop and make available data that

BOX 4.2
Definitions of Success for the NNI Goals

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

- A full spectrum of R&D—fundamental research, use-inspired basic research, application-driven applied research, and technology development—is being supported within the NNI.
- The NNI supports research that crosses boundaries—disciplinary, institutional, national, agency, and sector (government-university-industry)—to advance nanoscience and nanotechnology.
- The nanoscience and nanotechnology developed within the NNI are comparable to or better than the best in the rest of the world. In other words, NNI-supported research is world class.
- The frontiers of knowledge are being substantially advanced, commensurate with the NNI funding.
- Industrial sector-specific nanotechnology knowledge is used to inform application-driven research investment decisions.
- NNI dollars are spent wisely to advance world-class R&D effectively and efficiently.

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

- Vibrant, competitive, and sustainable industry sectors are developed in the United States that use nanotechnology to create new products, skilled, high-paying jobs, and economic growth.
- NNI-supported research is leading to valuable new technology that is being commercialized.

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

- A nanotechnology scientific and technical workforce is being trained and educated, and it contributes effectively to the U.S. economy, with the supply matching the growing demand for U.S.-based skilled nanotechnology workers.[1]
- Public understanding of, and interest in, nanotechnology and how it may impact our lives is expanded.
- Cohesive and substantial facilities and networks are being built that are of broad relevance to the nanotechnology community, and these facilities foster scientific collaboration.

can be (1) used to determine performance with respect to these definitions, (2) analyzed and used for strategic management, and (3) used by domain experts to independently evaluate success based on a combination of qualitative and quantitative metrics that relate to outcomes.

DATA SETS ESSENTIAL TO NNI ASSESSMENT

Based on these definitions of success, the committee identified one critical data set and eight additional data sets needed to assess the current state of the NNI and determine progress toward NNI goals.

1. *NNI-funded projects,* including such information as researcher name and affiliation, funding agency and amount, and abstract. Such an NNI-wide

- The amount and the types of infrastructure for nanotechnology advancement are appropriate for the funding levels.
- The technical needs of NNI stakeholders are met through NNI user facilities.
- Utilization rates for NNI infrastructure are high.

Goal 4: Support the responsible development of nanotechnology.

- Development, updating, and implementation of a coordinated program of environmental, health, and safety (EHS) research lead to development of tools and methods for risk characterization and risk assessment in general—including both hazards and the likelihood of exposure—and support a growing understanding of potential risks of broad classes of nanomaterials.
- Results of EHS research worldwide are public and easily available to researchers and users of nanomaterials.
- Businesses of all sizes are aware of potential risks of nanomaterials and know where to obtain current information about the materials' properties and best practices for handling them.
- To enable continued innovation, regulatory agencies have sufficient information to assess the risks posed by new nanomaterials.
- The NNI supports research to assess the societal impacts of nanotechnology in parallel with technology development.
- K-12 students are exposed to nanotechnology as part of their education and are aware of the potential applications and opportunities available to those who go into STEM disciplines.
- The general public has access to information about nanotechnology, and a growing proportion is familiar with the fundamental precepts.
- The NNI includes R&D aimed at applying nanotechnology to solve societal challenges such as affordable access to clean water, safe food, and medical care.

[1] A "nanotechnology worker" is, for example, a scientist or an engineer (such as a materials scientist, chemist, or physicist) who is trained to work on processes in the 1 to 100 nm range.

data set, made available publicly by the NNCO with the assistance of each of the participating agencies, will provide a range of indicators related to the definitions of success—for example, the amount of collaboration occurring across agency and organizational boundaries that can be used to monitor and track interagency, multi-institution, and multidisciplinary activity. It will also allow an assessment of the spectrum of R&D activities that are undertaken, from fundamental to applied, and their relevance to NNI signature initiatives. It will provide funding amounts for individual projects that are now reported for most agencies only in the total annual NNI investment. This is the single most critical set of data to be collected. Once these data are made public, some of the following data sets can be efficiently and effectively collected and analyzed using data-mining techniques. The committee believes that developing and maintaining this NNI portfolio data set is critical for tracking progress and measuring success for the NNI.

2. *Published documents arising from NNI activities,* including papers, patents, reports, material safety data sheets, and conference summaries. The document-based metrics lag the actual date of the research or discovery and take varied amounts of time to be published—for example, several years in the case of patents. The bibliometric data can provide indicators of the outputs of the NNI's activities, especially the more fundamental activities. These data are generically available in the public domain and will become readily searchable from Dataset 1. NNI success in acquiring and maintaining such a data set would lead to increases in the number of NNI-driven publications and in the breadth and depth of nanotechnology subjects addressed.
3. *Data related to impact,* including frequently cited and downloaded papers and patents, invited presentations, special sessions at conferences, and reports in the mass media for comparisons over time and across national boundaries. This data set can provide indicators of the global impact of NNI activities in driving global research directions (for example, as indicated by citations) and industry (for example, as indicated by downloads). Patent citations may be a useful indicator of technology transfer and of the translation of published NNI outputs into potential economic benefit. This data set is also largely available in the public domain and readily searchable by using Dataset 1 as input. NNI success in acquiring and maintaining such a data set would lead to an increase in the number of high-impact papers, presentations, press comments, and so on.
4. *Number of students supported.* This data set can provide an indicator of the development of an educated workforce (the nanotechnology workforce). These data are available essentially only from the participants in the NNI, and the NNCO would need to invest some effort to collect them. The com-

mittee notes, however, that many agencies already collect such data as part of project annual reports. There may be privacy concerns, and these data may be available only for release in aggregate form in the public domain. NNI success in acquiring and maintaining such a data set would lead to an increase in the number of graduates who have key skills relevant to advancing nanotechnology solutions to practical problems.

5. *User facility and network use,* measured via operational efficiency and effectiveness of key tools, including number of users, types of users, and their tool use. The purpose of this data set is to provide multiple indicators of the effectiveness of co-locating equipment, tools, and experienced personnel in specialized centers to address nanotechnology challenges. The data should provide insights as to best practices for center and network research management when used in conjunction with other information about management practices. Consideration of best practices should also lead to clearly articulated recommendations and guidelines for planning, coordination, and management. Some of the data are available from the centers and networks but require aggregation and analysis into a single data set. There may be difficulties in aggregating such data if definitions used by different management teams vary widely. It is hoped that the NNCO will be able to resolve such issues in collaboration with the participating agencies, but this is not known a priori. NNI success in acquiring and maintaining this data set would lead to increases in the operational efficiency and effectiveness of the NNI centers and networks.
6. *Data related to technology transfer,* including details of meetings, workshops, and conferences, and sessions in conferences. Other data should include standards development and small-business outreach (Department of Defense Small Business Innovation Research and Small Business Technology Transfer program) activities. The purpose of collecting this data set is to provide indicators of the variety of technology-transfer activities driven by the NNI and information on how NNI stakeholders are touched by these activities. Many of the data are available through the NNCO but only if provided by the participating agencies. Again, there may be difficulties in aggregating the data efficiently and effectively. NNI success in acquiring and maintaining such a data set would lead to increases in the numbers of such activities, of topics covered by the activities, and of people touched by the activities.
7. *Data related to education and outreach,* including workshops, activities aimed at K-12 students, and museum exhibits. The purpose of collecting this data set is to aggregate data that show the variety and scope of informal education and outreach activities being undertaken by the NNI. Many of the data are available to the NNCO—some on nano.gov if provided

by the participating agencies. There may be difficulties in aggregating the data efficiently. NNI success in acquiring and maintaining such a data set would lead to efficient distribution of educational tools and materials and to sustained or growing numbers of people being exposed to and learning about nanotechnology at all levels.

8. *U.S.-based nanotechnology job advertisements,* including all direct and indirect jobs pertaining to nanoscale expertise in the government, education, and commercial sectors.[6] The purpose of collecting this data set is to provide an indicator of demand for an educated nanotechnology workforce. Ideally, the data would be segregated by whether they are direct or indirect, by region, and by employment sector; at a minimum, the aggregate number should be tracked as a function of time. A substantial set of the data is easily obtained from job-aggregating public websites, such as Indeed.com and SimplyHired.com. The usefulness of such data in tracking nanotechnology jobs and economic growth will require further analysis. NNI success in acquiring and maintaining such a data set would lead to sustained or growing demand for workers in nanotechnology-related positions and businesses.
9. *NNI-related communications about environmental, health, safety, and societal implications of nanotechnology,* such as National Institute for Occupational Safety and Health guidance regarding nanomaterials in the workplace. The purpose of collecting this data set is to provide indicators of the NNI's activities and effectiveness in addressing social responsibility issues that arise in the creation and use of nanotechnology. The data are available only by direct input from the NNI participating agencies and the NNCO. NNI success in acquiring and maintaining such a data set would be indicated by an increase with time in the evidence of more people and organizations seeking, receiving, and using such information.

Finding: There are valid, measurable, and relatively transparent indicators of NNI success that are suitable for long-term tracking (in longitudinal studies) to assess impact and progress toward stated goals. Several types of data (for example, as seen in the list above) are useful and relatively easy to obtain; many are in the public domain already. With the help of appropriate models linking inputs, outputs, and outcomes, metrics for assessing success for the NNI can be developed from these data sets by tracking and evaluating them over time.

Recommendation 4-1: The nine searchable data sets listed above should be

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[6] A direct job is work where the job description is directly linked to usage of nanoscale expertise. An indirect job is one that is created due to the existence of one or several direct jobs.

collected annually and made available on the NNI website to allow the NNI's impacts and successes to be more effectively assessed by internal and external interested parties and used for resource allocation and planning.

Of these data sets, the first is the most critical and of highest priority; knowing nanotechnology research and development projects, people, and organizations funded by the NNI will allow progress to be tracked and greater value to be realized from the collective NNI investment.

OPERATIONAL ISSUES: COLLECTING, TRACKING, AND EVALUATING DATA

The committee notes that it is highly likely that many of the data required for assessment already exist in the participating agencies inasmuch as most of them are widely used by the agencies as indicators of activity and impact. With the exception of creating a publicly available database for NNI R&D projects, this is not a recommendation to create multiple large databases or data sets from scratch: The recommended data sets could be generated by data-mining experts from publicly available information and the NNI R&D projects database. The committee recognizes the variable and potentially significant cost associated with collecting the proposed data sets and leaves it to the NSET Subcommittee and the NNI agencies to identify an efficient and workable manner in which to collect the data, with a priority given to the first data set.

Recommendation 4-2: The NSET Subcommittee and the NNCO should obtain data-mining expertise to undertake the collection and collation of essential data sets, develop tools to analyze the data in accordance with the management and reporting needs of the NNCO and the agencies, and manage the process of making the data sets publicly available.

Once the data are gathered and analyzed, the NSET Subcommittee should engage a team of experts from both inside and outside the federal government to evaluate the validity of the data. To avoid the appearance of conflict, the group should consist predominantly of persons who are not members of the NSET Subcommittee or other NNI management stakeholders. The NSET Subcommittee should evaluate progress on the basis of the data analysis and report the results in the annual budget supplement. Progress will also be assessed by the National Nanotechnology Advisory Panel (NNAP)/The President's Council of Advisors on Science and Technology (PCAST) and the National Research Council (NRC) as part of their periodic reviews.

The field of R&D metrics has benefited in recent years from a great deal of technical and methodologic research by social scientists. That research has the potential to increase the possibilities to assess the impact and success of the NNI. Advances include the inexorable increases in computing power and database size, norms that encourage the opening of databases to public scrutiny (within the boundaries of privacy concerns), the tendency to make computation and problem-solving an "open-source" and public effort, advances in machine learning and data-mining algorithms, and the entry of private firms into bibliometric and personnel linkage. Taken together, those advances increase the possibility that the problem of metrics for the NNI can be partially solved by taking advantage of research that is going on outside the NNI agencies.

The committee notes that creating perfect data sets to assess and manage the NNI is neither reasonable nor possible. The NNI is a large program; as happens in most large organizations, the data returning to the management teams will often be incomplete, particularly at the beginning. The art of management of large organizations is getting the strategic directions right in the absence of perfect data, and the NNI should be no different in this regard. Any commentary regarding data, metrics, and interpretations should acknowledge the known limitations of the data sets and metrics. Provided that the data sets are made public, the committee expects that their fidelity will improve with time as the agencies and those whose work is included in the data sets identify and correct errors.

Finding: There are a wide variety of objectives, metrics, data formats, and reporting processes in the NNI participating agencies. Various research efforts on metrics are under way and are evolving quickly and benefiting from the application of big data computation of social science data that could be applied to the assessment of NNI progress.

Recommendation 4-3: Rather than try to mandate a particular data format, metric, or reporting process, the committee recommends that NNI social-science researchers make their code and processes public and their data available through an application programming interface (API). Open-code development and widespread availability of data through APIs will greatly facilitate database linkage, innovation, and convergence on best practices. Agencies that fund NNI research should support and require infrastructure development in the course of any research on commercialization metrics. The NNCO and NNI agencies should also encourage private firms to make their bibliometric tools and databases public.

With efforts to encourage the diffusion of best practices and their improvement in metrics development, it is hoped that individual agencies will eventually adopt a consistent data standard out of self-interest. Working-group meetings of data professionals in the different agencies would facilitate diffusion of best practices and convergence on standards.

Linking databases requires articulating relationships among a wide variety of "subjects," such as grants, papers, patents, products, and organizations. One useful way to link such subjects is to identify the people involved unambiguously. For example, they would include the principal investigator and graduate students who are funded on a particular grant, the papers and patents that they produce, and the organizations to which the graduate students disperse when their project is finished. Data on people can be disambiguated from large paper and patent databases or assigned permanently, perhaps with an Open Researcher and Community ID (ORCID) number. The ORCID approach aims to solve the name-ambiguity problem in scholarly communications by creating a registry of persistent unique identifiers for individual researchers and an open and transparent linking mechanism between ORCID, other ID schemes, and research objects, such as publications, grants, and patents.[7] Use of ORCID is now required for publication in American Physical Society journals. It will not be applied to publications retroactively and so cannot be used for historical study.

Finding: The ability to track people and link them to their work products and organizations would greatly facilitate an assessment of the efficiency and effectiveness of NNI investments.

Recommendation 4-4: NNI agencies should record NNI participants and link them to their work products and organizations by individual grants, using ORCID, and link these data to published paper and patent databases, which over time may be linked to social and economic outcomes.

Figure 4.1 illustrates how the inputs of funding and scientific personnel could be traced in their transformation toward economic impact.

[7] ORCID, "Our Mission," available at http://orcid.org/about/what-is-orcid/mission, accessed September 27, 2012.

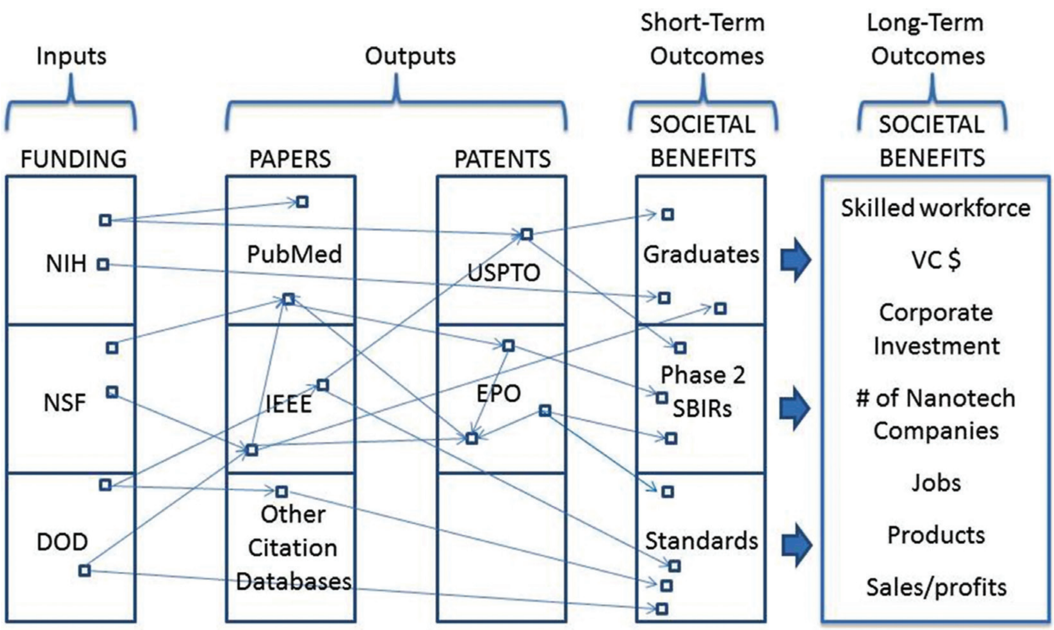

FIGURE 4.1 An idealized schematic that illustrates potential linkages between databases that would permit the impact of a research investment to be linked to publications and patents, personnel mobility, and social and economic outcomes. EPO, European Patent Office.

5

Planning, Management, and Coordination Framework for the National Nanotechnology Initiative

SIGNATURE INITIATIVES

In the annual report accompanying the 2011 budget, the National Nanotechology Initiative (NNI) announced three signature initiatives for the purpose of developing technology in fields that focused and closely coordinated support of research and development (R&D) between agencies and that could lead to more rapid advancements. Signature initiatives represent collaborations between the Office of Science and Technology Policy and NNI member agencies. The initial signature initiatives involved sustainable nanomanufacturing, solar energy collection and conversion, and nanoelectronics. One of the two additional signature initiatives created in 2012 is tasked with building a nanotechnology knowledge infrastructure, and the other, with developing nanotechnology-based biological and chemical sensors. Table 5.1 shows which agencies contribute to each signature initiative.

Over $300 million, or about one-sixth of the total NNI budget, is proposed in 2013 for the three signature initiatives that were introduced in 2011: $112 million for Nanotechnology for Solar Energy Collection and Conversion, $84 million for Sustainable Nanomanufacturing, and $110 million for Nanoelectronics for 2020 and Beyond. Those numbers, shown in Table 5.2, represent a 24 percent increase in signature initiatives investments compared with 2011 actual spending, well above the 4 percent increase for NNI as a whole. When the supplement to the President's 2013 budget was submitted to Congress on February 13, 2012, and the white papers for the additional two signature initiatives were introduced during May and July, funding levels for the two had yet to be reported.

TABLE 5.1 Agency Contributions to Signature Initiatives by Thrust Area

	Contributing Agencies															
Signature Initiative and Thrust Area	CPSC	DOD	DOD/DTRA	DOE	EPA	FDA	FS/USDA	IC/DNI	NASA	NIFA/USDA	NIH	NIOSH	NIST	NSF	OSHA	USDA/NIFA
Solar Energy Collection and Conversion																
Improved photovoltaic solar electricity generation				✓				✓	✓	✓			✓	✓		
Improved solar thermal-energy generation and conversion				✓				✓		✓			✓	✓		
Improved solar-to-fuel conversions				✓									✓	✓		
Sustainable Nanomanufacturing																
Design of scalable and sustainable nanomaterials, devices, and processes				✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	
Nanomanufacturing measurement technologies								✓			✓	✓	✓	✓	✓	
Nanoelectronics for 2020 and Beyond																
Exploring new or alternative state variables for computing		✓		✓				✓					✓	✓		
Merging nanophotonics with nanoelectronics		✓		✓				✓					✓	✓		
Exploring carbon-based nanoelectronics		✓						✓	✓				✓	✓		
Exploiting nanoscale processes and phenomena for quantum information science		✓						✓					✓	✓		
National Nanoelectronics Research and Manufacturing Infrastructure		✓											✓	✓		
Nanotechnology for Sensors and Sensors for Nanotechnology																
Develop nanoscale materials and engineered nanomaterials to resolve current technical barriers			✓		✓	✓			✓		✓		✓	✓		✓

continued

TABLE 5.1 Continued

Signature Initiative and Thrust Area	Contributing Agencies CPSC	DOD	DOD/DTRA	DOE	EPA	FDA	FS/USDA	IC/DNI	NASA	NIFA/USDA	NIH	NIOSH	NIST	NSF	OSHA	USDA/NIFA
Assess the impact of engineered nanomaterials across their life cycles on human health, safety, and the environment	✓				✓	✓						✓	✓	✓		
Nanotechnology Knowledge Infrastructure																
Enlarge a diversified community of scientists, engineers, and technical staff	✓	✓		✓	✓				✓		✓	✓		✓	✓	
Build a network that couples experimental basic research, modeling, and applications development	✓	✓		✓					✓		✓	✓		✓		
Build a cyber-toolbox to enable application of models to nanomaterials design		✓		✓					✓		✓	✓	✓	✓		
Create a robust digital nanotechnologic data and information infrastructure	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

NOTE: For a list of acronyms see Appendix B.

TABLE 5.2 NNI Approximate Funding (millions of dollars) for Three Nanotechnology Signature Initiatives, 2011-2013

Nanotechnology Signature Initiative	Participating Agencies	2011 Actual	2012 Estimated	2013 Proposed
Sustainable Nanomanufacturing	DOD, DOE, IC/DNI, NASA, NIOSH, NIST, NSF, USDA/FS	61	73	84
Solar Energy Collection and Conversion	DOD, DOE, IC/DNI, NASA, NIST, NSF, USDA/NIFA	88	89	112
Nanoelectronics for 2020 and Beyond	DOD, DOE, IC/DNI, NASA, NIST, NSF	97	104	110
Total		246	266	306

NOTE: For a list of acronyms see Appendix B.

SOURCE: The National Nanotechnology Initiative: Supplement to the President's 2013 Budget. 2012. National Science and Technology Council. Available at http://www.nano.gov/sites/default/files/pub_resource/nni_2013_budget_supplement.pdf, accessed 07/011/2012.

Each signature initiative is described in a white paper[1] that outlines the national need that it is intended to meet, the focus areas identified and prioritized as "thrusts," the expected outcomes, and the individual agency expertise to be involved. The white papers for the five signature initiatives vary widely in the specificity of technical targets, interagency planning, management, and coordination in meeting the scientific and technical targets, milestones, and roles that individual agencies play to meet the goals.

For example, the white paper on the Sustainable Nanomanufacturing signature initiatives[2] describes a path for "creating manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems" and provides metrics for success in terms of the outcomes, milestones, and time frames of specific planned, coordinated, and managed interagency endeavors. The growing effectiveness of interagency planning, management, and coordination processes was evident in updates given to the committee, as was the commitment to common long-term goals. Box 5.1 provides a summary of the Sustainable Nanomanufacturing signature initiative.

The white paper on the signature initiative on the Nanotechnology Knowledge Infrastructure (NKI) proposes long-term interagency collaboration among the disciplines of materials science, chemistry, biology, engineering, and advanced measurement and characterization science. To that end, the white paper indicates that the NKI signature initiative will leverage other federal efforts, such as the Big Data Research and Development Initiative (announced March 29, 2012) and the Materials Genome Initiative (MGI).[3]

In contrast, whereas the white paper on the signature initiative on Solar Energy, Collection, and Conversion[4] is notable for its clear and quantifiable technical targets

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[1] NNI, "Nanotechnology Signature Initiatives," available at http://www.nano.gov/signatureinitiatives, accessed December 10, 2012.

[2] National Science and Technology Council (NSTC), *National Nanotechnology Initiative Signature Initiative: Sustainable Nanomanufacturing—Creating the Industries of the Future,* Final Draft, Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, July 2010, available at http://www.nano.gov/ sites/default/files/pub_resource/ nni_siginit_sustainable_mfr_revised_nov_2011.pdf, accessed December 10, 2012.

[3] The Big Data Research and Development Initiative was announced by the Obama administration on March 29, 2012. The administration announced the Materials Genome Initiative on June 24, 2011. More information is available on each at http://www.whitehouse.gov/sites/default/files/microsites/ostp/big_data_press_release_ final_2.pdf and http://www.whitehouse.gov/sites/default/files/microsites/ostp/mgi_fact_sheet_05_14_2012_ final.pdf, respectively; both sites accessed December 17, 2012.

[4] NSTC, "National Nanotechnology Initiative Signature Initiative: Nanotechnology for Solar Energy Collection and Conversion," Final Draft, Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, July 2010, available at http://www.nano.gov/sites/default/files/pub_resource/nnisiginitsolarenergy finaljuly2010.pdf, accessed December 17, 2012.

(for example, "single junction silicon devices with improvements such as better band gap engineering at the nanoscale which will reach efficiencies of 28 percent [theoretical max 33 percent, best to date 25 percent])," it is also notable for its lack of description of interagency planning, management, and collaboration, with the exception of a joint request for proposal (RFP) between the National Science Foundation (NSF) and the Department of Energy (DOE). The lack of interagency activity was also reflected in the update to the committee in which the Solar signature initiative representative did not know of any interagency collaboration except the aforementioned DOE NSF RFP.

Given their strong connection to applications of nanotechnology, the signature initiatives are obvious vehicles for coordinating efforts and collaborating to support research investments with the private sector. For example, the Nanoelectronics Research Initiative (NRI), a consortium of member companies of the Semiconductor Industry Association (SIA) that contribute funding and other resources in a program of university research. Support for NRI research also comes from NSF and the National Institute of Standards and Technology (NIST), as well as from universities and state and local governments.[5] NRI partnerships among industry, NIST, and NSF have been highly effective at informing university research and moving results to the private sector. The NRI's success led to the creation of the signature initiative Nanoelectronics for 2020 and Beyond. For more information on the NRI see Box 5.2. This industry partnership has the opportunity to leverage the full NNI investment related to the Nanoelectronics signature initiative (valued at more than $100 million in 2012) and can provide industry input and perspective to the larger effort that includes DOE, Department of Defense (DOD), the intelligence community/Director of National Intelligence (IC/DNI), and the National Aeronautics and Space Administration (NASA) in addition to NSF and NIST.

According to the Government Accountability Office (GAO), an effective strategy includes the following six characteristics (described in greater detail in Table 5.3):

- Purpose, scope, and methods.
- Problem definition and risk assessment.
- Goals, activities, and performance measures.
- Resources, investments, and risk management.
- Organizational roles and responsibilities.
- Integration and implementation.

Table 5.3 shows an assessment of each of the signature initiatives on the basis of the GAO traits and associated white papers produced by the NNI.

[5] See SIA, "Nanoelectronics Research Initiative: A Model Government-Industry Partnership Promoting Basic Research," SIA Issue Papers, available at http://www.semiconductors.org/resources/sia_issue_papers/, accessed December 17, 2012.

BOX 5.1
Sustainable Nanomanufacturing Signature Initiative

The overarching goal of the Sustainable Nanomanufacturing signature initiative is to "establish manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems."[1] The key requirement of the initiative is the development of manufacturing processes that are

- Scalable.
- Precise, controllable, and sustainable.
- Safe and produce nanotechnology-based products that perform to specifications throughout their life cycle without harm to the environment or human health.

During the first year (2011), the initiative was funded at $61million. It is estimated that expenditures will be $73 million in 2012, and $84 million has been proposed for 2013.[2]

The initiative has two thrust areas:

1. Design of scalable and sustainable nanomaterials, components, devices, and processes.
2. Nanomanufacturing measurement technologies.

The initiative is supported by many federal agencies, whose roles include basic research and applied research (e.g., NSF, USDA, and DOE), metrology (e.g., NIST), manufacturing development (e.g., NSF and NIST), EHS (e.g., OSHA and NIOSH), and technology transfer and commercialization support (e.g., EPA and DOD).

Metrics and timelines have been developed for both thrust areas. Initial focus areas are carbon nanomaterials (NIST), optical metamaterials (NSF), and cellulosic nanomaterials (USDA).

For thrust area 1, success will be realized if within 2 years consortia (academic, industry, and government partners) have been established for the purpose of coordinating research on manufacturing methods; if within 4 years there has been a successful demonstration of processes that are scalable, sustainable, and safe; and if within 8 years materials and processes that are appropriate for production have been identified and technology transfer or adoption by U.S. manufacturers has occurred.

For thrust area 2, the initial focus area is roll-to-roll manufacturing. This thrust will be deemed successful if within 2 years, a consortium focused on metrology roll-to-roll processing has been formed, if within 4 years a real-time in-line measurement system has been demon-

The committee's analysis of the effectiveness of the signature initiatives Sustainable Nanomanufacturing and Nanoelectronics for 2020 and Beyond focuses on the following:

- Collaboration with federal and nonfederal partners.
- Defined metrics of success with timelines and outcomes.
- Effective communication, including updates to stakeholders.
- Periodic reviews of the plan and adjustments of plan as necessary.

strated, and if within 8 years a benchmarking of measurement systems has taken place with industrial partners to allow technology transfer.

To date, the signature initiative is on track to meet its goals. USDA has developed roadmaps and awarded $6.7 million for public–private collaborative research at seven universities for cellulosic-nanomaterials research and has installed a cellulose-nanomaterial pilot plant in the Forest Service Forest Products Laboratory in Madison, Wisconsin. NIST has held a workshop on carbon-based nanomaterials; there were participants from industry, academe, and government, and measurement barriers were identified. A cooperative research and development agreement is in place with Applied Nanostructured Solutions to understand the effect of growth conditions on the structure of carbon-based nanomaterials. The NSF Nanoscale Science and Engineering Center for Hierarchical Manufacturing is focused on advancing technologies for roll-to-roll processing. The center also supports the community through coordination of the National Nanomanufacturing Network and roadmap development.[3]

Interagency coordination is active. The NNCO staff person who supports the signature initiatives facilitates extensive and frequent interactions among the participating agencies.

The initiative participants interact regularly in person, via telephone, or via e-mail to share the scientific details of agency programs to identify opportunities to leverage activities and expand interagency collaboration.

The signature initiative Sustainable Nanomanufacturing has several participants in common with the Nanomanufacturing, Industry Liaison, and Innovation (NILI) Working Group, and communication between the two groups is strong. The co-chairs of NILI take strong personal interest in the initiative's goals and objectives. An update on the initiative is provided to the co-chairs of NILI, which has been helpful in identifying potential industry and academic partners. NILI has also provided outreach to the nanomanufacturing stakeholders in the industrial community.

[1] NSTC, 2010, "Sustainable Nanomanufacturing—Creating the Industries of the Future," Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, available at http://eprints.internano.org/1849/1/nni_siginit_sustainable_mfr_revised_nov_2011.pdf, accessed December 11, 2012.

[2] NNI, "Supplement to the President's 2012 Budget," available at http://www.nano.gov/sites/default/files/ pub_resource/nni_2012_budget_supplement.pdf.

[3] J. Alexander Liddle, NIST, "Nanomanufacturing Signature Initiative," presentation to the committee on July 10, 2012.

The Sustainable Nanomanufacturing signature initiative has been exemplary in its collaboration with federal and nonfederal partners and in its interaction with industry and academe. The role of each agency is clearly defined at the project level. This signature initiative is also to be commended for its effective communication with its stakeholders and with the Nanotechnology, Industry Liaison, and Innovation (NILI) Working Group.

The Nanoelectronics for 2020 and Beyond signature initiative strives to advance the field of nanoelectronics by exploring new and revolutionary materials, devices,

BOX 5.2
Nanoelectronics Research Initiative Model of Industry, Government, and University Collaboration

One industry that already is designing and manufacturing nanotechnology-based products is the semiconductor industry. The trend known as Moore's law states that the number of transistors (the devices that store and manipulate digital information) on a computer chip about the size of a fingernail will double every 18 to 24 months. Scaling has enabled the steady increase in performance and decrease in cost of integrated circuits (ICs) for everything from smart phones to credit card scanners. Cutting-edge ICs made today using silicon complementary metal oxide semiconductor (CMOS) technology have patterned features with a dimension of just 22 nm and require deposition of layers of materials that are only a few atoms, or about 1 nm, thick.

Continued improvement in performance and cost, which is vital to the competitiveness of the U.S. semiconductor industry and to technological leadership in support of national security, will require a new technology beyond CMOS. In 2005 a group of semiconductor companies formed a consortium—the Nanoelectronics Research Initiative (NRI)—to fund precompetitive university research in partnership with government with the mission to demonstrate the next logic switch. NRI awards research contracts based on competitive solicitation processes and to date has supported research at 57 universities involving more than 250 faculty researchers and 430 students.

NRI provides a model for industry collaboration and for public–private partnership. In addition to industry support, NRI research is funded by NIST, NSF, universities, and state/local governments. The collaborative industry investment would not be possible without the substantial NNI investment in nanoelectronics, e.g., the NSF program Science and Engineering Beyond Moore's Law. A key driver for other government agencies at all levels is economic development and the desire to see that the nanoelectronics industry takes hold in the United States or in their jurisdiction.

NRI employs a number of metrics with which to gauge success. Of greatest interest to industry members is progress toward the technical goal of demonstrating a superior logic switch. A set of parameters has been developed to compare the respective performance of each technology under investigation. Results of this benchmarking are used to guide research during the course of the project and to identify the most promising new devices. Other measures of NRI output include number of students supported and career positions following graduation; numbers of and citations to publications and patents/patent applications; and spin-off/start-up companies based on NRI research. An NRI metric that is perhaps unique for such an industry consortium is member company satisfaction with the program, based on annual surveys.

NRI is a research initiative, but its outputs eventually may play a role in the economic success of the semiconductor industry and of other industries that utilize semiconductor-powered technologies. One measure is based on sales. The U.S. semiconductor industry accounts for nearly half of the $300 billion world market and is the largest U.S. export over the past 6 years. A study of the economic impact of semiconductors over the past several decades based on data collected by the Department of Commerce concludes that the semiconductor industry grew 25 times faster than the U.S. economy as a whole between 1960 and 2007, and between 2000 and 2007 semiconductors accounted for 15 percent of the growth in sectors as diverse as motor vehicles and communications equipment.[1] Such quantitative estimates may not be possible for nanotechnology as a whole without modification of the data that are collected. However, the semiconductor industry can continue to be tracked and used as an example of the economic impact of nanoscale science and engineering.

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[1] J.D. Samuels, "Semiconductors and U.S. Economic Growth," draft, 2012, available at http://www.semiconductors.org/clientuploads/directory/DocumentSIA/ecoimpactsemidraft_Samuels.pdf.

TABLE 5.3 Strategic Characteristics Addressed by Each Signature Initiative

GAO National Strategy Characteristics	Solar	Nanomanufacturing	Nanoelectronics	Sensors	Knowledge
Characteristics of effective strategies	Addressed	Addressed	Addressed	Addressed	Addressed
Problem definition	Addressed	Addressed	Addressed	Addressed	Addressed
Goals, activities, and performance measures	Partially addressed	Partially addressed, but quantitative metrics are missing	Mostly addressed; additional quantitative goals could be included	Partially addressed; no performance measures	Partially addressed
Resources, investments, and risk management	Not addressed	Not addressed	Slightly addressed	Not addressed	Partially addressed
Organizational roles	Minimally addressed, only at thrust level, not project level	Addressed at project level, at thrust level, and at research level	Addressed only at thrust level, not project level	Partially addressed but only at mission level, not project level	Fairly well addressed (agencies and their roles identified)
Integration and implementation	Not addressed	Not addressed	Slightly addressed	Not addressed	Partially addressed

systems, and architectures and applying novel nanoscale fabrication processes and concepts to produce them. The initiative includes strong collaboration among industrial and academic partners, mainly through participation of NSF and NIST in the NRI. The NRI invests in large centers that coordinate across multiple universities and projects. In addition, input provided to NSF by industry members during the development of solicitations results in research grants that have well-defined metrics of success, timelines, and outcomes. Research is continuously guided via collaboration between university researchers and industrial scientists and engineers. Each project is formally reviewed at least once a year by all NRI partners, which provides comments, including recommended plan adjustments. University researchers prepare periodic reports and share them with industry members.

It is outside this committee's charge (see Box S.2 in the Summary) to determine specific goals and outcomes (definitions of success) and metrics for the individual signature initiatives, or to determine who is going to be assigned what role, what the milestones and timelines are, and how the signature initiative teams should plan, manage, and coordinate to meet their goals. However, the committee believes that it would benefit the NNI if the signature initiative teams considered developing and implementing formal interagency plans for the signature initiatives and reporting annually on their progress.

> **Finding:** Whereas the breadth of nanotechnology research and development under the NNI and the diversity of agency missions and needs make it difficult and impractical for the NSET Subcommittee to manage and coordinate the entire portfolio of activities in support of NNI goals, the signature initiatives offer clear opportunities and pathways for accelerating progress through "close coordination" in defined fields of scientific and technologic importance.

More active, explicit, and transparent interagency planning, management, and coordination are needed, including jointly planned and even executed research programs, in order to increase the progress and impact of the signature initiatives.

> **Recommendation 5-1:** Each signature initiative team should develop a strategic plan. The NSET Subcommittee and the signature initiative teams should expand the associated white papers to include specific goals (outcomes) with quantifiable technical targets where possible, milestones for reaching them, expected outputs and short-term outcomes, and roles and responsibilities of the (two or more) participating agencies, the NSET Subcommittee, and the NNCO. Planned actions and outputs and short-term outcomes to document progress should be reported online and in the annual report.

A key initial measure of success for the NNI will be the NSET Subcommittee and the signature initiatives teams' performance in developing and implementing the strategic plans.

The committee observes that the PCAST 2012 report made a similar although less-detailed recommendation in this regard.[6]

INTERAGENCY MANAGEMENT AND COORDINATION

Nanoscale Science, Engineering, and Technology Working Groups

As described in Chapter 3, the NSET Subcommittee has created four working groups—Global Issues in Nanotechnology (GIN), Nanotechnology Environmental and Health Implications (NEHI), Nanotechnology, Industry Liaisons, and

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[6] See President's Council of Advisors on Science and Technology (PCAST), *Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative,* April 2012, Executive Office of the President, available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST_2012_Nanotechnology _FINAL.pdf, accessed November 28, 2012.

Innovation (NILI), and Nanotechnology Public Engagement and Communications (NPEC)—to address subjects that could benefit from greater interagency focus and coordination. It is not clear to the present committee how effective those groups are. For example, although NEHI has been quite active, visible, and effective, it appears that other working groups have been, to different degrees, less so. It is difficult to determine what specific needs are identified by each working group, what their priorities are, and what the individual working groups have planned and accomplished. Even information on current membership and participation in the working groups is not completely transparent: the NEHI page lists member organizations in detail, but the NILI page simply states that membership is open to "all federal agencies and their component organizations," and the NPEC site states that "working group participation is open to all NSET members and/or their designees."

The four existing working groups are described below, as well as two more groups, proposed for consideration by this committee.

Global Issues in Nanotechnology (GIN)

The GIN working group has as its goals the strengthening of international R&D collaboration, capacity-building, and engagement on regulatory and trade issues. Chaired by the U.S. Department of State, this group also coordinates federal government activities in the Organisation for Economic Co-operation and Development (OECD) Working Party on Nanotechnology. The "international engagement" website at nano.gov provides more detailed information on various international nanotechnology groups and activities, although it does not link to the GIN working group website. A distinction is made between GIN's responsibilities on the international scale and that of the White House Office of International Regulatory Affairs:

> The Global Issues in Nanotechnology (GIN) Working Group helps to coordinate international activities among the various NNI member agencies, while the White House Office of International and Regulatory Affairs . . . promotes international regulatory cooperation in a number of venues, including Regulatory Cooperation Councils with Canada and Mexico and the High Level Regulatory Cooperation Forum with the European Union.[7]

The 2011 NNI strategic plan indicates that NIST works with the International Organization for Standardization's Technical Committee 229 and other standards organizations, including the OECD Working Party on Manufactured Nanomateri-

[7] NNI, "International Engagement," available at http://www.nano.gov/initiatives/international, accessed December 12, 2012.

als, in the development of standards and that these activities are coordinated with other agencies through the GIN working group.

Nanomanufacturing, Industry Liaison, and Innovation

The purpose of the NILI working group is to

> advance and accelerate the creation of new products and manufacturing processes derived from discovery at the nanoscale. This includes stimulating nanotechnology innovation in and by federal government agencies for their use and in transferring technology among industry, academe, and State and local organizations. The NILI Working Group serves to coordinate nanomanufacturing R&D and translation activities among the participating agencies, which also involves liaison and close coordination with the private sector, where nanomanufacturing innovations will be implemented. It also facilitates interagency cooperation and cooperation with industry, in the development of standards and nomenclature.[8]

NILI's goals include facilitating interactions between U.S. industry and state organizations to support nanotechnology development and technology transfer. Membership in the NILI working group is open to all federal agencies and their component organizations, but a specific list of participating agencies is not provided on the NILI working group website. It is not clear how the broad goals of the NILI working group—stated as a detailed list of activities to support, facilitate, and enhance nanotechnology development and technology transfer—are being worked toward.[9] Only one report was listed for "NILI" in a search of nano.gov publications.[10] However, a general search of the Internet reveals that an overview of the NILI work plan was given at the October 13, 2009, meeting of the NSET Subcommittee and the National Science and Technology Council (NSTC) meeting.[11] Although it is apparent that several reports address the goals of NILI, it is unclear what role NILI, as opposed to the NSET Subcommittee, had in guiding the activities. There are links to reports on the nano.gov/nili website, but it is unclear whether these are the output of the NILI working group. The 2009 overview advocated a number of laudable goals, including completion of NILI surveys on current status in four stakeholder sectors, increasing participation of groups and

[8] NNI, "Nanomanufacturing, Industry Liaison, and Innovation (NILI)," available at http://www.nano.gov/nili, accessed September 25, 2012.

[9] NNI, "Nanomanufacturing, Industry Liaison, and Innovation (NILI)."

[10] NILI Working Group, "Appendix E. NNI Agency Mechanisms for Industry and States," 2011, available at http://www.nano.gov/node/588), accessed December 19, 2012.

[11] M.C. Roco, NSF, NILI Chair, "Nanomanufacturing, Industry Liaison, and Industrial Innovation Working Group (NILI)," presentation to the Nanoscale Science, Engineering and Technology Subcommittee meeting, October 13, 2009, available at http://www.nano.gov/sites/default/files/nilioverview.pdf.

agencies involved in nanomanufacturing, partnering with industry and promoting technology transfer, disseminating the use of NNI infrastructure, evaluating the current environment for innovation in the United States, and creating a NILI website on nano.gov to include all relevant activities.

The 2012 PCAST Fourth NNI Assessment Report noted that the NNI had made progress on recommendations of the 2010 report and highlighted the progress made by NILI in "developing mechanisms to incorporate industrial input in NNI planning through public-private partnerships and in developing an agenda that focuses on job creation and state outreach." Another favorable aspect is that strong communication exists between NILI and the Sustainable Nanomanufacturing signature initiative. Information was also provided that NNCO is aligning staff assignments to new programmatic needs and had created the position of industry and state liaison.[12]

> **Recommendation 5-2:** Given the emphasis on the role of small business, the NSET Subcommittee should reach out to the Small Business Administration to gain insight into opportunities and mechanisms by which to support innovation better through this important and diverse sector.

Nanotechnology Public Engagement and Communications

The NPEC working group's goals are to promote best practices in public engagement and communication. The group's role is to educate and involve the public, policy makers, and stakeholder groups in discussions about nanotechnology and to assist in development of research-based guidance among stakeholders for the responsible development of nanotechnology. The NSET Subcommittee held a workshop on public participation in 2006.[13] The resulting report, released with additional information in February 2012, provided

> invaluable insights and guidance to the NPEC Working Group and the NSET Subcommittee as they plan ongoing NNI public outreach and engagement activities. For example, based in part on the workshop recommendations, the NSET Subcommittee organized a series of stakeholder workshops in 2009 and 2010 to guide the development of the 2011 NNI Strategic Plan and the 2011 NNI Strategy for Environmental, Health, and Safety Research. The subcommittee also established a website in 2010, the NNI Portal,[14] to obtain

[12] Sally Tinkle, Acting Director/Deputy Director of the National Nanotechnology Coordination Office, presentation to the committee, January 2012.

[13] NSTC, *Public Participation in Nanotechnology: Report of the National Nanotechnology Initiative Workshop, May 30-31, 2006*, available at http://www.nano.gov/sites/default/files/pub_resource/nni_public_participation_ws _report.pdf, accessed September 25, 2012.

[14] The NNI strategy portal is available at http://www.whitehouse.gov/blog/2010/07/15/nni-strategy-portal-a-pathway-new-ideas-nanotechnology-innovation, accessed September 25, 2012.

> stakeholder comment on these strategy documents. Through the NPEC Working Group and other avenues, the NSET Subcommittee is committed to improving and expanding the public's input into its activities and to fostering an open dialogue with American citizens on the subject of nanotechnology.[15]

Several PCAST reports have requested that the NNI, through NPEC and NNCO, "demonstrate more clearly to the public the value of nanotechnology and NNI-supported research and development."[16] There have also been presentations to the OECD Working Party on Nanotechnology at a Workshop on public engagement with nanotechnology, held in Delft, the Netherlands, in 2008.

Nanotechnology Environmental and Health Implications

The NEHI working group has an active agenda, with membership supported by many of the federal agencies centered on the protection of public health and the environment. This working group promotes communication of information related to research on environmental, safety, and health (EHS) implications of nanotechnology and provides information exchange among agencies regarding research, regulation, and guidelines related to nanomaterials and products that contain nanomaterials. Working with the NSET Subcommittee and other interagency groups, NEHI supports the development of tools and methods to identify, set priorities among, and manage strategies to enable risk analysis and regulatory decision making for nanomaterials and products that incorporate them. The group also supports development of consensus-based nanotechnology standards, including nomenclature and terminology, by working with international organizations and governments and shares its findings and EHS best practices with international organizations. NEHI takes responsibility for managing, coordinating, reviewing, and revising the interagency *Environmental, Health, and Safety Research Strategy* document.[17]

Over a period of years, NEHI has iteratively set goals and priorities; this has resulted in the 2011 NNI EHS research strategy, which includes recommendations

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[15] NSTC, *Public Participation in Nanotechnology: Report of the National Nanotechnology Initiative Workshop, May 30-31, 2006,* available at http://www.nano.gov/sites/default/files/pub_resource/nni_public_participation_ ws_report.pdf, accessed September 25, 2012, p. iii.

[16] See PCAST, *The National Nanotechnology Initiative: Second Assessment and Recommendations of the National Nanotechnology Advisory Panel,* Executive Office of the President, April 2008, available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST-NNAP-NNI-Assessment-2008.pdf, accessed November 15, 2012.

[17] NSTC, *National Nanotechnology Initiative: Environmental, Health, and Safety Research Strategy,* Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, Executive Office of the President, October 2011, available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/nni_2011_ ehs_research_strategy_final.pdf, accessed December 11, 2012.

from a series of stakeholder workshops conducted in 2009 and 2010. The workshops were organized by the NSET Subcommittee to guide the development of this strategic research plan.[18] The plan establishes clearer EHS and ethical, legal, and societal implications (ELSI) goals and research needs; principles for identifying high-priority nanomaterials; mechanisms for targeting and accelerating research; and the beginning of a framework for implementing research programs. However, it is important to heed the following caution of the National Research Council committee that reviewed the 2011 NNI EHS research strategy:[19]

> To advance the research strategy, mechanisms will be needed to ensure its effective implementation, to evaluate research progress, and to refine the strategy as the base of evidence evolves—elements that the committee considered integral to its charge. *Implementation will also require the integration of the various participants, both domestically and internationally, involved in nanotechnology-related EHS, including the NNI and the federal agencies; the private sector, such as nanomaterial developers and users; and the broader scientific and stakeholder communities, such as academic researchers.*
>
> *Successful implementation will require mechanisms that improve coordination and modify institutional arrangements.* Such modifications have been articulated by stakeholder groups involved in the nanotechnology-related EHS research enterprise. The committee concludes that attention to these implementation mechanisms is as integral to the success of the research strategy as the research priorities themselves, a key finding of the 2009 NRC review of the federal strategy. [Italics added.]

The 2012 Government Accountability Office (GAO) analysis of EHS echoed that view, saying that the EHS strategic plan lacked "performance information—such as targets, metrics and time frames for meeting those targets."[20]

The NEHI working group has made progress toward developing research priorities and is well positioned to take the next steps to develop more specific long-term goals and long-term outcomes, specific plans to reach them, and short-term outcomes and metrics. Suggested definitions of success and associated metrics for the NNI EHS program and NEHI are presented in Box 5.3.

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[18] For more information on this plan, go to NNI, "Key Concepts in the 2011—National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy," brochure, available at http://www.nano.gov/sites/default/files/pub_resource/2011_brochure_ehsresearchstrategy.pdf, accessed December 11, 2012.

[19] National Research Council, *A Research Strategy for Environmental, Health, and Safety Aspects of Engineered Nanomaterials,* The National Academies Press, Washington, D.C., 2012.

[20] GAO, "Nanotechnology: Improved Performance Information Needed for Environmental, Health, and Safety Research," GAO-12-427, 2012, p. 2, available at http://www.gao.gov/assets/600/591007.pdf, accessed September 25, 2012.

BOX 5.3
Suggested Definitions of Success and Metrics for EHS and NEHI

If one reflects on NNI Goal 4, which is "to support the responsible development of nanotechnology," it is clear that it encompasses the goals that the Nanotechnology Environmental and Health Implications (NEHI) Working Group sets and some aspects of other working groups. Responsible development of nanotechnology is central to advancing a world-class research and development (R&D) program (NNI Goal 1), educating the workforce and engaging the public (NNI Goal 3), and all aspects of nanomanufacturing and product commercialization (NNI Goal 2). Because of the complexity of Goal 4, related definitions of success (outcomes) are particularly challenging to summarize, but they may include the following:[1]

- NNI develops, updates, and works to implement a coordinated program of environmental, safety, and health (EHS) research that will develop tools and methods for risk characterization and assessment in general—including both hazard and likelihood of exposure—and support expanding understanding of potential risks of broad classes of nanomaterials. Publicly available results of EHS research worldwide are made available broadly to researchers and users of nanomaterials.
- Businesses of all sizes are aware of potential risks of nanomaterials and know where to obtain current information about properties and best practices for handling.
- Regulatory agencies have sufficient information about risks of new nanomaterials to enable sound risk assessment that promotes innovation.
- NNI supports research to assess the societal impacts of nanotechnology in parallel with technology development.
- The general public has access to information about nanotechnology and a growing percentage is familiar with the fundamental precepts.
- NNI includes R&D aimed at applying nanotechnology to solve societal challenges such as affordable access to clean water, safe food, and medical care

Possible metrics for Goal 4 could include the following:[1]

- EHS collaborations and projects/centers funded.
- Number of NNI EHS research results that are made easily accessible, e.g., through an NNI-managed clearinghouse or in cooperation with international organizations.
- Publicly available guidance documents developed.
- Number of faculty/students supported for research in these areas.
- Number of K-12 students and educators engaged by NNI-related funded researchers, including Department of Energy laboratory outreach and National Science Foundation-funded researchers, and the impacts.
- Data from NNI-related funded research on public awareness and attitude regarding nanotechnology.
- Analysis of online information and news items related to nanotechnology.
- Evidence that NNI agencies are engaged in international forums discussing and developing standards, norms, and strategies for responsible development of nanotech.
- Number of NNI agency representatives to various international forums.
- Compilation of commercialized or commercializable technologies.
- Number of companies offering EHS, nanotoxicity, and/or nanotechnology safety services.
- Evolution of outcomes and impact resulting from sustained funding in EHS and the social dimensions of NNI.

[1] National Research Council, *Interim Report for the Triennial Review of the National Nanotechnology Initiative, Phase II*, The National Academies Press, Washington, D.C., 2012 (reprinted in Appendix E).

Proposed Working Group: User-Facility Oversight and Coordination

The NNI has been highly successful in creating substantial user facilities that benefit academic, government, and industrial researchers throughout the nation. A prime example is the DOE Nanoscale Science Research Centers (NSRCs), which provide access to state-of-the-art experimental facilities without user fees for publishable research. Other prime examples are NSF's National Nanotechnology Infrastructure Network (NNIN); the National Institutes of Health's (NIH's) Nanotechnology Characterization Laboratory, in conjunction with NIST and the Food and Drug Administration; and the NIST Center for Nanoscale Science and Technology. Those facilities represent a substantial achievement of the NNI, but opportunities for further optimization of the facilities probably lie in better interagency coordination. Although there is evidence of interaction and even collaboration among the several centers or facilities reporting to the same agency (such as the five DOE NSRCs and the NSF NNIN facilities, which are regularly reviewed), there appears to be no clear mechanism for sharing of best practices, strategic planning, user information, and so on, among centers in different agencies. Similarly, the committee's impression is that although there is strong regional coverage of user facilities, there are no clear mechanisms for interagency coordination of the capabilities and methods of access in the facilities. For example, when a major new suite of instruments is established in an NSF, DOE, or NIH facility, there should be a ready forum for discussion to ensure that there is coordinated acquisition and distribution of critical equipment. The committee believes that oversight for addressing such issues continuously could be facilitated by the formation of a new working group.

Proposed Working Group: Education and Workforce Development

Nanotechnology education and workforce development are recognized as vital for achieving the full benefits of the NNI programs and are explicitly called out in the program's high-level goals. The agencies appear to be using a variety of programs and organizations to address their needs. However, in the NNI 2013 budget supplement, only one listed activity (of four) shows a higher level of coordination, with two agencies involved (NSF and the Department of Education). Given the broad spectrum of individual agency activities,[21] finite resources, and the variety of expertise in nanotechnology education and worker training, there appears to be

[21] The 2013 budget supplement describes individual efforts of DOD, DOE, Department of Education, FDA, IC/DNI, NASA, NIH/NCI, NIST, NSF, USDA/FS, and USDA/NIFA. See NSTC, *The National Nanotechnology Initiative—Supplement to the President's 2013 Budget,* February 2012, available at http://www.nano.gov/sites/default/files/pub _resource/nni_2013_budget_supplement.pdf, accessed January 10, 2013.

an opportunity to enhance current investment in education and training through greater coordination by establishment of a new working group or refinement of the scope of the existing NPEC working group. In addition, agencies that have a mission to promote workforce development and training, such as the Department of Labor, should be included in this working group.

Finding: There appears to be substantial opportunity to revise roles of working groups or to create new working groups in user-facility oversight and coordination and in education and workforce development.

The NNI and the global nanotechnology landscape have evolved since the working groups were established; therefore it is both timely and important that the NSET Subcommittee reevaluate and, if appropriate, update the working group portfolio.

Recommendation 5-3: The NSET Subcommittee should regularly assess the working groups to ensure that each is serving a useful management and coordination role related to the goals and objectives of the NNI strategic plan. Working groups that are no longer useful should be redefined or eliminated, and new working groups should be formed as needed. In particular, the NSET Subcommittee should consider creating new groups in the areas of user facility oversight and coordination and education and workforce development.

Recommendation 5-4: Each working group should address specific goals and objectives and should develop and annually update plans for outputs and short-term outcomes that are related to longer-term outcomes. Ties to signature initiatives should be highlighted. The NNI annual report should include working group plans, such as information about the annual objectives, activities, management, and accomplishments.

Given the diverse nature of the working group activities that affect the advancement of knowledge and the progress of nanotechnology, all working groups should be responsible for identifying and sharing information among agencies and with the broader community through the NNI website.

High-Level Interagency Engagement

The human resources that the agencies commit in the form of participation in the NSET Subcommittee and working groups are substantial. However, in its 2010 assessment, PCAST expressed concern that the level of the agency participants was such that they were not able to make decisions on behalf of their agencies. PCAST therefore recommended that the President and Congress "require each agency to task senior representatives with decision-making authority to participate in coordination activities of the NNI."[22] The committee appreciates the intent of that recommendation but also sees great value in the corps of expertise and long-term participation of many members of the NSET Subcommittee and the working groups.

Finding: High-level agency awareness and engagement are important, but there may be a trade-off between authority in the agencies and the ability to devote time and effort to the many NNI coordinating activities.

Recommendation 5-5: To improve engagement by senior NNI participating agency officials and decision makers, the NSET Subcommittee should inform and obtain input from the NSTC Committee on Technology on NNI objectives and plans at least annually.

SETTING RESEARCH DIRECTIONS: ROADMAPPING

An essential component of coordinating and managing goal-oriented R&D, such as the signature initiatives, is determination of targets and pathways for reaching them. Federal agencies that fund basic research often tend to focus on identifying opportunities. For example, DOE held a series of workshops that resulted in a set of reports on basic research needs for various energy technologies.[23] Some fields have turned to the National Academies for expert advice on research opportunities, including the decadal survey of research in astronomy and astrophysics, most recently updated in 2010.[24]

A field of research that has been driven by planning and cooperation in industry is semiconductor technology. That industry is one of the world's largest (about $300 billion in annual revenue worldwide). Since 2005, products of the U.S. semiconductor industry have been the largest contributor to U.S. exports.[25] That success

[22] PCAST, *Report to the President and Congress on the Third Assessment of the National Nanotechnology Initiative,* March 29, 2010, Executive Office of the President, available at http://www.whitehouse.gov/sites/default/ files/microsites/ostp/pcast-nano-report.pdf, accessed November 15, 2012.

[23] For more information, go to U.S. Department of Energy, "News and Resources: Basic Research Needs," available at http://science.energy.gov/bes/news-and-resources/reports/basic-research-needs/, accessed December 13, 2012.

[24] National Research Council, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2010.

[25] D. Hatano et al., "Doubling Semiconductor Exports Over the Next Five Years—An Economic Analysis by the Semiconductor Industry Association," July, Semiconductor Industry Association, San Jose, Calif., 2010, available at http://www.sia-online.org/clientuploads/directory/DocumentSIA/Export/Doubling_Exports_Paper_0610.pdf, accessed December 13, 2012.

is due, in part, to several approaches to precompetitive collaboration in R&D, including public-private partnerships such as SRC and SEMATECH. Those consortia have been guided and coordinated in their research efforts by the International Technology Roadmap for Semiconductors (ITRS). The industry-wide roadmapping effort, which has been fueled by the industry commitment to maintaining the increase in performance/cost ratio, has enabled scaling to ever smaller dimensions, as expressed by Moore's law, and by the integration of new functionalities.

Two decades of history and success of the ITRS[26] have inspired the development of additional roadmaps. There is room for similar activities in other industries enabled by nanotechnology. By building consensus on future technology needs, such roadmaps can foster commercialization and improve efficiency throughout an R&D supply chain. That continues to be true in the semiconductor industry, in which continued scaling of transistor size is enabled by a wide variety of complex, continually developing technologies that must be coordinated at least partially to provide reasonably efficient return on R&D investment. Other industries in which fundamental or platform nanotechnology advances would benefit the entire sector could also create roadmaps to expedite overall progress. As in the case of the ITRS, NNI-agency representatives can be important contributors to such efforts. In addition, the NNI could consider the development of such "technology needs" roadmaps to coordinate interagency efforts toward, for example, the "grand challenges" addressed by signature initiatives.

The best practices principles for technology roadmapping that are used in developing each biennial edition of the ITRS are these:

- Focus on identification of technology needs rather than on specific potential solutions.
- Indicate quantitative needs as a function of time out to a "rolling horizon" (such as 10-20 years) to help to identify consistent sets of solutions for each future technology generation.
- Characterize the adequacy of current resources by addressing each future need (for example, green, yellow, and red color codes for "pass", "borderline," and "fail").
- Highlight "grand challenges."
- Enlist broad participation (by industry, academe, and government) in "technology working groups" to write topical chapters of the roadmap. Include participants in the relevant supply chains.

[26] W.J. Spencer, L.S. Wilson, and R.R. Doering, "The Semiconductor Technology Roadmap," *Future Fab International* 18, January 12, 2005.

- Hold public conferences to gain additional feedback during updates and rollouts of the roadmap.
- Publish the roadmap on the Internet.[27]

Fundamentally, a roadmap created by an industry that uses voluntary, open, and transparent processes is a common good that allows every business in the sector to benefit and grow. Overarching benefits of industry-wide roadmapping include the following:

- Providing a guide for research worldwide.
- Synchronizing technology development and timely availability of manufacturing tools and methods.
- Increasing efficient use of R&D resources.
- Promoting market growth and job creation by reducing unknowns and increasing confidence.

As the semiconductor industry approaches the end of scaling complementary metal-oxide semiconductor technology as the primary ITRS driver, it has been evaluating how roadmapping can be used in general to address a broader set of technology needs. The resulting necessary conditions for any industry-wide technical roadmap effort include[28]

- A restricted set of performance measures against which progress can be gauged.
- Convergence of opinion among a majority of key players on the progress trends that the figures of merit are expected to follow.
- A potential market of substantial size that induces wide applicability of the roadmap (that is, the roadmap effort must be worth doing).
- Willingness to share information.
- Existence of a community of stakeholders.

Although the semiconductor industry sometimes is viewed as uniquely able to form consortia to fund basic research, one can argue that every industry can point to fundamental, platform science, engineering, and technologies for which each participating company would be willing to forgo exclusivity to make progress faster and less expensive through a consortium approach. Moreover, such roadmapping

[27] L.S. Wilson, ed., "The International Technology Roadmap for Semiconductors," 2011 Edition, available at http://www.ITRS.net.

[28] W. Arden et al., eds. "More than Moore," white paper, available at http://www.itrs.net/Links/2010ITRS/IRC-ITRS-MtM-v2%203.pdf, accessed September 25, 2012.

could be especially helpful in realizing progress in the signature initiatives. The challenge at the outset is to form a community of industry participants that are willing to share information.

The federal government can encourage industries to take those first steps. The proposed Advanced Manufacturing Technology Consortium program (AMTech) is intended to stimulate early-stage technology development based on industry needs by incentivizing industry-led consortia (new or existing) that would support long-term basic and applied research on enabling technologies. AMTech would provide grants to consortia to develop roadmaps of critical long-term industry research needs and to fund facilities, equipment, and research directed at meeting the needs.

AMTech is consistent with the recommendations of the PCAST report on advanced manufacturing released in June 2011[29] and was "strongly endorsed" by the NIST Visiting Committee on Advanced Technology (VCAT) in February 2012.[30] The VCAT report noted that the SRC NRI "stood out" among management models and recommended that AMTech be managed through consortia, led by industry, that include participation by universities and government agencies.

> **Finding:** The NSET Subcommittee could consider efforts that encourage industry consortia to plan and fund long-term research, similar to the proposed AMTech program.

> **Recommendation 5-6:** The NSET Subcommittee should incentivize groups in nanotechnology-enabled industries to participate in developing roadmaps and in partnering to address long-term research needs. Roadmapping would be especially helpful in realizing progress in the signature initiatives.

BUILDING A NANOTECHNOLOGY COMMUNITY

The vision and structure of the NNI require planning, coordination, and management throughout a complex and diverse set of federal agencies. NNI planning and management at the interagency level have evolved over the years, and a few best practices that make it reasonably strong have been established, but they are not sufficiently widespread.

Definitions of success for the NNI are inextricably linked to the management and coordination framework adopted by the NSET Subcommittee of the NNCO

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[29] See PCAST, *Report to the President on Ensuring American Leadership in Advanced Manufacturing,* June 2011, Executive Office of the President, available at http://www.whitehouse.gov/sites/default/files/microsites/ ostp/pcast-advanced-manufacturing-june2011.pdf, accessed September 26, 2012.

[30] NIST, *NIST Visiting Committee on Advanced Technology: Recommended Design Principles for AMTech,* February 7, 2012, available at http://www.nist.gov/director/vcat/upload/VCAT-Mfg-Summary-Recommendations.pdf, accessed 09/26/2012.

Committee on Technology and by the NNCO itself.[31] In looking at the practices of specific agencies, the present committee has found that the ones that conduct focused workshops, program reviews, and similar activities are often more effective in informing and helping to coordinate planning and execution among their stakeholders. Fairly high levels of communication and awareness can be found among the following agencies: DOE and its Nanoscale Science Research Centers, NSF and its Nanoscale Science and Engineering Networks, and the Alliance for Nanotechnology in Cancer, which all exemplify successful practices. However, coordination among the remaining NNI agencies is considerably less intensive and less effective. Stakeholders that are not members of such intra-agency communities are often missing out. The NSET Subcommittee and the NNCO can and should do more to involve such stakeholders.

The planning, management, and coordination framework needed depends on the complexity of the goal, the agencies and other stakeholders involved, the interconnectedness of planned outcomes, and the duration of the collaboration required to meet the goal. For example, ensuring soundness of federal government investments in nanotechnology by avoiding redundancy in and among agencies requires at least regular information-sharing. If information-sharing is the goal, holding regularly scheduled joint project reviews or workshops might be sufficient to ensure appropriate management and coordination. But in the much larger and more challenging context of the NNI, achieving longer-term goals will require much more formal planning and management. For example, ensuring that technologies developed with NNI-based federal funding have a clear pathway to commercialization requires that the barriers to such pathways are identified, that plans are developed to reduce or remove them, and that sufficient management and coordination are in place to execute the prescribed actions. Needs in that regard include interagency approaches to intellectual property policies, development and implementation standards, EHS requirements and public information-sharing, and education and workforce development.

The organizational structure of the NNI, depicted in Figure 1.1, provides both opportunities for and obstacles to addressing those challenges. The framework seeks to link agency programs and federal investments to metrics and progress toward the NNI's long-term desired outcomes. Assessing the effectiveness of the linkage is a major concern of the present report.

This chapter describes current processes and recommends changes in the planning, coordination, and management frameworks to enable the NNI to add more value to a whole that exceeds the sum of the parts in the nation's nanoscale initiative. The findings and recommendations in this chapter address the building of a larger, healthier U.S. nanotechnology community in which there is better vertical

[31] For the structure of the NNI, see Figure 1.1.

interaction of the NNCO and the NSET Subcommittee with the higher levels of the government. They also aim for greater coordination in the planning and execution of major efforts such as the signature initiatives; adoption and promulgation of best practices, such as technology roadmapping; enhanced information management and sharing through a restructured, more interactive website; and enhanced coordination with entities outside the U.S. federal government.

Specifically, this section considers the need and opportunity for substantially increased interagency information-sharing and access to information by the wide variety of NNI stakeholders, especially through the NNI website. This chapter also discusses the role of the five signature initiatives and the NSET Subcommittee working groups in supporting the NNI community and recommends specific actions to strengthen interactions between the NSET Subcommittee and the NNI community.

Information Management and Communication: Website Clearinghouse

The effective acquisition and sharing of information is important for the success of any organization. It is essential in an enterprise as diverse, interdisciplinary, and complex as the NNI. Indeed, there are probably few initiatives in which effective communication with such a wide variety of stakeholders is as vital for success as the NNI.

Every one of the participating NNI agencies supports and executes mission-oriented communication processes of its own. Some are complex, especially in the larger, more research-oriented agencies. A principal responsibility of the NNCO is communication: taking advantage of and building on agency processes and the information that they represent to ensure enhanced interagency awareness, communication, and coordination. The complexity of the NNI stakeholder communities described in Chapter 3 requires a creative approach to the nanotechnology communication challenge.

The NNI's communication could play an even more vital role in encouraging economic activity in nanotechnology by increasing general awareness of emerging technologies, by encouraging students to enter STEM fields related to nanotechnology in order to develop an educated workforce, and by educating the public on EHS and other effects of nanotechnology. Those activities necessarily cover a wide demographic range—K-12 students, universities, business circles, and the general population. The tools to address communication are varied and need to be appropriate to the intended audience; they may include methods as diverse as workshops, web resources, and even educational games. They will change as new communication technologies emerge and communication norms change.

The World Wide Web's nano.gov is a primary vehicle for meeting that challenge, and it has been successful and valuable in several ways. It provides considerable information on programs, resources, news, and events. For some purposes, it can be navigated and mined with reasonable ease. For example, it provides introductory material on nanotechnology aimed at the K-12 and more general populations; provides links to NNI reports, workshop announcements, and research centers and user facilities; and in some cases provides opportunities for collaboration and funding.

However, the committee believes that there are important unmet stakeholder needs and opportunities for the NSET Subcommittee and the NNCO, where the solutions could be addressed through the NNI website. These opportunities fall under two main headings. First, organizing the website to provide portals and paths to guide specific stakeholders—for example, educators, small businesses, local governments, and nongovernment organizations (NGOs)—to resources would improve NNI communication substantially. Second, the website could be structured to be highly interactive and easily searchable throughout agency-centric content. For example, the site provides a comprehensive list of, and links to, the many NNI-related user facilities. But a central resource that cuts across all the relevant centers and facilities regardless of hosting agency would enable potential users to identify the instruments, capabilities, and expertise in each facility and center and provide links for accessing them.

In the same vein, such an improved website could be the central resource for the project-related data called for in Chapter 4. Such a searchable database would allow all stakeholders to identify projects of interest to them and the participants involved and to the agencies funding the work. It would also aid agency program managers in remaining cognizant of related programs and investments by other agencies and thereby enhance the NNI's management and coordination capabilities. Furthermore, a searchable database would enhance technology transfer and commercialization of nanotechnology R&D. Often industry—particularly small businesses—does not have the appropriate awareness or resources to mine the databases of current R&D projects on agency websites. Organizing the information and having it searchable along stakeholder lines may ease the transition across the "valley of death" for nanotechnologies. The committee therefore offers a twofold recommendation.

> **Recommendation 5-7:** The NNI website (nano.gov) should be redesigned and its content organized to provide portals and guidance directed to the NNI stakeholder communities (industry, facilities, users, educators, mass media, and so on). The information should be appropriately integrated across the participating NNI agencies.

An essential ingredient in this redesign should be the incorporation of an easily searchable database of NNI research projects, facilities and centers, associated instruments and expertise, and the agencies and program offices providing project funding.

Interaction and Coordination with Entities Outside the U.S. Federal Government

As described earlier in this report, a number of groups have an interest in nanotechnology and the NNI, and many of them are outside the federal government. The committee believes that the NNI could better achieve its goals of fostering technology transfer and ensuring responsible development of nanotechnology if it engaged nonfederal stakeholders, including international organizations.

Stakeholder Workshops

Stakeholder workshops are among the most successful and effective contributions of the NNI. The NSET Subcommittee, assisted by the NNCO, has sponsored or endorsed many workshops on virtually all aspects of nanotechnology. Workshops were organized to help in the planning and preparation of the NNI strategic plans and in executing recommendations made by PCAST and prior National Research Council reviews.

> **Finding:** The NNI has spurred a substantial amount of information-sharing among the various participating agencies and other stakeholders that otherwise probably would not have occurred. Much of the information exchange has happened through workshops and publications. The NNCO, in partnership with the NSET Subcommittee, has facilitated many of the activities. The present committee endorses the activities and their continuation.

International Initiatives

The PCAST 2012 nanotechnology report[32] included a brief section on international developments (PCAST 2012). PCAST noted that the United States leads the world in nanotechnology R&D, but that other nations are gaining ground. For example, Russia is investing aggressively. The Russian Nanotech Corporation (RUSNANO) now ranks second worldwide in nanotechnology spending and plans to increase investment.[33]

Within the European Union (EU), there were plans for major investment in science and technology, including substantial components in nanotechnology. In particular, the EU recently completed the process of selecting flagship initiatives (FIs) as part of the Europe 2020 plan.[34] Each FI is expected to represent an invest-

[32] PCAST, *Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative,* April 2012.

[33] Ibid, p. 13.

[34] For more information on the Europe 2020 plan, see European Commission, "Europe 2020," available at http://ec.europa.eu/europe2020/index_en.htm, accessed November 16, 2012.

ment of 1 billion euros over a program lifetime of 10 years. Among the selected was an FI on graphene.

In addition to national and regional programs worldwide, there are many international activities, a number of which are listed on nano.gov. The GIN working group provides a forum for agencies to share information and coordinate such international activities, which include multilateral and bilateral cooperation and participation in international and regional forums and other events. The global nature of information-sharing in nanotechnology research can be seen in the international government groups, NGOs, and companies that participate in the annual International Nanotechnology Conference on Communication and Cooperation (for example, INC9 2013 in Berlin[35]) and in the World Technology Evaluation Center (WTEC) panel report *Nanotechnology Research Directions for Societal Needs in 2020*.[36] As part of that community, the NSET Subcommittee tracks progress in foreign nanotechnology R&D and helps to promote the trade and commercial interests of the United States in the development of a global marketplace for nanotechnology products.

> **Recommendation 5-8:** The Global Issues in Nanotechnology Working Group should expand activities aimed at development of a healthy global marketplace for nanotechnology, including international efforts on governance, environmental health and safety, and standards in the annually updated working group plan called for earlier in this chapter.

U.S. Regional, State, and Local Stakeholder Initiatives

Since the launch of the NNI, many states have begun programs aimed at supporting emerging nanotechnology university programs and businesses with the goal of leveraging federal investments and staking a leadership position as the field grows economically. According to the 2009 NNI workshop report *Regional, State, and Local Initiatives in Nanotechnology*, there are 34 regional initiatives supporting thousands of organizations performing nanotechnology research. One example is in New York, where the College of Nanoscale Science and Engineering at the University at Albany, State University of New York, has been built with $14 billion in public and private funding, including a substantial amount from the state. Other states have also funded efforts aimed at attracting and promoting the fledgling nanotechnology industry.

The NNI has taken steps to reach out to regional, state, and local nanotechnology efforts through a series of workshops, the most recent in May 2012 in Portland,

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[35] Ninth International Nanotechnology Conference on Communication and Cooperation website at http://www.inc9.de, accessed October 24, 2012.

[36] M.C. Roco, C.A. Mirkin, and M.C. Hersam, *Nanotechnology Research Directions for Societal Needs in 2020—Retrospective and Outlook,* 1st Edition, Springer, 2011.

Oregon. These workshops provide a forum at which leaders of regional, state, and local efforts can gather to

- Exchange information and stimulate collaboration between the workshop participants.
- Explore mechanisms for linking the NNI and regional, state, and local initiatives.
- Explore the roles of federal, regional, state, and local entities in nanotechnology transfer, education and training, and economic development.
- Identify common goals and objectives among the initiatives.
- Identify paths to enhance the effectiveness of the initiatives through collaboration, information exchange, and resource-sharing.

The workshop reports and other resources aimed at assisting regional, state, and local nanotechnology-related efforts can be found on the NNI website at nano.gov/initiatives/commercial/state-local.

In addition, following a recommendation by PCAST in its 2012 review of the NNI, the NNCO created a staff position dedicated to engagement with industry and states. Having a single contact for all activities related to those communities should improve the NNI's ability to provide them support.

ROLE OF THE NATIONAL NANOTECHNOLOGY COORDINATION OFFICE

The NNCO plays a critical role in the functioning of the NNI—facilitating information sharing internally and externally and providing administrative and technical support. The NNCO brings considerable value in coordinating the NSET Subcommittee, its working groups, and the signature initiatives. The NNCO also provides essential support and maintenance of the NNI website, which is the government's portal to information about nanotechnology and about activities and services throughout the government.

Finding: In light of the findings noted in this report—particularly the need for coordinating signature initiatives, providing centralized cross-initiative information access, and collecting and aggregating data to support metrics—the responsibilities of the NNCO will probably expand and require additional resources.

R**ecommendation 5-9:** The NSET Subcommittee should ensure adequate support for the NNCO to execute its current and future assigned responsibilities.

6

Technology Transfer and Commercialization

One of the four goals of the National Nanotechnology Initiative (NNI) is to "foster the transfer of new technologies into products for commercial and public benefit." The process of technology transfer varies widely from sector to sector and even from technology to technology. There is no one-size-fits-all solution. The most widespread mechanism for technology transfer is publications and presentations of technical findings at conferences, workshops, tutorials, webinars, and the like. The importance of those activities cannot be overstated. Any forum in which new ideas and results are aired will probably stimulate other activity, and forums in which industry and academe are brought together are of particular importance. Industry participants often take away a new idea or a new solution to a problem from a presentation without its being obvious to the presenter; this is the nature of confidentiality in the industrial sphere. Another important mechanism of knowledge transfer is the migration of human resources between different positions and sectors, for example, from academe to industry. The data on such migration patterns are far from complete.

The NNI touches many aspects of the commercialization process, for example, through federally funded user facilities, the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) programs, and other grant processes. In addition, the NNI supports research in fields that are critical for commercialization, including novel materials and processes, metrology and characterization, instrumentation, and nanomanufacturing.

Manufacturing research is especially ripe for technology transfer and can make commercialization of results in many other fields of research possible. In its 2008 review of the NNI, the President's Council of Advisors on Science and

Technology (PCAST) recommended substantially increasing the amount spent on nanomanufacturing research. The private sector echoed the importance of support for manufacturing research and development (R&D) in a 2011 report by Battelle and *R&D Magazine*.[1] Although this finding was not specific to nanotechnology, the U.S. companies surveyed, according to the report, ranked support for academic R&D in manufacturing second among recommended government actions. The recommendations were to

- Provide tax credits or incentives to companies that had active manufacturing R&D programs (67 percent).
- Support academic R&D in manufacturing (46 percent).
- Increase technology-transfer support from U.S. national laboratories to industry (39 percent).
- Create manufacturing R&D programs in U.S. national laboratories (36 percent).
- Create a manufacturing "challenge" program (28 percent).
- Increase tariffs on products manufactured offshore (25 percent).

Commercialization of nanotechnology encompasses the application of nanotechnology derived from both NNI-related funded research and other sources. The NNI supports commercialization broadly—providing access to facilities and programs that help to bridge the "valley of death" from basic research, regardless of whether it was funded by the NNI, through development to practical application. Hence, a large fraction of the innovations now coming to market have roots in NNI-related funded research.

Since passage of the Patent and Trademark Law Amendments Act (also known as the Bayh-Dole Act) and the Stevenson-Wydler Technology Innovation Act of 1980, technology transfer has been a right and even a responsibility of recipients of federal research funding. Now, more than a quarter-century after those landmark pieces of legislation, numerous public and private entities are striving to promote technology transfer. Aside from its novelty, and hence the existence of little in the way of standards and regulatory certainty, nanotechnology is not unique in the challenges and obstacles to moving discoveries from the laboratory into commercial application and use.

What is different about nanotechnology is the existence of the NNI—its strong coordination among participating agencies and its ability to reach the private sector and the public at large, for example, through the National Nanotechnology

[1] Battelle and *R&D Magazine*, "2012 Global R&D Funding Forecast," December 2011, available at http://battelle.org/docs/default-document-library/2012_global_forecast.pdf?sfvrsn=2, accessed November 15, 2012.

Coordination Office (NNCO) and the NNI website. The NNI makes it possible to support technology transfer in ways that typical research programs cannot.

The 2003 legislation that authorized the NNI included technology transfer as an element of the program and explicitly called for a number of actions,[2] including the following:

1. Program activities are to include "accelerating the deployment and application of nanotechnology research and development in the private sector, including startup companies." (p. 117)
2. The triennially updated strategic plan is to include plans for use of federal programs, such as the SBIR and STTR programs.
3. The NNCO is to "promote access to and early application of the technologies, innovations, and expertise derived from Program activities to agency missions and systems across the Federal Government, and to United States industry, including startup companies." (p. 117)
4. NIST is to "utilize the Manufacturing Extension Partnership program to the extent possible to ensure that the research . . . reaches small- and medium-sized manufacturing companies." (p. 117)

Moreover,

> The Secretary of Commerce or his designee, in consultation with the National Nanotechnology Coordination Office and, to the extent possible, utilizing resources at the National Technical Information Service, shall establish a clearinghouse of information related to commercialization of nanotechnology research, including information relating to activities by regional, State, and local commercial nanotechnology initiatives; transition of research, technologies, and concepts from Federal nanotechnology research and development programs into commercial and military products; best practices by government, universities and private sector laboratories transitioning technology to commercial use; examples of ways to overcome barriers and challenges to technology deployment; and use of manufacturing infrastructure and workforce. (p. 117)

CURRENT NANOTECHNOLOGY COMMERCIALIZATION ACTIVITIES

National Nanotechnology Initiative-Directed Efforts

The NNI agencies and the NNCO have taken a number of steps to boost technology transfer of NNI research results. Making technology transfer a primary goal and reporting on progress in the annual budget supplement, including the amount

[2] Public Law 108-153, "21st Century Nanotechnology Research and Development Act," December 3, 2003, available at http://www.whitehouse.gov/files/documents/ostp/Issues/Nano%20Act%202003.pdf, accessed November 15, 2012.

of SBIR and STTR funds going to nanotechnology research, help to increase awareness in the participating agencies and among those who read the report. However, the general readership probably does not include many who are in the throes of starting a company or developing a nanotechnology application.

The NNCO, through the NNI website, is to some extent accomplishing the objectives of items 3 and 5 above. Up-to-date information about the various user facilities—such as the Department of Energy (DOE) Nanoscale Science Research Centers, the National Institute of Standards and Technology (NIST) Center for Nanoscale Science and Technology, the National Science Foundation (NSF) National Nanotechnology Infrastructure Network, and the National Cancer Institute Nanotechnology Characterization Laboratory—is maintained by the facilities themselves, and links to the information are on the NNI website.

Multiple NNI workshops on regional, state, and local programs related to nanotechnology have helped to identify the extent of such activities, whose primary goals are, for the most part, technology transfer and workforce and economic development. The workshops provide forums for sharing information, networking, and, through the resulting reports, compilations of information on the programs and best practices. The report of the most recent such workshop also includes an appendix of technology-transfer activities and programs throughout the federal government. Regional efforts naturally have a limited geographic scope, but other commercial and noncommercial activities operate at the national or international level.[3]

End-product commercialization of nanotechnology is frequently implemented through companies that are distinct from the original research institutions (such as universities, government laboratories, and start-up companies). Therefore, it is important to provide mechanisms for creating awareness of R&D results, needs, and opportunities between these parties. Understanding of technology readiness level and manufacturing readiness level is critical for all parties involved. Originators of concepts often believe that they are closer to technology readiness than they are and therefore have unrealistic estimates of the value of their inventions or the challenges in commercialization. At issue is the availability of resources in prospective commercializing entities for identifying and selecting from the plethora of new potential-technology developments for further evaluation. Creating venues to showcase NNI-related funded research is critical in the commercialization chain. As in connection with several of this report's general recommendations, there are already examples of NNI activities of this type that would help showcase NNI-

[3] See, for example, National Science and Technology Council (NSTC), *Regional, State, and Local Initiatives in Nanotechnology: Report of the National Nanotechnology Initiative Workshop, April 1-3, 2009,* available at http://www.nano.gov/sites/default/files/pub_resource/nni_2009_rsl_workshop_report.pdf, and National Nanotechnology Initiative, "RSL 2012: Speaker Presentations and Posters," available at http://www.nano.gov/node/835, both accessed January 30, 2013.

related funded research. Again, however, there are elements of best practices that the committee specifically recommends for consideration.

The nanotechnology-showcase activity in the annual TechConnect conference[4] sponsored by a partnership of industrial sponsors is a good example of this type of exposure. The event

- Invites startup companies that have technologies of identified commercialization interest to participate.
- Arranges meetings between sponsors and start-ups for detailed assessment of specific commercialization opportunities, such as entering into joint-development partnerships and licensing agreements.
- Includes both nanotechnology and nano-enabled technologies in one large conference.

Some of the NNI agencies are to be congratulated for their efforts to hold similar types of showcase events. An example is the Navy SBIR program's Beyond Phase II Conference.[5] The committee urges that agencies consider how to engage more closely with potential commercializing entities and industries to maximize the participation at and impact of such events. Many companies that are seeking to commercialize nanotechnology have teams in "new technology evaluation," "strategic marketing," "acquisitions," or "corporate ventures," which are natural contacts for NNI agencies that want to partner in the organization of showcase events.

Other entities outside government are in a position to facilitate technology transfer, such as the Nano Business Commercialization Alliance (www.nanobca.org), which helps small, medium, and large businesses, along with investors, entrepreneurs, and inventors to network with NNI representatives. Industry-specific professional organizations, for example, the American Association for the Advancement of Science, the Institute of Electrical and Electronics Engineers (IEEE), the American Physical Society, the Materials Research Society, the American Vacuum Society, the Optical Society of America, SPIE (the international society for optical engineering), and the American Chemical Society have all contributed substantially to nanotechnology knowledge dissemination and technology transfer. SEMI (Semiconductor Equipment and Materials International) has a technology showcase ("The Extreme Electronics Tech Zone," http://www.semiconwest.org/exhibits/techzone) at its annual Semicon West conference and trade show, at which inventors

[4] Matthew Laudon, private communication, open session of the Panel on Review of the National Nanotechnology Initiative: Phase II, Irvine, Calif., May 15, 2012. See also the TechConnect World website at http://www.techconnectworld.com, accessed February 27, 2013.

[5] See Beyond Phase II Conference, available at http://www.beyondphaseii.com/, accessed February 16, 2013.

and entrepreneurs have an opportunity to exhibit and present to potential clients, partners, and investors.

The above is just a sample of the non-federal-led activities that support technology transfer, especially of nanotechnology solutions. The NNI can—for example, through its website—help to connect those who have ideas and those who want to and can help to move ideas into practice.

Relevant Government Programs Focused on Commercialization

Mission-oriented agencies—such as DOE, the Department of Defense, and the National Institutes of Health—engage with medium-size and large companies in a number of ways, including contracts and grants, with the goal of technology development and technology transfer. The funding provided to companies is not tracked as part of the NNI.

The well-established SBIR and STTR programs encourage small businesses to engage in innovation research and to cooperate with universities and federal government laboratories. The programs are a vital source of funding for start-up companies that are in the early stages of product development, and SBIR and STTR activity is a measure of commercial activity in nanotechnology. On the basis of NNI-reported funding data, it is apparent that nanotechnology activities are represented in those programs, but it is difficult to track the commercialization success of SBIR, STTR, and other processes, and parsing the data to reveal NNI-related impact is not now possible.

The NSF Innovation Corps (i-Corps) program (www.nsf.gov/news/special_reports/i-corps/) is a relatively new federal program aimed at supporting technology transfer from NSF-funded research. It provides supplemental funding and entrepreneurial mentorship to NSF grantees to help to move ideas from the laboratory to a point where other funding might be obtainable. It was launched in 2011 as a 3-year pilot program, and some of the initial grantees have successfully competed for SBIR and STTR funding. This program is expected also to address multiple NNI-related activities.

As mentioned in Chapter 5, NIST is proposing an Advanced Manufacturing Technologies Consortia program (AMTech) as a means of promoting and supporting industry-led consortia to develop roadmaps for long-term research needs and to address the needs in collaboration with NIST, universities, and national laboratories.[6] The program is modeled on NIST's successful partnership with the Semiconductor Research Corporation (SRC) Nanoelectronics Research Initiative.

The National Network for Manufacturing Innovation is a proposed network of

[6] For more information about the proposed AMTech program see *Federal Register* 76(141), July 22, 2011, available at http://www.gpo.gov/fdsys/pkg/FR-2011-07-22/pdf/2011-18580.pdf, accessed September 27, 2012.

up to 15 institutes that are to serve as "regional hubs of manufacturing excellence."[7] The network is to be funded by a one-time $1 billion authorization, which was included in the 2013 President's budget request. The recently established National Additive Manufacturing Innovation Institute (namii.org) will serve as a pilot for the larger program. There are expected to be synergies between the NNI array of activities and these manufacturing-specific activities.

Collection and aggregation of data to support metrics that allow us to understand the synergies and interactions between the NNI and each of those programs are recommended in Chapter 4.

Relevant Nonfederal Programs

A number of state and regional technology-transfer programs that are not nanotechnology-specific are nonetheless relevant. Some examples of nonfederal funding and mentoring programs are these:

- The Pennsylvania Ben Franklin Partnership, which has over 20 years of successfully stimulating technology transfer (www.benfranklin.org).
- Technology-transfer initiatives at the state level that affect specific technology fields in various regions. An example is the New York State Energy Research and Development Agency, which has Directed Energy and Entrepreneur in Residence programs (www.nydirectedenergy.org, http://htr.org/nyserda_entrepreneurs_in_residence_program.asp) that target energy-related technologies in cooperation with university partners, such as the University of Buffalo's Science, Technology Transfer, and Economic Outreach program.
- Pre-seed workshops that seek to help entrepreneurs and inventors to decide whether they have a commercializable product and whether they should pursue commercialization. They may be particularly important in organizations that do not have a strong culture of start-up activity because of various impediments, such as intellectual property (IP) policy limitations, tenure-track requirements, or a lack of funding, mentoring, or incubator access. For example, the State University of New York has funded pre-seed workshops of 2½ days to over 2 weeks in which each new business is partnered with local experienced IP, legal, business, financial, and other professionals in a team; addresses key business issues one by one; and then presents a pitch to a panel of investors. Such a process can serve as a practi-

[7] National Institute of Standards and Technology, "President Proposes National Network for Manufacturing Innovation," News Release, March 9, 2012, available at http://www.nist.gov/public_affairs/releases/manufacturing-030912.cfm, accessed September 27, 2012.

cal prescreening tool (according to Neworks LLC, www.neworks.biz, about 50 percent of participants decide not to go ahead), and successful participants can move on to company formation, i-Corps, and other activities.

International Benchmarking

The strong and successful linkage in the United States between research and economic development suggests that international R&D trends may indicate economic competiveness. Battelle and *R&D Magazine* collaborated on the 2012 Global R&D Funding Forecast,[8] which reports that Asian countries increased their share of the global researcher pool from 16 to 31 percent from 2003 to 2007. The report forecasts mixed trends for 2012 U.S. R&D spending: federal, down 1.6 percent to $125.7 billion; industrial, up 3.8 percent to $279.7 billion; and university, up 2.85 percent to $12.3 billion. Although U.S. industrial R&D spending is predicted to increase, the U.S. share of global R&D spending is forecast to continue to decline, from 32.8 percent in 2010 and 32.0 percent in 2011 to 31.1 percent in 2012. Its share is being lost primarily to Asia: 34.3 percent in 2010, 35.5 percent in 2011, and 36.7 percent in 2012.

The divergent trends in U.S. R&D investment according to sector have a number of implications. In contrast with federal and university spending, U.S. industrial R&D spending is overwhelmingly for "development" rather than "research," which relies on foundational research by the federal and university sectors. Thus, the impact of shrinking federal support for basic research may not be felt for many years.

Finding: In an era of constrained federal budgets, to support U.S. competitiveness agencies will be faced with a need to set priorities for R&D investments and even greater pressure to coordinate in fields, such as nanotechnology, in which advances affect multiple agency missions.

The recent report "Global Funding of Nanotechnologies and Its Impact"[9] continues to demonstrate the U.S. lead in global nanotechnology transfer. However, it also demonstrates the qualitative nature of assessments based on economic models (developed for non-nanotechnology).

[8] Battelle and *R&D Magazine*, "2012 Global R&D Funding Forecast," December 2011, available at http://battelle.org/docs/default-document-library/2012_global_forecast.pdf?sfvrsn=2, accessed November 15, 2012.

[9] Cientifica, Ltd., "Global Funding of Nanotechnologies and Its Impact," July 2011, available at http://cientifica.com/wp-content/uploads/downloads/2011/07/Global-Nanotechnology-Funding-Report-2011.pdf.

Trends in R&D spending by other nations constitute only one potential indicator of future economic competitiveness. A report by PCAST[10] compared domestic and foreign practices in addition to R&D investment that can enhance the environment for a high-technology economic sector, including nanotechnology-enabled industries. The report focused on the United States, China, Taiwan, and Singapore and highlighted differences in tax benefits, subsidy programs, currency valuation, science-based industrial parks, and worker training. The PCAST study shows that policy makers need to consider multiple "points of friction" and controls within their reach for smoothing the path from research to commercialization.

Finding: Given the novelty of nanotechnology, international best practices in nurturing the business environment for nanotechnology commercialization and related trends in commercialization activity are subject to change.

Recommendation 6-1: The NSET Subcommittee should periodically review the changing status of the competitive environment for nanotechnology-enabled industry in the United States relative to that of other nations.

Role of National Nanotechnology Initiative User Facilities in Commercialization

User facilities that support research at the nanoscale are operated by NIST, DOE laboratories, and universities that host NSF-funded centers. They allow access to state-of-the-art equipment, expertise, and, in the case of university NSF centers, potential candidates for recruitment. They have a regional, as well as a national, function and constitute a concrete achievement of the NNI, establishing an infrastructure that actively supports commercialization.

One of the charges given to the committee for this triennial review was the assessment of the ability of the NNI "to maximize the opportunities to transfer selected technologies to the private sector." As discussed in the committee's interim report, the federal agencies that participate in the NNI do not have consistent metrics for measuring the effectiveness of technology transfer. Many of the potential metrics can be obtained through effective data mining—for example, data on SBIR grants, patents, licenses related to federal research grants, and the diffusion of knowledge by publications, students moving into industry, and standards development. However, they may not be fully appropriate for understanding actual processes related to creating commercialization paths. Furthermore, the complexity of

[10] PCAST, *Sustaining the Nation's Innovation Ecosystems, Information Technology Manufacturing and Competitiveness,* January 2004, available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-04-itreport.pdf, accessed November 15, 2012.

collecting metrics is related to the NNI focus on the translation process as opposed to "the development and commercialization of technology for the marketplace"[11] that is the focus of industry.

In lieu of quantitative metrics, the committee received useful anecdotal input from federal agencies, national laboratories, industry, professional societies, and trade associations on the translation process. The information gathered was used in developing the recommendations related to identifying best practices in IP management and expanding the scope of the NNI website to aid those interested in technology transfer and commercialization.

Standards

Standards are important to commerce and innovation, aiding suppliers and customers in the specification and characterization of products. Nanotechnology standards-development bodies include the International Organization for Standardization (ISO) Technical Committee (TC) 229, International Electrotechnical Commission (IEC) TC 113, ASTM International (formerly American Society for Testing and Materials) Committee E56, and IEEE. These organizations are open and involve industry and government participants, and the NNI has been extremely active. Until his retirement, Clayton Teague, former director of NNCO, coordinated the national effort and was also the convener for the U.S. American National Standards Institute (ANSI) Accredited Technical Advisory Group to ISO TC 229. In addition, ASTM Committee E56 is led by NIST, the U.S. ANSI-Accredited Technical Advisory Group to ISO TC 229 Working groups on metrology and on environmental, health, and safety (EHS) are led by NIST and the National Institute on Occupational Safety and Health (NIOSH), respectively, and the ISO TC 229 Working Group on EHS is led by NIST. EHS guidance developed by NIOSH has recently been adopted in an ISO TC 229 technical report. The U.S. Department of Agriculture is heavily involved in standards development for cellulosic nanomaterials through the Technical Association of the Pulp and Paper Industry.

In the U.S. government, standards are a primary activity of NIST, and the agency is heavily involved in creating evermore accurate standards for the fundamental/primary measures of length, time, etc., at the nanoscale and beyond.

The era of commerce in products enabled by nanotechnology has created new technical challenges with respect to metrology at the nanoscale, a regime in which it can be difficult to distinguish the measuring instrument from the object being measured and fundamental work is needed. For example, NIST has developed

[11] W.H. Schacht, Specialist in Science and Technology Policy, Congressional Research Service, "Technology Transfer: Use of Federally Funded Research and Development," 7-5700, www.crs.gov RL33527, December 3, 2012.

standard methods for determining electrical resistance of individual nanowires and their contacts to other structures with an electronic device.[12] Many more metrology challenges stand in the way of commercial use of nanotechnology. Thus, the committee encourages NIST and other NNI participating agencies to work with industry to identify metrology challenges and barriers and to engage the broader research community to focus on the creation of nanocharacterization tools and standards that address these barriers.

In addition to standards in physical measurement and characterization methods, nanotechnology commercialization needs international standards for risk management. Some of them will be voluntary standards, such as the ISO 9000 and 14000 series.

Many important nanotechnology risk management standards will be related to EHS. For example, a recent effort led by the International Life Sciences Institute (ILSI) is looking at the rates of release of nanoparticles from composite materials and correlation to actual exposure and uptake in biological and environmental systems.[13] Such data are needed along with toxicity information in order to make appropriate standards and regulations. The committee encourages the NNI agencies, as appropriate, to continue and extend cooperative efforts with other nations in EHS-related standards setting. In order to be practical, such standards for nanotechnology need to address both technical effectiveness and economic viability.[14]

Recommendation 6-2: Standards development is critical for commercialization, use, and sound regulation of nanotechnology. The NNCO and NIST have played leading roles in this activity. NNI agencies should continue their active participation in standards development organizations and in the development of metrology and characterization tools, standard reference materials, terminology, and nomenclature.

Communication

It is critical that the NNI seek to target those aiming to bring new nanotechnologies or nanotechnology-enabled products to market. That population has specific needs, such as dealing with regulatory bodies and finding investors.

[12] C.A. Richter et al., "Metrology for the electrical characterization of semiconductor nanowires," *IEEE Transactions on Electron Devices* 55(11), 2008.

[13] See more about ILSI NanoRelease project at International Life Sciences Institute, "NanoRelease Consumer Products—News and Updates," available at http://www.ilsi.org/ResearchFoundation/RSIA/Pages/NanoRelease1.aspx, accessed April 15, 2013.

[14] V. Murashov and J. Howard, "The U.S. must help set international standards for nanotechnology," *Nature Nanotechnology* 3:635-636, 2008.

The World Wide Web is an important communication medium for the NNCO. However, despite the wealth of information that is available in its reports and on its website, a frequent complaint is that small businesses in particular are not aware of or cannot readily find relevant information.

The nano.gov website could be improved by making it easier to access material that addresses the needs of those involved in technology transfer and commercialization. For example, providing access to the database called for earlier in this report—including project titles, principal investigator information, patents, and publications—would help interested parties to connect with each other. If project, researcher, and center-of-excellence information were more readily accessible, there might be more opportunities for industry to seek out and develop collaborative relationships with other research centers.

Information about the use and regulation of nanomaterials could be made more readily available by, for example, creating prominent links to NIOSH websites that have recent safe practices guidelines. The Nanotechnology Environmental and Health Implications working group could develop and post a regulatory roadmap with an overview of procedures and regulatory requirements for new products. To avoid liability, appropriate language would direct website users to confer with appropriate agencies or legal sources.

> **Recommendation 6-3:** The NNCO should expand the scope of its website and reorganize it to focus on information aimed specifically at aiding and guiding those who are interested in technology transfer and commercialization.

MODELS FOR TECHNOLOGY TRANSFER AND COMMERCIALIZATION

Potential models for accelerating promising research to the point of commercialization are of broad interest. For example, the June 2011 PCAST *Report to the President on Ensuring American Leadership in Advanced Manufacturing* examined a wide range of international models for government investments in promoting manufacturing and economic growth and found that

> even as U.S. manufacturing leadership is waning, other nations are investing heavily in growing and revitalizing their manufacturing sectors and are crafting policies to attract and retain production facilities and multinational companies within their borders. Such policies include partnerships, physical structures such as science parks or technology clusters, tax and regulatory incentives, and concentrated investment in commercialization of promising technologies. Some of these policies amount to industrial policy—making clear bets on specific firms and industries, but others support pre-competitive activities that would be regarded as within the scope of appropriate government intervention in the U.S.

However, there are effective public-private partnership models that are compatible with U.S. practice and constitute obvious pathways for the NNI agencies to foster commercialization of a selected portion of the NNI nanotechnology research portfolio. In particular, models that seem promising for the NNI to exploit include the following:

- *SRC Consortium model*—academe supported by a consortium of companies to perform precompetitive research of mutual benefit to all industrial partners.
- *DOE Innovation Hub model*—integrated research centers that combine basic and applied research with engineering to accelerate scientific discovery in critical energy issues.
- *Fraunhofer-Gesellschaft model*—applied-research laboratories of direct utility to private and public enterprise and of wide benefit to society.

Each of those models provides a means for government agencies to work closely with companies toward the common goal of commercializing research funded solely by the government or jointly with industry. They differ in details of the handling of research funding, guidance, technology transfer, and so on, but all have worthwhile best practices.

The SRC Consortium Model

A particularly effective form of partnership is a consortium that shares the cost and risk of R&D among its members. The primary members of such consortia are companies within an industry that, although they are normally competitors, are able to build consensus on a set of precompetitive R&D goals. In some cases, the companies divide most of the R&D tasks among themselves and share the results; the U.S. Council for Automotive Research is an example of this type.[15] In other cases, the companies may use a central R&D facility as the research provider, such as HRL Laboratories (formerly Hughes Research Laboratories); such a central facility may be partly staffed by "assignees" from the member companies, as in the case of SEMATECH. SEMATECH is an example of a public-private partnership; it received half of its funding from a Defense Advanced Research Projects Agency (DARPA) contract during its first decade of operation and receives matching funds from the state of New York today. SEMATECH is also an example of an R&D consortium in the nanotechnology domain.

[15] See the U.S. Council for Automotive Research website at http://www.uscar.org, accessed January 29, 2013.

SRC is a pioneering nanotechnology R&D consortium that has sponsored university research since 1982. It consists of several subconsortia that serve the integrated-circuit and related industries. Most of them also include public-private partnerships, of which two, the Semiconductor Technology Advanced Research Network (STARnet)[16] and the Nanoelectronics Research Initiative (NRI),[17] are specifically addressing frontiers in nanotechnology in partnership with DARPA and with NIST and NSF, respectively. The NRI partnership with NSF is connected to the NNI signature initiative Nanoelectronics for 2020 and Beyond and is implemented through joint sponsorship of specific projects added to some of the NSF nanoscale interdisciplinary research teams. The committee believes that this type of partnership is one of many examples of best practices in R&D consortia that should be encouraged in multiple nanotechnology (and other) commercial sectors.

A more detailed look at the NRI example reveals specific best practices that could be further leveraged by NNI agencies in promoting the commercialization of nanotechnology. The main value of an NRI-style consortium in this regard is that its main purpose is indeed to foster commercialization of research results from the providers (universities in this case) through the consortium members (industry). A related purpose is to provide a supply of relevantly educated graduate students for recruitment by the members. Hiring students who have completed thesis research on projects of interest to the members is one of the best forms of technology transfer from university research to industry. NRI best practices for industrial consortia sponsoring university research can be summarized as follows:

- Consortium members build consensus on the scope of *precompetitive* R&D that will be funded.
- The consortium issues requests for proposals (RFPs) from the university research community on selected topics. In the case of NRI, the RFPs are developed, announced, and evaluated in cooperation with the NNI-partner agencies as appropriate.
- Project results are presented and industrial feedback on the progress is given at annual reviews open to all consortium members and university researchers under contract.
- Technologies are benchmarked to allow researchers to measure and compare progress toward key metrics of performance.

[16] See SRC, "Semiconductor Technology Advanced Research Network," available at http://www.src.org/program/starnet/, accessed April 15, 2013; STARnet is the follow-on program to the Focus Center Research Program, see SRC, "Focus Center Research Program (Legacy)," available at http://www.src.org/program/fcrp/, accessed April 15, 2013.

[17] For more information on NRI, see SRC, "Nanoelectronics Research Initiative," available at http://www.src.org/program/nri/, accessed April 15, 2013.

- In addition to their dues, the consortium members contribute scientists and engineers as "industrial assignees" who guide and participate in the university research on a full-time basis. To ensure complete coverage of timely guidance on projects, the consortium also establishes "industrial advisory boards" of part-time participants.
- If patents are created as part of the research, the universities own the patents, even if filing and maintenance are funded by the consortium; but in all cases, the consortium members receive royalty-free licenses to the IP.
- The consortium maintains a searchable database of research project summaries, periodic research reports, publications, and student résumés.
- The consortium sponsors an annual technical conference and job fair ("TECHCON") at which students present research results.
- The consortium organizes monthly webinars that provide tutorials and updates on research topics.

Those elements combine to ensure rapid progress in technology transfer. They lead to higher value for industry partners, more informed research, and enhanced education of students; most important, they increase national benefit. In addition, SRC has internal processes to measure the relevance of research to its members and its impact on the broader semiconductor community, to track students and connect them with industry opportunities (internships and employment), and to follow evolution of research from the university to industry.

Finding: The user facility infrastructure is outstanding, and government user facilities have a wide array of IP policies. However, although some are user-friendly, some make use difficult, especially for businesses. Bayh-Dole and Stephenson-Wydler requirements are interpreted differently, and complications can occur at the state level and where contractors manage government-owned laboratories. Universities also have widely differing Bayh-Dole interpretations and policies.

The committee urges that templates for cooperative R&D agreements (CRADAs) and other cooperative mechanisms should be developed and should be practical and equitable so that NNI projects are not "orphaned" because of IP conflicts. For precompetitive IP, the SRC consortium model (with a perpetual nonexclusive royalty-free license and university ownership of the IP) may offer some guidelines for best practices.[18]

[18] For more information, see N. Logar, L.D. Anadon, and V. Narayanamurti, "The Semiconductor Research Corporation as a Model for Cooperative Private (and Public) Partnerships," Kennedy School of Government, Harvard University. Private communication, submitted for publication to Research Policy.

There is evidence that that model has been used extensively and successfully by SRC. However, if the technology is at the competitive stage, a company typically pays the university to do the work and the company owns the IP or an exclusive license. Another template version should address national-laboratory user facilities, and a draft CRADA template should be used as appropriate. Newer user facilities, such as the NIST NanoFab and DOE nanotechnology centers with a high ratio of external to internal users, may yield important insights into how to make the template user-friendly while meeting laboratory needs.

DOE Innovation Hub Model

Since 2010, DOE has established five energy innovation hubs. Each hub brings leading scientists from DOE national laboratories, universities, and companies together to collaborate on specific critical energy challenges. Through a competitive process, proposals are solicited and evaluated for hubs; the funding for each hub is about $125 million over 5 years. The Manhattan Project and AT&T Bell Labs are the two models on which the DOE energy innovation hubs are based, specifically to "develop innovation through a unique approach, where scientists and engineers from many disciplines work together to overcome the scientific barriers of development. In this environment, they can accomplish greater feats more quickly than they would separately."[19]

The hubs differ from the Fraunhofer institutes in having their total funding competitively awarded by the federal government over a medium term rather than supported mostly by a succession of overlapping contracts on a single theme. It remains to be seen whether the energy hub model, like the Fraunhofer and SRC models, will provide successful pathways to commercialization. Box 6.1 briefly describes the energy-efficient buildings hub.

Fraunhofer-Gesellschaft Model

The Fraunhofer-Gesellschaft[20] was founded in 1949 and constitutes a German public-private partnership that develops technologic innovations and novel systems solutions that reinforce the competitive strength of the German and European economy. The business model is as follows: "The Fraunhofer-Gesellschaft's research work is oriented toward concrete applications and results. Pure basic research, as practiced at universities, is funded to almost 100 percent by public grants. Indus-

[19] U.S. Department of Energy, "Energy Efficient Buildings Hub," August 1, 2010, available at http://energy.gov/articles/energy-efficient-buildings-hub, accessed December 19, 2012.

[20] More information about the Fraunhofer-Gesellschaft business model is available at http://www.fraunhofer.de/en/about-fraunhofer/business-model.html, accessed November 15, 2012.

BOX 6.1
The Energy-Efficient Buildings Hub

The energy-efficient buildings hub consists of performers from research universities, DOE laboratories, industrial firms, economic development agencies, and community and technical colleges funded by DOE, the Economic Development Administration, NIST, the Small Business Administration, and the Commonwealth of Pennsylvania. The hub is focused on performing research needed to integrate disparate technologies in a building to optimize energy performance; researching and developing the technologies, models, and analytic tools needed to do this better (where technical solutions are not available or are not optimized); demonstrating the results in buildings, measuring results, and cycling back to continue to optimize the whole building approach; and scaling solutions that involve cost considerations, job training, marketing, policies, and so on. The hub's efforts span technology readiness levels from discovery through applied research to demonstration.

trial R&D, up to prototype level, is largely financed by private enterprise. The Fraunhofer-Gesellschaft receives funding both from the public sector (approximately 30 percent) and through contract research earnings (roughly 70 percent)."[21] The total annual research budget is about 1.65 billion Euros, and about 18,000 people are directly employed in the R&D efforts. The 60 Fraunhofer institutes perform both contract research up to commercialization and application-focused basic research. As part of its operation, the Fraunhofer-Gesellschaft encourages the formation of start-up companies as offshoots of the institutes and supports cooperative ventures between spin-off companies and Fraunhofer institutes by a variety of means. In addition to the Fraunhofer institutes in Germany, the Fraunhofer-Gesellschaft has established seven Fraunhofer centers in the United States ("Fraunhofer U.S.") to partner with the German institutes in moving innovative concepts to commercialization.

The Fraunhofer model is distinguished primarily by having a substantial portion of its budget from public funds despite its being focused almost entirely on promoting the economy through direct involvement and even creation of companies. This model has been consistently supported since 1973. It appears to have been an inspiration for the U.S. National Network for Manufacturing Innovation. It is not an NNI signature initiative but will probably have centers devoted to nanomanufacturing. NIST has established a website (manufacturing.gov) for it.

[21] Fraunhofer-Gesellschaft, "Fraunhofer Business Model," available at http://www.fraunhofer.de/en/about-fraunhofer/business-model.html, accessed December 18, 2012.

CONCLUDING OBSERVATIONS

Each of the above models, as well as the current infrastructure of user facilities, networks, centers, etc., requires mechanisms by which IP rights are managed and made available in support of technology transfer. Universities and government user facilities have a wide range of IP policies, some of which are user-friendly and some of which pose difficulties, especially for businesses. Bayh-Dole and Stephenson-Wydler requirements are interpreted differently, and in addition, complications can occur at the state level and when contractors manage government-owned laboratories.

The committee urges that templates for CRADAs and other cooperative mechanisms be developed that are practical and equitable so that NNI projects are not "orphaned" due to IP conflicts. For precompetitive IP, the SRC consortium model (perpetual nonexclusive royalty-free license—university owns the IP) may offer some guidelines for best practices.[22] There is evidence that this model has been used extensively and successfully by SRC.

If a technology is at the competitive stage, a company normally pays a university to do the work and the company owns the IP or an exclusive license. Another template should address national laboratory user facilities, and a draft CRADA template should be used as appropriate. Newer user facilities, such as the NIST NanoFab and DOE Nanoscale Science Research Centers, which have a high ratio of external to internal users, may have useful insights on how to make the template user friendly yet meet laboratory needs.

> **Recommendation (6-4):** Each NNI agency should identify best practices in intellectual property management and transfer those practices that were developed by it or by other institutions and then share among all agencies the recommended templates and guidelines for such best practices.

[22] For more information, see N. Logar, L.D. Anadon, and V. Narayanamurti, "The Semiconductor Research Corporation as a Model for Cooperative Private (and Public) Partnerships," Kennedy School of Government, Harvard University. Private communication, submitted for publication to Research Policy.

7

Overarching and Crosscutting Themes and Priorities

This report is the most recent triennial review by the National Research Council of the National Nanotechnology Initiative (NNI) as called for by the 21st Century Nanotechnology Research and Development Act of 2003. The overall objective of this review is to make recommendations to the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee and the National Nanotechnology Coordination Office (NNCO) that will improve the value of the NNI's strategy and portfolio for basic research, applied research, and the development of applications to provide economic, societal, and national security benefits to the United States.

The NNI has a vision of the future in which nanoscience and nanotechnology enable economic and societal benefits.[1] That vision and the current set of NNI goals are broad and encompass a host of activities and outcomes that support the nanotechnology "ecosystem" in the United States. In addition to NNI-related funded research and infrastructure, nonfederal activities are under way; for example, companies are investing in research and development, state and regional agencies are providing support, and standards bodies are developing new standards. Unlike such a program as the Human Genome Project, the NNI is not designed to accomplish a single clear goal. Moreover, the participating agencies allocate resources in accordance with their missions, not in a centralized or top-down manner. As a result, management of the NNI as a whole by the NSET Subcommittee of the National Science and Technology Council's Committee on Technology and

[1] National Nanotechnology Initiative, "NNI Vision Goals and Objectives," available at http://www.nano.gov/ about-nni/what/vision-goals, accessed December 17, 2012.

the NNCO has been limited primarily to coordination and information-sharing. Although that approach has led to a system that creates knowledge and educates future scientists and engineers, the request for the present report is a recognition that the NSET Subcommittee and the NNCO want to explore specific pathways to increase the value of the NNI to the nation and expedite progress toward economic and societal goals.

In assessing the three parts of the task statement—technology transfer and commercialization, metrics of progress toward goals, and overall management and coordination—the committee identified five crosscutting concepts that informed the recommendations offered in the chapters of this report and that can serve as approaches to enhancing the NNI.

First, it is essential to identify and support the members of the NNI nanotechnology community. Many researchers do not know that their projects are counted as part of the NNI. Program managers do not necessarily know what other agencies are funding. Businesses cannot readily find researchers who are working in fields of interest. To address those disconnects, the committee recommends that the NSET Subcommittee develop a public, up-to-date, searchable database of projects included in the NNI portfolio and make it available on the NNI website. The project database would include information on each activity, including project title; names of principal investigators, researchers, and students supported; funding agency and amount; affiliation with signature initiatives; and other information needed to identify research activities uniquely. Researchers funded under the NNI need to be informed that they are part of the community and also need information on the resources and programs available, such as notification of selection for funding. The NNI signature initiatives could benefit from identifying those involved and therefore responsible for meeting the cross-agency signature initiative goals. With respect to technology transfer and commercialization, the NNI should support events that bring together those making discoveries and those who have an interest in developing and commercializing the discoveries.

Second, strengthening NNI planning, management, and coordination can be enabled by developing and implementing interagency plans for focused areas—the signature initiatives and the working groups. Effective plans include goals, desired outcomes (from short term to long term), and models and actions that link investment, outputs, and short-term outcomes to ultimate long-term outcomes. The plans must also identify agency roles and responsibilities, milestones and metrics, and reasonable time frames. The NNI agencies have already identified signature initiatives as "ripe for expedited advancement" through such coordination, planning, and management. The working groups are similarly focused and could increase their effectiveness for the NNI community substantially through greater planning. The plans—and progress reports—would naturally be included in the NNI supplement to the President's annual budget.

Third, the NNI website (www.nano.gov) needs to serve the various stakeholder groups—including researchers, small and large businesses, educators and students, and the mass media—better. The website is a repository of NNI reports and links to many agency resources. It also provides good introductory information about nanotechnology. However, it can be expanded and improved to be more service-oriented. For example, it can be a portal to NNI user facilities with a searchable database on publicly available facilities, capabilities, and equipment in the agencies; it can also provide clear guidance on technology transfer and commercialization, including worker safety and regulatory issues.

Fourth, the NSET Subcommittee, NNI agencies, and the NNCO need to take advantage of advances in technology and methods for data collection and social-network analysis to develop and test specific metrics for assessing progress toward NNI goals and informing program management. Many of the metrics recommended in this report are based on data that are publicly available or may already be collected by the agencies. For example, starting with the information contained in the recommended searchable database of NNI projects, publications, patents, citations, students trained, and other information on NNI outputs can be collected and linked from other publicly available databases. The committee emphasizes the need for review, with domain experts, of those and other suggested metrics and the proposed models linking the metrics to desired NNI outcomes for collection and analysis of the data collected over at least 3 years to assess whether the metrics both reflect progress toward the desired outcomes and inform NNI management decisions in a cost-effective manner.

Fifth, the NNI would benefit from identifying, sharing, and implementing best practices, such as those described in this report, especially related to technology transfer and commercialization. The diversity of processes and agreements used by agencies, federal laboratories, and universities—and in some cases lack of flexibility—can be a barrier to transitioning research results to practical and commercial use, particularly by small companies and start-ups. In addition to more conventional pathways for transitioning research from universities and government laboratories to businesses, such as sponsored research and licensing, the NNI agencies could work together to partner with industry consortia to identify and address long-term research needs of sectors that have potential for high economic impact.

The NSET Subcommittee, the NNI agencies, and the NNCO are to be commended for their work and progress in coordinating such a diverse multiagency program. The NNI has been a leader among interagency initiatives in many ways. Now it has an opportunity to be more effective and as a result more valuable to the nanotechnology community and the nation. The committee believes that the recommendations in this report will help the NNI to fulfill its goals and facilitate progress toward its vision.

Appendixes

A

Statement of Task

The NRC 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) 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.

1. Examine the role of the NNI in maximizing opportunities to transfer selected technologies to the private sector, provide an assessment of how well the NNI is carrying out this role, and suggest new mechanisms to foster transfer of technologies and improvements to NNI operations in this area where warranted;
2. Assess the suitability of current procedures and criteria for determining progress towards NNI goals, suggest definitions of success and associated metrics, and provide advice on those organizations (government or non-government) that could perform evaluations of progress;

3. Review NNI's management and coordination of nanotechnology research across both civilian and military federal agencies.

In addition to the proposed statement of task, the National Academies' National Materials and Manufacturing Board will support this work through strategic planning and program initiation activities that will include a board meeting, developing the proposed program of work for the committee, identifying nominees for consideration for committee membership, monitoring the progress in the study, and developing ideas for the report's dissemination and follow up activities.

B

Acronyms and Abbreviations

AAAS	American Association for the Advancement of Science
AMTech	Advanced Manufacturing Technology Consortium program
ANC	Alliance for Nanotechnology in Cancer
ANSI	American National Standards Institute
API	application programming interface
ARPA-E	Advanced Research Projects Agency-Energy
ASTM	American Society for Testing and Materials
ATE	Advanced Technological Education
CMOS	complementary metal oxide semiconductor
CoT	Committee on Technology
CPSC	Consumer Product Safety Commission
CRADA	cooperative research and development agreement
CSSI	Center for Strategic Scientific Initiatives
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DNI	Director of National Intelligence
DOD	Department of Defense
DOE	Department of Energy
DOEd	Department of Education
DOI	Department of the Interior

DOJ	Department of Justice
DOS	Department of State
EHS	environmental, health, and safety
ELSI	ethical, legal, and social issues
EPA	Environmental Protection Agency
FCRP	Focus Center Research Program
FDA	Food and Drug Administration
FI	flagship initiative
FY	fiscal year
GAO	Government Accountability Office
GIN	Global Issues in Nanotechnology
HR	human resources
IC	integrated circuit, intelligence community
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	intellectual property
ISO	International Organization for Standardization
IT	information technology
ITRS	International Technology Roadmap for Semiconductors
MGI	Materials Genome Initiative
NACK	Nanotechnology Applications and Career Knowledge
NAMII	National Additive Manufacturing Innovation Institute
NASA	National Aeronautics and Space Administration
NCI	National Cancer Institute
NCL	Nanotechnology Characterization Laboratory
NCN	Network for Computational Nanotechnology
NEHI	New England Healthcare Institute
NIC	Nanotechnology in Cancer
NIH	National Institutes of Health
NILI	Nanotechnology, Industry Liaison, and Innovation
NIOSH	National Institute for Occupational Safety and Health
NISE	Nanoscale Informal Science Education Network
NIST	National Institute of Standards and Technology

NKI	Nanotechnology Knowledge Infrastructure
NMMB	National Materials and Manufacturing Board
NNAP	National Nanotechnology Advisory Panel
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NNIN	National Nanotechnology Infrastructure Network
NPEC	Nanotechnology Public Engagement and Communications
NRC	National Research Council
NRI	Nanoelectronics Research Initiative
NSET	Nanoscale Science, Engineering, and Technology (subcommittee)
NSF	National Science Foundation
NSTC	National Science and Technology Council
NYSERDA	New York State Energy Research and Development Agency
OECD	Organisation for Economic Co-operation and Development
OMB	Office of Management and Budget
ORCID	Open Researcher and Community ID
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy
PCA	program component area
PCAST	President's Council of Advisors on Science and Technology
PI	principal investigator
RFP	request for proposal
SBIR	Small Business Innovation Research
SEMATECH	not-for-profit consortium (from Semiconductor Manufacturing Technology)
SIA	Semiconductor Industry Association
SPIE	An optics society
SRC	Semiconductor Research Corporation
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer
SUNY	State University of New York
TC	technical committee
USDA	U.S. Department of Agriculture
USPTO	U.S. Patent and Trademark Office

VCAT	Visitor Committee on Advanced Technology
WTEC	World Technology Evaluation Center

C

Specific Examples of NNI Stakeholders

The breadth of NNI stakeholders can be seen from the participants in the Strategic Planning Stakeholder Workshop held July 13-14, 2010. The goal of the NNI-sponsored workshop was "to obtain input from stakeholders, both those new to nanoscale science, engineering, and technology and those already familiar with these fields and with the NNI. . . ." The diversity of the workshop participants (Table C.1) is indicative of the many actors involved in translating research to technology development and commercial applications and in creating a highly capable workforce, as well as the impact of scientific research on U.S. society at large.

TABLE C.1 NNI Stakeholders

NNI Stakeholder	Organization
Federal departments, agencies, laboratories, and offices	Departments of Agriculture, Commerce, Defense, Education, Energy, Health and Human Services, and Labor; Consumer Product Safety Commission, FDA, EPA, OSHA, NIOSH, NIST, National Institutes of Health (NHGRI, NIEHS, NIMH, MIEHA, NCMRR), Defense Threat Reduction Agency, National Science Foundation, U.S. Forest Service, National Reconnaissance Office, International Trade Administration/Commerce, Office of Nuclear Regulatory Research/Nuclear Regulatory Commission, Federal laboratories and centers (Oak Ridge National Laboratory, Navy and Marine Corps Public Health Center, Sandia National Laboratories, Army Research Laboratory, NASA Glenn Research Center, USACE Engineer Research and Development Center, Nanotechnology Characterization Laboratory (NIH/FDA/NIST), FDA Center for Devices and Radiological Health, Idaho National Laboratory), National Academy of Sciences, OSTP, NNCO
Congress	Representative Daniel Lipinski, Offices of Representative Lipinski, Senator Mark Pryor
Nonprofits	CNA
Labor	AFL-CIO
Policy centers	Center for Policy on Emerging Technologies, Woodrow Wilson International Center for Scholars, Children's Environmental Health Network, International Federal Technology Watch, Science and Technology Policy Institute, Institute for Advanced Sciences Convergence, Intellegere Foundation
Universities	Johns Hopkins Applied Physics Laboratory; University of California, Berkeley; Purdue University; Norwich University Applied Research Institute; Oklahoma State University; University of Virginia; University of Northeastern; University of Rochester; Pennsylvania State University; Arizona State University; Rice University; Harvard University; University of Southern California; California Institute of Technology
Research foundations	International Life Sciences Institute, Norwich Park Research Institutes (U.K.)
Nano institutes, networking and trade associations	Network for Computation Nanotechnology, NanoBusiness Alliance, NanoScience Exchange, Rushford Institute for Nanotechnology, Nano-Link Regional Center, Oklahoma Nanotechnology Initiative, NanoStar Institute, PA Bio Nano Systems, LLC
Traditional trade associations	American Chemistry Council, Association of Science-Technology Centers, AAAS, Council for Chemistry Research, American National Standards Institute, American Forest and Paper Association, Nano Association of Natural Resources and Energy Security, Council for Chemical Research
News organization	Inside Washington Publishers
Commercial	Pixelligent Technologies, Lockheed Martin, Evonik Degussa Corp., NanoTox, Applied Nanostructured Solutions, Luna Innovations Inc., Rushford NanoElectroChemistry Co., Eikos, Inc., Zyvex, Intel, System Planning Corp., General Dynamics AIST, Science Applications International Corporation, Notable Solutions, Inc., PSI, Inc., Semiconductor Research Corporation

TABLE C.1 Continued

NNI Stakeholder	Organization
Technology assessments	World Technology Evaluation Center, International Center for Technology Assessment
Law firms	Arnold & Porter, K&L Gates
Other	Federal Technology Watch

NOTE: This list of workshop participants shows the breadth of NNI stakeholders and not the total number of stakeholders. The workshop listed only the stakeholders attending in person an event that ran at full capacity. Those not able to attend in person, and therefore not on the list, could also access the event via a webcast, and stakeholder input could be provided in writing. For additional information, see National Nanotechnology Initiative, available at http://www.nano.gov/node/256, accessed January 9, 2013.

SOURCE: Information from the final report of the Strategic Planning Stakeholder Workshop, July 13-14, 2010.

D

Committee Biographies

CAROL A. HANDWERKER (*Co-chair*) is the Reinhardt Schuhmann, Jr., Professor of Materials Engineering at Purdue University, having joined Purdue in August 2005 after serving for 9 years as chief of the NIST Metallurgy Division. Handwerker's research is focused on the thermodynamics and kinetics of interface processes, with applications to microelectronics, nanoelectronics, and printed electronics. She received a B.A. in art history from Wellesley College and an S.B. in materials science and engineering, an S.M. in ceramics, and an Sc.D. degree in ceramics from MIT. Following a year's postdoctoral research at MIT on electronic packaging, she joined the NBS in 1984 as an NRC-NBS postdoctoral research associate, working on the relationship between stress and diffusion in solids and on composition effects on sintering and grain growth. She became a permanent staff member at NBS in 1986, group leader of the Materials Structure and Characterization Group in 1994, and division chief of the Metallurgy Division in March 1996. She is a fellow of ASM International and of the American Ceramic Society (ACS) and is past chair of the American Ceramic Society's Basic Science Division. She serves on the Technical Advisory Committee and the Environmental Leadership Steering Committee for iNEM and has served on numerous other boards, including the Board of Trustees of the Gordon Research Conferences, the advisory committees of Carnegie Mellon University's Mesoscale Interface Mapping Project and of MIT's Department of Materials Science and Engineering, and the editorial board for the *Annual Reviews of Materials Research*. She has written more than 100 scientific publications. Her expertise includes materials science and engineering and research management.

MICHAEL N. HELMUS (*Co-chair*) is a consultant who specializes in medical devices, drug delivery, nanotechnology, and tissue engineering. Helmus has more than 28 years' experience managing the R&D and business development of medical and controlled drug delivery devices. He focuses on developing commercialization strategies of potentially disruptive technology as well as managing intellectual property development (36 issued U.S. patents) and supporting patent litigation. Many of his patents are focused on utilizing nanotechnology to improve the functionality of medical devices. He supports testing and regulatory submissions and performs due diligence evaluations of medical devices, biomedical materials (synthetic and biologic), biodegradable compositions, controlled drug delivery, nanotechnology, medical technology, and tissue engineering. Helmus is an expert in biomaterials, biocompatibility, and biomaterial databases (committee chair, ASM International, Materials for Medical Devices Database). His medical device experience includes drug eluting stents and coatings, large- and small-diameter vascular grafts, mechanical and biologic heart valves, central venous catheters, wound dressings, sealants such as fibrin sealant, and percutaneous connectors. He has presented and written on commercializing nanotechnology. He has a Ph.D. and an M.S. in biomedical engineering from Case Western Reserve University and was a Timken Honors Fellow, and he has a B.S. in metallurgy and materials science from Lehigh University with highest honors, Departmental Honors Phi Beta Kappa, and Tau Beta Pi. His professional activities include adjunct associate professor, Department of Biomedical Engineering, Worcester Polytechnic Institute; fellow of the American Institute of Medical and Biological Engineering; and member of the Science Advisory Board, University of Massachusetts, Boston. His expertise includes research management; technology development; technology insertion; manufacturing processes and management.

ROBERT R. DOERING is a senior fellow and research manager at Texas Instruments (TI). He is also a member of TI's Technical Advisory Board, Kilby Labs Review Board, External Development and Manufacturing Leadership Team, and Executive University Research Steering Team. His previous positions at TI include manager of CMOS and DRAM process development, director of the Microelectronics Manufacturing Science and Technology (MMST) Program, director of Scaled-Technology Integration, manager of Future-Factory Strategy, and manager of Technology Strategy. He received a B.S. degree in physics from the Massachusetts Institute of Technology in 1968 and a Ph.D. in physics from Michigan State University in 1974. He joined TI in 1980, after several years on the faculty of the Physics Department at the University of Virginia. His physics research was on nuclear reactions and was highlighted by the discovery of the Giant Spin-Isospin Resonance in heavy nuclei in 1973 and by pioneering experiments in medium-energy heavy-ion reactions in the late 1970s. His early work at Texas Instruments was on SRAM, DRAM, and NMOS/CMOS device physics and process-flow design. Management responsibilities during his first 10 years at TI included overall CMOS and DRAM device/process technology development as well as advanced lithography R&D. The teams that he led developed the first process flows integrating silicide-clad, lightly doped-drain, shallow-trench-isolated, CMOS transistors, which were forerunners of all modern submicron CMOS devices. Non-planar (doped-face trench) DRAM bit cells were also developed under his leadership. Doering is an IEEE Fellow and chair of the Semiconductor Manufacturing Technical Committee of the IEEE Electron Devices Society. He is also a fellow of the American Physical Society (APS) and chair of the Corporate Associates Advisory Committee of the American Institute of Physics. In addition, he is chair of the Governing Council of the Nanoelectronics Research Initiative (NRI) consortium. Doering was a member of the Semiconductor Industry Association (SIA) committee that founded the International Technology Roadmap for Semiconductors (ITRS) and is one of the two U.S. representatives to the International Roadmap Committee, which currently governs the ITRS. He also served on the SIA committees that founded the Focus Center Research Program (FCRP) and NRI consortia of the Semiconductor Research Corporation (SRC) as well as on the APS committee that founded the Forum on Industrial and Applied Physics (FIAP). He is a former member of the SRC Board of Directors, and, overall, has served on 88 industry/university/government boards, advisory committees, and study groups. He has also authored and/or presented 232 publications and invited papers and talks and has 20 U.S. patents.

LEE FLEMING is the faculty director of the Fung Institute for Engineering Leadership in the College of Engineering at the University of California, Berkeley. He designs and teaches engineering leadership courses and advises multidisciplinary engineering commercialization projects for masters' and professional students. Fleming earned his B.S. in electrical engineering from the University of California, Davis. He then spent 7 years at Hewlett Packard Company in research, design, manufacturing, and application engineering. He has published in Hewlett Packard's technical literature and holds two patents in the area of custom integrated circuit testing. During his time at Hewlett Packard, Fleming earned an M.S. in engineering management from Stanford University in the Honors Cooperative Program. He received his Ph.D. in organizational behavior in the Department of Industrial Engineering at Stanford. He also completed an M.S. in statistics during his doctoral years. Fleming's research investigates how managers can increase their organization's chances of inventing a breakthrough through types of collaboration, the integration of scientific and empirical search strategies, and the recombination of diverse technologies. Fleming's research has appeared in *Management Science*, *Administrative Science Quarterly*, *Research Policy*, *Organization Science*, *Industrial and Corporate Change*, *Strategic Management Journal*, and the *Harvard Business Review*, *California Management Review*, and *Sloan Management Review* practitioner journals. His awards include the best student paper in the Academy of Management technology division, the Richard R. Nelson Prize of 2005 (with Olav Sorenson), the 2007 Accenture Award for the best paper in *California Management Review* (with Matt Marx), and the 2011 Strategic Management Society Conference Best Paper Award (with Ken Younge and Tony Tong). He won the 2009 Apgar Award at the Harvard Business School for innovation in teaching (with Joe Lassiter and Forest Reinhardt). He is the department editor for the Entrepreneurship and Innovation section of *Management Science.* Fleming is currently on leave from his position as the Albert J. Weatherhead III Professor of Business Administration at Harvard University. He joined the Harvard Business School faculty in 1998. He designed and teaches the course "Inventing Breakthroughs and Commercializing Science," which integrates business, science, engineering, and medical students from across the university in multidisciplinary science commercialization projects. He has also taught technology and operations management, managing innovation and product development, building green businesses, executive education courses in innovation and product development and intellectual property, doctoral courses and seminars, research methods and innovation, and a university seminar in applied statistical methods.

PAUL A. FLEURY (NAE, NAS) is the Frederick William Beinecke Professor of Engineering and Applied Physics and a professor of physics at Yale University. He is the founding director of the Yale Institute for Nanoscience and Quantum Engineering. He served as dean of engineering at Yale from 2000 until January 2008. Prior to joining Yale, Fleury was dean of the School of Engineering at the University of New Mexico from January 1996 following 30 years at AT&T Bell Laboratories. At Bell Laboratories he was director of three different research divisions covering physics, materials, and materials processing research between 1979 and 1996. During 1992 and 1993 he was vice president for research and exploratory technology at Sandia National Laboratories, where he was responsible for research in physical sciences, high-performance computing, engineering sciences, pulsed power, microelectronics, photonics, materials and process engineering, and computer networking. Fleury is the author of more than 130 scientific publications on nonlinear optics, spectroscopy and phase transformations in condensed matter systems and he has co-edited three books. He is a fellow of the American Physical Society and the American Association for the Advancement of Science; a member of the National Academy of Engineering and the National Academy of Sciences; and a fellow of the American Academy of Arts and Sciences. He received the 1985 Michelson-Morley Award and the 1992 Frank Isakson Prize of the American Physical Society for his research on optical phenomena and phase transitions in condensed matter systems. He has been a member of numerous National Research Council study panels, including that of the 2007 National Nanotechnology Initiative review (National Research Council, *A Matter of Size: Triennial Review of the National Nanotechnology Initiative*, The National Academies Press, Washington, D.C., 2006). He has served on the Secretary of Energy's Laboratory Operations Board and the University of California President's Council on the National Laboratories. He has also served on review committees for Brookhaven, Lawrence Berkeley, Sandia, and Los Alamos National Laboratories. He is currently active on Sandia and LANL committees in addition to his service on the Visiting Committee for Advanced Technology for the National Institute of Standards and Technology, and the Board on Physics and Astronomy of the National Research Council. He received his B.S. and M.S. in 1960 and 1962 from John Carroll University and his doctorate from the Massachusetts Institute of Technology in 1965, all in physics.

LIESL FOLKS has a Ph.D. in physics from the University of Western Australia, and an MBA from Cornell University. She first moved to the United States to join IBM Almaden Research Center in 1997 and later transitioned to Hitachi Global Storage Technologies through a corporate acquisition that was finalized in 2004. Her field of expertise is magnetism and magnetic materials, and her significant technical contributions are in the fields of nanostructured permanent magnetic materials, bit patterned recording media, magnetic force microscopy, spin transfer torque device physics, and semiconductor-based nonmagnetic field sensors. Currently she manages the advanced media technologies development program within Hitachi Global Storage Technologies. She is also president-elect of the IEEE Magnetics Society, and she maintains active collaborative links with academics in relevant fields.

ROBERT HULL is the Henry Burlage Professor and head of the Materials Science and Engineering Department at Rensselaer Polytechnic Institute, which he joined in January 2008. He received a Ph.D. in materials science from Oxford University in 1983. He then spent 10 years at AT&T Laboratories in the Physics Research Division. He next joined the faculty of the Materials Science and Engineering Department at the University of Virginia, where he was the Charles Henderson Professor of Engineering, director of the National Science Foundation Center on Nanoscopic Materials Design, and director of the university's Institute for Nanoscale and Quantum Engineering, Science, and Technology (NanoQuest). His recent research focuses on the development of new techniques for nanoscale assembly, fabrication, and characterization using focused ion and electron beams, with a particular emphasis on epitaxial semiconductor structures and applications to nanoelectronics. He has published well over 250 journal and conference papers, edited several books and proceedings in the fields of semiconductor materials and devices, given about 100 keynote and invited talks at national and international conferences, and presented more than 100 additional seminars at universities and government and industrial laboratories. He is a member of multiple editorial and advisory boards, a fellow of the American Physical Society and of the Materials Research Society, and a member of the European Academy of Sciences, and he has served as president of the Materials Research Society. He has served on multiple national committees, including serving as the chair of a committee of visitors for the Division of Materials Science at NSF.

JACQUELINE A. ISAACS is a professor in the Department of Mechanical and Industrial Engineering at Northeastern University and an associate director of the NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN)—a collaborative partnership among Northeastern University, the University of Massachusetts Lowell, and the University of New Hampshire. She leads the Responsible Manufacturing Research Thrust for the CHN. Isaacs is responsible for her own research on assessing economic and environmental trade-offs in nanomanufacturing, as well as oversight of a team of faculty in political science, philosophy, and worker safety. The goal of this research is to concurrently assess the regulatory, economic, environmental, and ethical issues facing the development of nanomanufacturing processes. Isaacs' research group works on life-cycle assessment of various processes under development and assesses alternatives to uncover more environmentally benign processes or products. Her 1998 NSF Career Award was one of the first that focused on environmentally benign manufacturing. Isaacs also guides research on development and assessment of educational computer games. She received a B.S. from Carnegie Mellon University and S.M and Sc.D. degrees in materials science and engineering from the Massachusetts Institute of Technology. She has been recognized by Northeastern University, receiving the President's Aspiration Award in 2005 and a University-wide Excellence in Teaching Award in 2000. Her expertise includes nanotechnology, materials science and engineering, manufacturing processes, and management.

DONALD H. LEVY, the Albert A. Michelson Distinguished Service Professor in Chemistry, is the University of Chicago's vice president for research and for national laboratories; CEO of UChicago Argonne, LLC; vice-chairman of the Board of Governors for Argonne; and a member of the Board of Directors for Fermilab. Named to the university position in 2007, Levy has oversight responsibilities for the management contracts for both Argonne National Laboratory and Fermi National Accelerator Laboratory, the Office of Technology and Intellectual Policy, the Office of University Research Administration, University-Argonne Research Centers, and all issues related to human subjects research. The annual research budget of the university is more than $400 million. The combined annual research budget for Argonne and Fermilab is $900 million. In addition to his responsibilities for research across the university and Argonne campuses, Levy chairs the Science Policy Council, a collaboration with Argonne, Northwestern University, and the University of Illinois, established in 2005 to enhance Argonne's scientific capabilities, to strengthen the state's technological base and workforce preparation, and to improve Illinois' ability to compete for federal research funding. Levy joined the University of Chicago faculty in 1967. He is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences, the American Physical Society, and the American Association for the Advancement of Science. He is a former chairman of the Chemistry Department, and he played an important leadership role in planning the new Gordon Center for Integrative Science. A physical chemist, Levy was a leader in developing and using supersonic jet cooling to study the structure of molecules. Levy was editor of the *Journal of Chemical Physics* from 1998 to 2008. His awards include the E. Bright Wilson Award in Spectroscopy and the Ellis Lippincott Award from the Optical Society of America.

CELIA MERZBACHER is the vice president for Innovative Partnerships at the Semiconductor Research Corporation (SRC). She is primarily responsible for developing novel partnerships with stakeholders in government and the private sector in support of SRC's research and education goals. Prior to joining SRC, 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, 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, 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. 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. She received her B.S. in geology from Brown University and M.S. and Ph.D. degrees in geochemistry and mineralogy from Pennsylvania State University. Her expertise includes nanotechnology, research management, and technology transfer/commercialization.

OMKARAM (OM) NALAMASU is the chief technology officer (CTO) for Applied Materials, Inc. In this role, he reports to chairman and CEO Mike Splinter and provides critical technological insight to maintain Applied's technology leadership in the industries it serves. Nalamasu leads the company's R&D and innovation strategies, funding of global academia and consortia, and venture capital investments into start-ups, as well as value-added strategic partnerships with academia, research institutes, customers, supply chain partners, and government funding agencies. He previously was vice president of research and a NYSTAR (New York State Foundation for Science, Technology and Innovation) distinguished professor of materials science and engineering at Rensselaer Polytechnic Institute (RPI). At RPI, he conceived and founded the Center for Computational Nanotechnology Innovations (CCNI), a $100 million program that created the world's fastest university-based computing center at RPI in partnership with the state of New York and IBM. He was also the founding director of the $20 million Center for Future Energy Systems that was created to help meet 25 percent of New York state's energy needs from renewable sources by the year 2012. Prior to joining RPI in 2002, Nalamasu was the CTO of the New Jersey Nanotechnology Consortium, the nation's first public/private nonprofit enterprise to foster precompetitive nanotechnology research with Bell Labs, New Jersey, and other academic and industrial partners. From 1986 to 2002, he held key R&D leadership positions at AT&T Bell Laboratories, Bell Laboratories/Lucent Technologies, and Agere Systems. Nalamasu is a recognized expert in materials science and technology with more than 180 publications, review articles, book chapters, and two books to his credit, and he has approximately 50 issued or filed patents. He has won several national and international awards, including the 2004 ACS Roy W. Tess Award, the 2000 ACS Team Innovation Award, the 1998 Japan Photopolymer Science and Technology Award, two R&D 100 Awards, and the 1997 Bell Labs President's Gold Medal. Nalamasu is a member of the Board of Directors of Semiconductor Research Corporation, the San Jose Tech Museum, and Plextronics, and he has served on the National Research Council's Panel on Materials Science and Engineering, as well as several technical advisory boards and university advisory committees. He received his Ph.D. from the University of British Columbia, Vancouver, Canada.

WOLFGANG POROD is the Frank M. Freimann Professor of Electrical Engineering at the University of Notre Dame. He received his Diploma (M.S.) and Ph.D. degrees from the University of Graz, Austria, in 1979 and 1981, respectively. After appointments as a postdoctoral fellow at Colorado State University and as a senior research analyst at Arizona State University, he joined the University of Notre Dame in 1986. He is the recipient of the Electrical Engineering Department's 2000 Joel and Ruth Spira Award for Excellence in Teaching and the College of Engineering 2005 Kaneb Teaching Award. He now also serves as the director of Notre Dame's Center for Nano Science and Technology. His research interests are in the area of nanoelectronics, with an emphasis on new circuit concepts for novel devices. He is the co-inventor of the Quantum-Dot Cellular Automata (QCA) concept, which is a new way of representing information by electronic charge configurations at the molecular level. In recent years, he has demonstrated nanomagnetic implementations of the original QCA concept, which now is known as Nanomagnet Logic (NML). NML is one of the emerging device technologies pursued by the Nanoelectronics Research Initiative sponsored by the Semiconductor Research Corporation. He has authored some 300 publications and presentations. He is a fellow of the IEEE and has served as the vice president for publications on the IEEE Nanotechnology Council and as an associate editor for the IEEE *Transactions on Nanotechnology*. He has been active in organizing special sessions and tutorials and as a speaker in IEEE distinguished lecturer programs. In 2009, he was awarded a Hans Fischer Senior Fellowship with the Institute for Advanced Study at the Technical University of Munich, which is sponsored by the German Excellence Initiative. In Germany, he participated in the study "Nanoelectronics as a Future Key Technology for Information and Communication Technologies in Germany," organized by the German National Academy of Science and Engineering. His expertise includes nanotechnology, materials science and engineering, and research management.

ALAN RAE is managing member at TPF Enterprises, LLC, a technology commercialization and business development company he founded in 2009, based at the UB Technology Incubator. He has worked in the electronics, ceramics, nanotechnology, and "clean tech" industries for more than 25 years in the United Kingdom and United States, managing global businesses and technology development at a start-up, operating company, and corporate level. Rae is active in electronics industry associations and standards work. He is director of research for iNEMI and is also active with SMTA, IMAPS, IPC, and JISSO. He holds director and vice-president positions with four new companies and consults for two Fortune 100 companies in alternative energy. He is technical editor for *Global Solar Technology*, a leading alternative energy publication; an Entrepreneur in Residence with NYSERDA; and a member of the Directed Assistance Committee for NYSERDA's Directed Energy Program. His expertise includes nanotechnology, research management, technology insertion, manufacturing processes and management, and economics.

ELSA REICHMANIS (NAE) is a professor of chemical and biomolecular engineering at the Georgia Institute of Technology. Prior to joining Georgia Tech, she was director of materials research at Bell Labs, Alcatel-Lucent. She is noted for the discovery, development, and engineering leadership of new families of lithographic materials and processes that enable very-large-scale integration manufacturing. Her research interests include the design and development of polymeric and hybrid organic/inorganic materials for electronic and photonic applications. A particular focus relates to organic/polymer semiconducting materials and processes for plastic electronics and photovoltaics. She is the recipient of several awards, was elected to the National Academy of Engineering in 1995, and has participated in several

National Research Council (NRC) activities. She currently serves as a member of the NSF Math and Physical Sciences Advisory Committee, recently served as co-chair of the NRC Board on Chemical Sciences and Technology, and was a member of the Visiting Committee on Advanced Technology of the National Institute of Standards and Technology (NIST). She is an elected member of the Bureau of the International Union for Pure and Applied Chemistry (IUPAC). She has been active in the American Chemical Society throughout her career, having served as 2003 president of the society. In other technical activities, she served as a member of the Air Force Scientific Advisory Board, and she is an associate editor of the ACS journal *Chemistry of Materials*. Her expertise includes materials science and engineering, technology development, technology insertion, manufacturing processes, and management.

JUDITH STEIN obtained her B.A. in chemistry from Douglass College and a Ph.D. in inorganic chemistry under the mentorship of Prof. John Fackler at Case Western Reserve University. After an IBM-sponsored postdoctoral fellowship with Prof. Earl Muetterties at the University of California, Berkeley, she joined GE in 1982. She has more than 29 years of experience in silicone chemistry materials science, surface science, catalysis, and nanoscience and has contributed to a variety of commercialized GE products, including Silicone II construction sealant, LIM 8040 liquid silicone rubber, and UV 9305 and SL 6000 release coatings. Stein has served as the principal investigator on numerous government contracts, including a DARPA contract in which a team composed of industry, government, and university partners developed foul release coatings technology that was commercialized by Fuji Hunt Smart Surfaces. In 2001, Stein became one of the founding members of the Nanotechnology AT program, in which she benchmarked nanotechnology efforts worldwide. Previous research areas include superhydrophobic coatings, ice-phobic coatings, magnetic cell separations, and contrast agent-mediated therapy. She is currently the associate director of the Energy Frontier Research Center for Electrocatalysis, Transport Phenomena, and Innovative Materials for Energy Storage, and she also serves as the technical regulations and standards advocacy leader at GE Global Research. She served two terms on the Technical Advisory Group to the President's Council of Advisors to Science and Technology. She also serves on the board of the Michigan Nanotechnology Institute for Medicine and Biological Sciences and on the editorial board of *Biofouling*. She co-authored *Research Directions II: Long-Term Research and Development Opportunities in Nanotechnology*, the report of the National Nanotechnology Initiative 2004 Workshop, and *Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function*. Stein has chaired numerous conferences, including the NSF Inorganic Chemistry Workshop, and she has served as vice chair of the Organic Coatings and Films Gordon Research Conference. She has been elected a U.S. nanotechnology expert for the International Organization for Standardization and currently leads the Strategy Task Group for Nanotechnology Terminology and Nomenclature. She has also served as an ad hoc member of the NIH Nanotechnology Study Group. Stein holds 48 U.S. patents, and she received a GE 125 Publications Award in 2007.

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E

Interim Report

This appendix is a reprint of the main text of the National Research Council's *Interim Report for the Triennial Review of the National Nanotechnology Initiative, Phase II* (The National Academies Press, Washington, D.C., 2012) by the Committee on Triennial Review of the National Nanotechnology Initiative: Phase II.

Summary

Nanotechnology has become one of the defining ideas in global research and development (R&D) over the last decade. In 2001, the National Nanotechnology Initiative (NNI) was established as the U.S. government interagency program for coordinating nanotechnology R&D among federal agencies and facilitating communication and collaborative activities in nanoscale science, engineering, and technology throughout the federal government. The NNI defines nanotechnology on its Web site[1] as "science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers."[2] The NNI focuses on four goals aimed at creating "a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society." The 26 federal agencies that participate in the NNI collaborate to (1) advance world-class nanotechnology research and development, (2) foster the transfer of new technologies into products for commercial and public benefit, (3) develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology, and (4) support the responsible development of nanotechnology.

As part of the second triennial review of the NNI, the Committee on Triennial Review of the National Nanotechnology Initiative: Phase II was asked to provide

[1] See http://www.nano.gov/nanotech-101/what/definition. Accessed August 28, 2012.

[2] For another definition of nanotechnology, see, for example, National Research Council, *A Matter of Size: Triennial Review of the National Nanotechnology Initiative,* The National Academies Press, Washington, D.C., 2006.

advice to the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council's Committee on Technology and the National Nanotechnology Coordination Office as follows:

- *Task 1*—Examine the role of the NNI in maximizing opportunities to transfer selected technologies to the private sector, provide an assessment of how well the NNI is carrying out this role, and suggest new mechanisms to foster transfer of technologies and improvements to NNI operations in this area where warranted.
- *Task 2*—Assess the suitability of current procedures and criteria for determining progress toward NNI goals, suggest definitions of success and associated metrics, and provide advice on those organizations (government or non-government) that could perform evaluations of progress.
- *Task 3*—Review NNI's management and coordination of nanotechnology research across both civilian and military federal agencies.

The present interim report offers the committee's initial comments on current procedures and criteria for determining progress toward achievement of NNI goals, the proper role of metrics in assessing the NNI, some characteristics of good metrics, and possible metrics and their links to suggested short-term and long-term NNI goals.

This report reflects the committee's view that measuring something just because it can be measured is not good enough: metrics must be indicators of desired outcomes. There must be a model that accurately relates what is measured to a desired outcome and an equally accurate system to perform the measurement. Having both constitutes a metric. Without both, measurements have little value for program assessment and management.

The committee recognizes the great difficulty in defining robust models and metrics for a field as diffuse as nanotechnology, for agencies as diverse as the 26 NNI participating agencies, and for goals as far-reaching and cross-cutting as the four NNI goals. However, the committee emphasizes that whatever models and metrics are applied must be rigorous and stand up fully to scientific scrutiny. If the data used are inaccurate or if the models linking even accurate data to desired outcomes have not been properly established, evaluation, rational decision-making, and allocation of resources become compromised. In general, computational and data capacities have outrun the accuracy of measurement systems and understanding of the phenomena that relate metrics to desired outcomes. The result may be exciting graphical representations whose meaning remains uncertain. A key part of any solution would be to get scientists in the NNI community to work together to develop models that can be tested to validate current measures. Research on indicators and processes to support metrics would also be highly valuable. In its final report, the committee will provide recommendations based on the concepts presented in this interim document and will address Tasks 1 and 3 in addition to exploring Task 2 more fully.

1

Background

The National Nanotechnology Initiative (NNI), a multiagency, U.S. government research and development (R&D) initiative, was established in fiscal year (FY) 2001 to accelerate R&D in the emerging field of nanotechnology:[3]

> The vision of the NNI is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society. The NNI expedites the discovery, development, and deployment of nanoscale science, engineering, and technology to serve the public good, through a program of coordinated research and development aligned with the missions of the participating agencies.

Starting with eight core agencies in 2001, the NNI now coordinates nanotechnology-related R&D of 26 federal agencies, focusing on four goals (see Box 1.1).

The view of how to achieve the NNI vision has evolved. Starting with the 2004 Strategic Plan, general descriptions of each goal were provided along with selected individual examples. Now the NNI has qualitative, semiquantitative, and quantitative subgoals—as many as five—for each major goal. In addition, the NNI has established five interagency signature initiatives, cross-sector collaborations designed to accelerate innovation in subjects of high national priority through coordination of multiagency resources to meet specific agreed-on scientific and technologic goals; to promote development of joint research solicitations; and to

[3] See National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed April 24, 2012.

BOX 1.1
Goals of the National Nanotechnology Initiative

The National Nanotechnology Initiative focuses on four major goals:

- To advance world-class nanotechnology research and development.
- To foster the transfer of new technologies into products for commercial and public benefit.
- To develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology.
- To support the responsible development of nanotechnology.

engage in sponsorship of a wide variety of interagency meetings, workshops, and forums to support knowledge-sharing.

The federal government has given high priority to the alignment of nanotechnology R&D with the missions of the individual agencies. For most agencies, nanotechnology R&D is not an end in itself but rather, in some cases, an enabling technologic means of accomplishing their missions. Each agency determines its budget for nanotechnology R&D as part of its overall mission R&D priorities in coordination with the Office of Management and Budget, the Office of Science and Technology Policy, and Congress. The NNI is planned and coordinated by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC) Committee on Technology, through which the agency members present their priorities and establish shared goals, strategies, and activities when their agency priorities align. The 2011 NSET Strategic Plan describes the agencies, their missions, how they view the NNI, and how the NNI fits into their missions. Each NNI participating agency is obliged to carry out its mission and achieve its goals while coordinating and collaborating with other agencies in subjects of mutual interest and mission need.[4]

To focus interagency collaboration in strategic fields, the NSET Subcommittee has established four cross-agency working groups: Global Issues in Nanotechnology; Nanotechnology Environmental and Health Implications; Nanomanufacturing, Industry Liaison, and Innovation; and Nanotechnology Public Engagement and Communications. The National Nanotechnology Coordination Office (NNCO) provides technical and administrative support to the NSET Subcommittee, serves as the central point of contact for federal NNI R&D activities, and reaches out to

[4] Department of Defense Director, Defense Research and Engineering, *Defense Nanotechnology Research and Development Program*, December 2009. Available at http://www.nano.gov/sites/default/files/pub_resource/dod-report_to_congress_final_1mar10.pdf. Accessed March 3, 2012.

the public on behalf of the NNI.[5] The current cumulative NNI investment is now about $18 billion, which includes the president's request for FY 2013.[6]

Pursuant to Section 5 of Public Law 108-153, the director of the NNCO requested that the National Research Council conduct the second triennial review of the NNI. The statement of task for the Committee on Triennial Review of the National Nanotechnology Initiative: Phase II is given in Appendix A. The overall objective of the committee's review is to make recommendations to the NSET Subcommittee and the NNCO that will improve the value of the NNI's strategy and portfolio for basic research, applied research, and development of applications to provide economic, societal, and national-security benefits to U.S. citizens.

The statement of task reflects the broad attention to and interest in optimizing the federal government's investments to advance the commercialization, manufacturing capability, national economy, and national security of the United States. For example, the President's Council of Advisors on Science and Technology (PCAST) 2010 *Report to the President and Congress on the Third Assessment of the National Nanotechnology Initiative* stated that "the NNCO must develop metrics for program outputs" and "work with the Bureau of Economic Analysis to develop metrics and collect data on the economic impacts of the NNI."[7] The NSET 2011 Strategic Plan established the objective to "develop quantitative measures to assess the performance of the U.S. nanotechnology R&D program relative to that of other major economies, in coordination with broader efforts to develop metrics for innovation."[8] The PCAST 2012 *Report to the President and Congress on the Third Assessment of the National Nanotechnology Initiative* reiterated its earlier recommendation, calling for the NNCO to "track the development of metrics for quantifying the Federal nanotechnology portfolio and implement them to assess NNI outputs."[9,10]

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[5] See http://www.nano.gov/about-nni/nnco. Accessed February 21, 2013.

[6] See http://www.wtec.org/nano2/Nanotechnology_Research_Directions_to_2020/chapter00-2.pdf. Accessed February 21, 2013.

[7] Report to the President and Congress on the Third Assessment of the National Nanotechnology Initiative, President's Council of Advisors on Science and Technology, March 2010.

[8] National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan*, February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed April 24, 2012.

[9] Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative, President's Council of Advisors on Science and Technology, April 2012.

[10] A related study on this subject is the 2012 National Research Council report *Improving Measures of Science, Technology, and Innovation: Interim Report* (National Academies Press, Washington, D.C., 2012), which examines the current status of science and technology indicators developed and published by the National Science Foundation's National Center for Science and Engineering Statistics (NCSES) to measure (1) the condition and progress of U.S. science, technology, engineering, and mathematics (STEM) education and workforce development, (2) U.S. innovation and competitiveness in science, technology, and R&D compared with other countries, and (3) whether the NCSES's

The NNI has now reached a level of achievement and maturity such that its participating agencies are examining the possibility of developing better definitions of success and associated metrics that will guide the agencies individually and the NNI as a whole in expediting "the discovery, development, and deployment of nanoscale science, engineering, and technology to serve the public good"[11] to accomplish the four highly integrated NNI goals. This interim report provides the committee's initial comments related to Task 2: to assess whether the current procedures and metrics are suitable for determining progress toward NNI goals and to suggest alternative definitions of success and their associated metrics. Recommendations related to this task and to Tasks 1 and 3 will be offered in the committee's final report.

statistical activities are focused properly to produce the information that policy-makers, researchers, and businesses need for decision-making.

[11] National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan*, February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed April 24, 2012.

2

Observations on the Current Procedures and Criteria for Determining Progress Toward Achievement of National Nanotechnology Initiative Goals

The 26 federal agencies that participate in the National Nanotechnology Initiative (NNI) are listed in Table 2.1; the top 15 in the list have NNI-related programs funded through the federal appropriations process. The eight cross-cutting NNI program component areas (PCAs), which are defined in the 2003 authorizing legislation as major subject areas in which related projects and activities are grouped, are listed in Table 2.2, and the relationships between the PCAs and missions, interests, and needs of the participating NNI agencies are shown in Table 2.3.

In the 2011 NNI Strategic Plan, each agency articulated how nanotechnology had or will have an effect on its achieving its mission and how this maps into the cross-agency PCAs. Examples are provided here in excerpts from the statements made by the Department of Defense (DOD; Box 2.1), the National Institutes of Health (NIH; Box 2.2), and the Department of Labor/Occupational Safety and Health Administration (DOL/OSHA; Box 2.3). Those statements from three representative NNI participating agencies provide a view of what they regard as success for the NNI. For example, DOD seeks "sensors . . ., communications, and information processing systems needed for qualitative improvements in persistent surveillance," OSHA seeks to "educate employers on their responsibility to protect workers and educate them on safe practices in handling nanomaterials,"

TABLE 2.1 Agencies Participating in the National Nanotechnology Initiative in 2012

Federal Agencies with Budgets Dedicated to Nanotechnology Research and Development
Agricultural Research Service (U.S. Department of Agriculture, USDA)
Consumer Product Safety Commission
Department of Defense
Department of Energy
Department of Homeland Security
Department of Transportation (DOT, including the Federal Highway Administration)
Environmental Protection Agency
Food and Drug Administration (Department of Health and Human Services [DHHS])
Forest Service (USDA)
National Aeronautics and Space Administration
National Institute for Occupational Safety and Health (Centers for Disease Control and Prevention, DHHS)
National Institute of Food and Agriculture (USDA)
National Institute of Standards and Technology (Department of Commerce [DOC])
National Institutes of Health (DHHS)
National Science Foundation
Other Participating Agencies
Bureau of Industry and Security (DOC)
Department of Education
Department of Justice
Department of Labor (including Occupational Safety and Health Administration)
Department of State
Department of the Treasury
Director of National Intelligence
Nuclear Regulatory Commission
U.S. Geological Survey (Department of the Interior)
U.S. International Trade Commission
U.S. Patent and Trademark Office (DOC)

SOURCE: National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed April 24, 2012.

and NIH seeks "new classes of nanotherapeutics and diagnostic biomarkers, tests, and devices." With respect to collaboration among NNI participating agencies, the 2011 NNI Strategic Plan identified specific subjects for close, targeted interaction, including nanotechnology signature areas, "to foster innovation and accelerate nanotechnology development."[12]

The NNI reports progress toward the four NNI goals annually in the NNI supplement to the president's budget as required by the Nanotechnology Research and Development Act of 2003 (Public Law 108-153). Issued by the Nanoscale Science, Engineering, and Technology Subcommittee of the National Science and

[12] National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed April 24, 2012.

TABLE 2.2 National Nanotechnology Initiative Program Component Areas

Program Component Area	Description
Fundamental Nanoscale Phenomena and Processes	Discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biologic, and engineering sciences that occur on the nanoscale. Elucidation of scientific and engineering principles related to nanoscale structures, processes, and mechanisms.
Nanomaterials	Research aimed at the discovery of novel nanoscale and nanostructured materials and at a comprehensive understanding of the properties of nanomaterials (ranging across length scales and including interface interactions). Research and development (R&D) leading to the ability to design and synthesize, in a controlled manner, nanostructured materials with targeted properties.
Nanoscale Devices and Systems	R&D that applies the principles of nanoscale science and engineering to create novel devices and systems or to improve existing devices and systems. Includes the incorporation of nanoscale or nanostructured materials to achieve improved performance or new functionality. The enabling science and technology must be at the nanoscale, but the systems and devices themselves need not be.
Instrumentation Research, Metrology, and Standards for Nanotechnology	R&D pertaining to the tools needed to advance nanotechnology research and commercialization, including next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems. Also includes R&D and other activities related to development of standards, including standards for nomenclature, materials characterization and testing, and manufacture.
Nanomanufacturing	R&D aimed at enabling scaled-up, reliable, and cost-effective manufacturing of nanoscale materials, structures, devices, and systems. Includes R&D and integration of ultraminiaturized top-down processes and increasingly complex bottom-up or self-assembly processes.
Major Research Facilities and Instrumentation Acquisition	Establishment of user facilities, acquisition of major instrumentation, and other activities that develop, support, or enhance the nation's scientific infrastructure for the conduct of nanoscale science, engineering, and technology R&D. Includes continuing operation of user facilities and networks.
Environment, Health, and Safety	Research directed primarily at understanding the environmental, health, and safety effects of nanotechnology development and corresponding risk assessment, risk management, and methods for risk mitigation.
Education and Societal Dimensions	Education-related activities, such as development of materials for schools, undergraduate programs, technical training, and public communication, including outreach and engagement. Research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, workforce, educational, ethical, and legal implications.

SOURCE: National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed April 24, 2012.

TABLE 2.3 Relationships Between Program Component Areas and Missions, Interests, and Needs of Agencies Participating in the National Nanotechnology Initiative

	Fundamental Nanoscale Phenomena and Processes	Nanomaterials	Nanoscale Devices and Systems	Instrumentation Research, Metrology, and Standards	Nanomanufacturing	Major Research Facilities and Instrumentation Acquisition	Environment, Health, and Safety	Education and Societal Dimensions
BIS (DOC)	•	✓	✓	✓	•			
CPSC	•	•	✓	✓	•		✓	•
DOD	✓	✓	✓	•	✓	•	•	•
DOE	✓	✓	•	•	•	✓	•	•
DOEd							•	✓
DHS	•	•	✓	✓	•	•		
DOJ/NIJ			✓					•
DOL		•			•		✓	✓
DOS	•	•	•	•	•	•	✓	✓
DOT	✓	✓	✓		•		•	
DOTreas		✓	✓					
EPA	•	✓	✓	•	✓		✓	•
FDA (DHHS)	•	•	•	•	•		✓	
FS (USDA)	•	✓	✓	•	✓		•	
IC/DNI	✓	✓	✓	•	✓			
NASA	•	✓	✓		•	•		
NIFA (USDA)	✓	✓	✓	•	•		✓	✓
NIH (DHHS)	✓	✓	✓	•	•	•	✓	•
NIOSH (DHHS)		•			•		✓	•
NIST (DOC)	✓	✓	•	✓	✓	✓	•	•
NSF	✓	✓	✓	•	✓	✓	✓	✓
U.S. NRC		✓	•					
ARS (USDA)		✓	✓		•		✓	
USGS (DOI)	✓			✓			✓	
USITC		✓	✓		✓			
USPTO (DOC)		✓	✓	✓	✓			✓

NOTE: A check mark denotes a primary relationship and a bullet a secondary relationship. SOURCE: National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/ pub_resource/2011_strategic_plan.pdf. Accessed 4/24/2012.

BOX 2.1
Department of Defense Statement

The following is excerpted from DOD's statement in the 2011 NNI Strategic Plan.

Department of Defense (DOD) leadership considers nanotechnology to have high and growing potential to contribute to the warfighting capabilities of the nation. Because of the broad and interdisciplinary nature of nanotechnology, DOD leadership views it as an enabling technology area that should receive the highest level of department attention and coordination. The vision and capability construct of Defense Research and Engineering includes nanotechnology as one of four exemplary foundational technologies, along with advanced materials, advanced electronics, and manufacturing technology. DOD Basic Research acknowledges that realizing the potential of nanotechnology is a key research objective. In particular, nanotechnology is an enabling technology for new classes of sensors (such as novel focal plane arrays and chemical/biological threat sensors), communications, and information processing systems needed for qualitative improvements in persistent surveillance. The DOD also invests in nanotechnology for advanced energetic materials, photocatalytic coatings, active microelectronic devices, structural fibers, strength- and toughness-enhancing additives, advanced processing, and a wide array of other promising applications.

SOURCE: National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed 04/24/2012.

BOX 2.2
National Institutes of Health Statement

The following is excerpted from NIH's statement in the 2011 NNI Strategic Plan.

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

SOURCE: National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed 04/24/2012.

BOX 2.3
Department of Labor Statement

The following is excerpted from DOL's statement in the 2011 NNI Strategic Plan.

> The Department of Labor (DOL) Occupational Safety and Health Administration (OSHA) plays an integral role in nanotechnology by protecting the nation's workforce. Through the NNI interagency efforts, OSHA accomplishes its mission by collaborating and sharing information with other Federal agencies. As part of this effort, OSHA's goal is to educate employers on their responsibility to protect workers and educate them on safe practices in handling nanomaterials. OSHA is developing guidance and educational materials promoting worker safety and health that will be shared with the public and through the NNI.

SOURCE: National Science and Technology Council, *National Nanotechnology Initiative Strategic Plan,* February 2011, available at http://www.nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf. Accessed 04/24/2012.

Technology Council's Committee on Technology, the annual supplement includes budget information by agency and by PCA for the prior year (actual spending), the current year (estimated), and the coming year (planned). The NNI also reports the amount of funding that went to nanotechnology-related Small Business Innovation Research (SBIR) awards and Small Business Technology Transfer (STTR) awards to date. (The amount of SBIR and STTR funding that is invested in nanotechnology is not planned, so only prior-year data are available.) The agencies provide examples of specific activities as evidence of progress toward each of the four NNI goals, including coordinated activities with "other agencies, disciplines, industrial sectors, and nations."[13] The annual report released in 2011 (accompanying the president's FY 2012 budget) included for the first time estimated spending in 2011 and planned spending in 2012 for each of three multiagency signature initiatives (Solar Energy Collection and Conversion, Sustainable Nanomanufacturing, and Nanoelectronics for 2020 and Beyond).

The data on budget and expenditures reported in the annual NNI supplement to the president's budget and in reports to Congress provide a picture of how resources are being allocated by agency to each of the PCAs. However, progress toward achieving the four NNI goals is reported in largely anecdotal form. Several agencies provide examples of successful projects, some provide numerical data,

[13] The National Nanotechnology Initiative, Supplement to the President's 2013 Budget. Available at http://www.nano.gov/sites/default/files/pub_resource/nni_2013_budget_supplement.pdf. Accessed August 8, 2012.

and some present short summaries without many details. Interagency activities are reported in the same manner. That approach is consistent with how the NNI agencies manage their overall portfolios, how they gather information to report to the president, and what is included in the NNI supplement to the president's budget.

There is no common method or system across the NNI participating agencies for measuring and tracking progress toward achieving the four NNI goals (see Box 1.1). Broad generalizations about progress are made, but there are few details except for specific examples of successful projects, discoveries, and products related to the agencies' statements, which are mapped onto the four goals. At the agency level, individual projects are monitored and evaluated with respect to their agreed-on deliverables by using processes and metrics developed by the sponsoring agencies. But such evaluations typically are program-specific, and the deliverables and outcomes are generally reported in forms that cannot be easily aggregated and analyzed. Consider, for example, Goal 1—to advance world-class nanotechnology research and development. The generation of world-class scientific publications, the body of published work associated with an activity, could be considered an indicator of success; metrics would include number of publications, topics, quality of journals, number of citations, and so on. However, there is no comprehensive compilation of publications for NNI-funded R&D for any agency, much less for the whole NNI. The challenge of developing metrics that align with all the NNI goals is the focus of Chapters 3 and 4 of this interim report.

3

The Role of Metrics

Metrics are necessary for evaluation, rational decision-making, and appropriate allocation of resources. It is useful to distinguish three classes of metrics: for inputs, outputs, and outcomes. Inputs are often measured in dollars spent, in part because such figures are relatively easily determined. Outputs are activity and productivity, whereas outcomes are effects and progress toward overall goals. Outcomes depend heavily on program objectives. Often, inputs are used as a proxy for outputs, but they are generally a poor substitute in that they do not account for the effectiveness or efficiency of a funded activity. A good metric for output should be an accurate measure of whether the desired outcomes of an activity have been achieved—outcomes that represent the value that the activity was intended to generate. In fact, however, many accepted quantitative metrics are used to measure what can be easily measured rather than the value created in the course of the activity.

The relationship between metrics for output and for outcomes of the National Nanotechnology Initiative (NNI) can be illustrated by analogy with manufacturing. In manufacturing, a material or product is measured for three reasons: for quality control, for quality improvement, and to establish that a legal requirement specified in a contract between a supplier and a customer has been met. In the first case, all that is needed is a simple, reliable measure to identify when an acceptable outcome is no longer being produced; measurement yields a result as simple as "acceptable/unacceptable," and the information that it provides stays local to provide quality control. In the second case, measurement is more quantitative and guides changes to produce better outcomes than previously obtained. In the third case, a supplier agrees to provide to the customer a material that has specific properties as measured by specific agreed-on, standardized techniques. In each of those cases, there is a well-established model that relates the measurement to the desired outcome, and the measures may be different for the three different functions of metrics.

Applying that to the NNI, many NNI metrics are designed primarily for quality control within the individual agencies on the basis of their individual missions, and many of the possible metrics listed in Chapter 4 of this interim report are in that category. The issue, however, is how to assess the success of the NNI as a whole, as opposed to the success of the individual agencies in fulfilling their missions. Output data gathered by different NNI participating agencies cannot now be usefully compared. The measurement systems are not the same, and the metrics and processes used for quality control are peculiar to each agency, its mission, and its historical way of doing things. Furthermore, researchers and organizations know that they have been funded by a particular agency and are familiar with the agency's metrics and desired outcomes. The committee learned, in contrast, that many programs and associated researchers do not know that their federally funded research and development (R&D) projects have been included in their funding agencies' reported NNI program dollars.

METRICS FOR ASSESSING THE NATIONAL NANOTECHNOLOGY INITIATIVE—SOME CONSIDERATIONS

The NNI is being asked to establish metrics for *quality improvement*, that is, improvement of the NNI and its R&D system for addressing the four NNI goals, and *contractual* metrics, that is, regarding the effective customer-supplier contracts between, such as taxpayers and the government, Congress and the NNI, principal investigators or companies and the agencies, workers and those who regulate nanotechnology in the workplace, and consumers and agencies that are responsible for food and product safety. For such sets of "customers-suppliers," there must be a model that relates what is measured—outputs—to the short-term, intermediate-term, and long-term outcomes that the customer is paying for, and there must be an accurate system of quantitative and qualitative metrics that support the model. Without the model, metrics for output probably will lead to an incomplete and inaccurate assessment of whether the outcomes are being met—that is, whether the quality of the NNI program is high, the NNI is increasing its impact, and the NNI is meeting its "contract" with all its "customers."

Additional characteristics of a good metric are that the information supporting it are reliably and relatively easily obtainable and that, at the very least, the benefits contributed by the metric to evaluation, strategy, and priority-setting justify the cost of obtaining the information. The information generated by the metric also should be able to provide the basis of program decision-making; in other words, it should be actionable. Many metrics are too general to contribute to the discussion of any specific, important issue.

The quest for good metrics is often framed as a quest for quantitative metrics, which can be measured in an objective way and for which the result is a number or a collection of numbers. However, the emphasis on having objective, numerical metrics often leads to collecting output data that are peripheral to the goals and outcomes of an activity. For example, the number of papers published per year by a researcher is not the only metric of scholarly achievement. Clearly, some consideration of *quality and impact* of output is also required. Various metrics related to citation may be of partial use in evaluating the quality of a body of publications, but if, for example, the *utility* of the results presented in publications is the quality or value being sought, citation-count metrics are poor indicators. Furthermore, there is general awareness that the choice of metrics may change the behavior of participants in ways not necessarily conducive to successful outcomes. That is a known and difficult problem that has received considerable attention. Academe's answer to such problems is to evaluate a person on the basis of a model of academic success that uses a set of subjective, qualitative metrics supported by quantitative data on output and subjective evaluation of the data. That combination of subjective evaluations and quantitative output metrics has evolved to support a model of academic success for faculty at different career stages and performance levels, from assistant to full professor. Dependence on the subjective evaluation of a group of experts chosen for some mix of technical expertise, judgment, and breadth of knowledge of a field is key to this approach. Although the results of the application of qualitative metrics are subjective, such metrics have been demonstrated both to be reasonably reproducible and to encourage desired outcomes successfully; this suggests that the model on which they are based and the methods are reliable. The process has also been developed to ensure that the experts who provide the assessments are in positions of sufficient personal independence from the people being evaluated that they can render objective evaluations.

Notwithstanding those issues, given the investment in and the scope of the NNI, quantitative and qualitative metrics can be applied to assess the impacts of NNI-related activity. Many major federal funders of nanotechnology research are working on the problem of defining a set of quantitative metrics that relate program outputs to desired outcomes in arenas that overlap with the NNI. A prime example is National Institute of Standards and Technology's (NIST's) leadership in developing metrics for technology transfer from federal agencies that have research facilities to the commercial marketplace.[14] The resulting metrics should be taken into account in the review of NNI activities with qualitative and semiquantitative

[14] See http://www.nist.gov/tpo/publications/upload/DOC-FY2011-Annual-Tech-Transfer-DOC.pdf. Accessed August 27, 2012.

assessments by experts. Ideally, such assessments would improve the efficiency, quality, and completeness of the review process. Such a collection of metrics, taken as a whole, may be viewed as an indicator of impact or success and provide guidance for decision-making and for allocation of resources.

Quantitative metrics require various kinds of output and outcome data—such as people trained, jobs created, papers published, awards earned, patents filed, companies started, and products created—measured over time for the agencies or organizations, researchers, and so on. To provide sound input for assessments, those data must be melded in weighted fashion in a manner that respects the missions, nature, and objectives of the responsible agencies or programs. Clearly, uniform models and metrics for all 26 NNI participating agencies are neither practical nor appropriate. Five agencies (the National Science Foundation [NSF], the Department of Defense, the Department of Energy, the National Institutes of Health, and NIST) account for well over 90 percent of the funds and effort expended. The other agencies play different, although still critical, roles in the development of nanotechnology and the NNI. The committee believes that it is important to select output and outcome metrics to minimize the burden on each agency of gathering and reporting data that are not central to its mission or that would require substantial added effort without substantial benefit to the NNI.

The committee recognizes the great difficulty in defining robust models and metrics for a field as diffuse as nanotechnology and for agencies as diverse as the 26 NNI participating agencies. However, it urges that, as difficult as this task may be, whatever models and metrics are applied should be rigorous, that is, should have clearly and publicly defined assumptions, sources, methods, and means to test whether the models and data are accurate. Despite the recognizable value of many of the data provided to and by the NNI agencies and the National Nanotechnology Coordination Office, the origins of the data or assumptions used in collecting or collating the data were not always clear. Furthermore, the committee believes that data arising from "self-identification" or "self-reporting" do not always give an accurate and complete picture of the status of a field. If the data used are inaccurate or if the models or understanding that link even accurate data to desired outcomes have not been well established, evaluation, rational decision-making, and allocation of resources become compromised.

The provenance of data, including the original assumptions and calculations used to develop them, must be clearly established, documented, and maintained. Although source data are not likely to be perfect, the intent should be to make the process of data selection and the results as transparent as possible.

The committee sees promise in many of the aspects of the NSF Star Metrics project[15] but also grounds for concern. Directly accessing institutional human-

[15] See www.nsf.gov/sbe/sosp/workforce/lane.pdf. Accessed September 27, 2012.

resources databases to automate data collection on personnel, for example, seems excellent. However, the software algorithms used to parse project summaries to identify emerging fields of research may not be ready for application, given the sample outputs shown to the committee, so implementation of the Star Metrics approach to define fields and current funding levels without independent validation could lead to erroneous conclusions. That observation reflects the state of research that applies machine learning to social-science problems; advances in machine learning and automated inference from large datasets have proceeded rapidly, but validation of the calculated measures has lagged far behind. The lag results from the difficulty of validation, which requires careful sampling of adequate observations for field-work validation, such as interviews, surveys, and historical case studies; lack of collaboration between experts in quantitative data analysis and social-science field research methods; and lack of validated models that relate the output data to the desired outcomes.[16]

Although software algorithms and data-mining offer promising approaches to data collection, the committee believes that use of a specific set of keywords or field categories, identified by research investigators or program managers, could be improved sufficiently with relatively little effort to be useful for future data collection. However, the committee was surprised to learn that the current software system for project monitoring in NSF, called FastLane—whereby investigators enter data into multiple fields to describe project participants, results, and outcomes, including papers published—apparently could not be used to mine the data supplied by NNI-supported projects.

In general, metrics will be poor if they present misleading information about actual or probable success in accomplishing desired goals, that is, the desired outcomes. There are several characteristics to avoid or minimize in developing metrics. For example, ambiguity in the definition of a metric can lead to combining incoherent data and to analyses of questionable value. Such ambiguity can result from metrics that are too complex. It is better to have simple metrics without too many qualifiers. Another type of problematic metric is one for which optimization of an individual result is easily accomplished at the expense of another important goal, especially if the latter is not captured by a corresponding metric. A great deal of care must be taken to understand the use of specific metrics in different NNI communities and agencies. For example, some communities write more and shorter papers and cite sparsely, whereas others write fewer and longer papers and cite generously. The different practices can produce different distributions of measures of output and impact, and comparisons among fields can become problematic. The effectiveness of a metric may also be compromised by lack of availability or accuracy of the corresponding data, owing, for example, to small samples,

[16] G. King, Ensuring the Data-rich Future of the Social Sciences, *Science* 331:719-721, 2011.

a dearth of accurate sources, estimation errors, and the burden of responding to numerous requests for data. For all those reasons, a model that has a balanced set of metrics should be established.

In summary, the committee finds that strictly quantitative metrics of output are not by themselves dispositive in evaluating the success of the NNI in achieving its goals. Well-crafted qualitative and semiquantitative metrics and their review, supported by quantitative metrics, are more likely to be useful in producing evaluations that measure success and can be applied in setting NNI goals and policy.

A POSSIBLE FRAMEWORK FOR ASSESSING SUCCESS

The goal of this interim report is to consider definitions of success for the NNI (the desired short-term, intermediate-term, and long-term outcomes), metrics, and methods for assessing the NNI's progress toward its goals.

Establishing the connections between inputs, outputs, and short-term to long-term outcomes is difficult and requires articulation and validation of a model. A possible open framework of a model and system for assessing success in achieving desired outcomes for the individual funding agencies and the NNI as a whole is shown in Figure 3.1. Application programming interfaces and linked databases provide access to input and output data that may be used to trace the connections between inputs, outputs, and some short-term outcomes. Inputs may originate with persons or grants, whereas outputs can include publications and patents or organizations; arrows show explicit connections. The arrows suggest the direction of collaborations or connections between people and organizations, number of times that papers are cited in other publications, and outputs.

Essentially, the framework links NNI research products, including grants, papers, and patents; NNI people; NNI agencies and other corporate, government, and academic institutions; and short-term, intermediate-term, and long-term NNI outcomes. Many of the proposed metrics for assessing output are available to or are under development by various agencies and firms. Google Scholar, for example, has disambiguated and linked the publication and patenting careers of many scientists and inventors (although that effort remains proprietary) and highlights the importance of an open framework. Once in place, such a framework could be used to generate metrics of output at various levels of analysis, including specific awards, principal investigators, institutions, or entire nanotechnology subfields. The resulting metrics for output will require careful validation, as discussed above. Although the framework would require substantial investment in record linkage and disambiguation, it would provide flexibility and allow reuse of investment in different scientific fields and bibliometric databases.

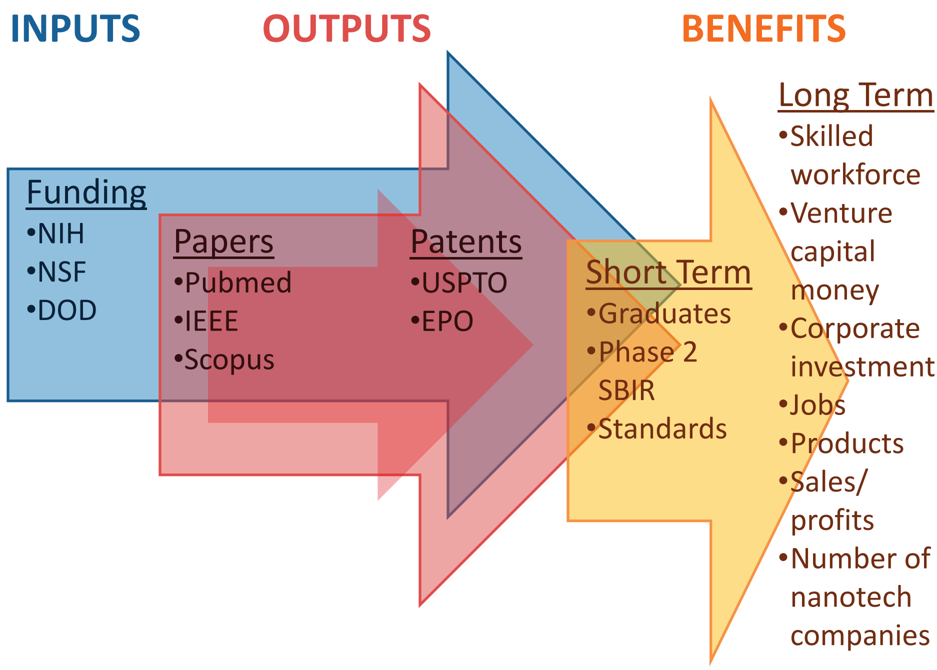

FIGURE 3.1 How inputs lead to outputs and, eventually, benefits: National Nanotechnology Initiative-related research funded through federal agencies leads, in one mode of translation, to publications and patents, which in turn lead to societal benefits realized in the creation of new knowledge, products, companies, and jobs.

4

Definitions of Success and Metrics

NATIONAL NANOTECHNOLOGY INITIATIVE GOAL 1: TO ADVANCE WORLD-CLASS NANOTECHNOLOGY RESEARCH AND DEVELOPMENT

Support for nanotechnology research and development (R&D) is the activity most strongly associated with the National Nanotechnology Initiative (NNI) and the one that has received the largest share of funding. The NNI has funded R&D performed by individual investigators, small teams, and large multidisciplinary centers, facilities, and networks of researchers in academe, industry, and government.

Definitions of success that might be applied to NNI Goal 1 include the following:

- A full spectrum of R&D, including fundamental research, "use-inspired" basic research, application-driven applied research, and technology development is being supported.
- The NNI supports research that crosses boundaries—research that is multidisciplinary, multi-institutional, multinational, multiagency, and multisectoral (government-university-industry).
- The performance of the U.S. NNI is comparable with or better than that of the best in the rest of the world.
- An appropriate scientific and technical workforce is being trained and educated, and it contributes effectively to the U.S. economy. (See Goal 3.)
- The frontiers of knowledge are being substantially advanced in a way that is commensurate with the scale of funding.

- NNI-supported research is world-class.
- NNI-supported research is leading to valuable new technology. (See Goal 2.)
- Industrial, sector-specific nanotechnology knowledge is used to inform application-driven research investment decisions.
- NNI dollars are spent wisely to advance world-class R&D efficiently and effectively.
- Cohesive and substantial facilities and networks that are of broad relevance to the nanotechnology community are being built, and these facilities foster collaboration. (See Goal 3.)

Possible metrics of progress toward success as defined above for Goal 1 are outlined below.

- Spectrum of R&D assessment funded or supported, on the basis of expenditures categorized according to the following:
  - "Basic research," "applied research," or "technology development" based on definitions of the Office of Management and Budget or definitions similar to those used by the Department of Defense (DOD) (6.1, 6.2, and so on).[17] (Understanding the distribution among these categories over time can help to ensure a balanced portfolio and to track the maturation of nanotechnology from a primarily basic-research endeavor to one that includes substantial application and development investments.)
  - Distribution of funds by size of grant, to assess coverage of large and small projects.
  - Nature of research performers (academic, government, small, midsize, or large company, nonprofit). Collaboration among sectors should be noted because such collaborations are important for knowledge diffusion and translation to applications (especially if industry is involved).
- Number of publications based on NNI-funded R&D, with analysis of authorship to assess the share that is multidisciplinary, multidepartmental, multiuniversity, multinational, and multisectoral (for example, academe-industry or academe-government).
- Number of publications in the array of disciplines and sectors related to nanotechnology.
- Number of citations to NNI-funded publications by other publications, with additional analysis to assess share of citations that are by authors in industry, another discipline, outside the United States, and other characteristics.

[17] See http://www.rand.org/content/dam/rand/pubs/monograph_reports/MR1194/MR1194.appb.pdf. Accessed February 22, 2013.

- Number of citations to NNI-funded publications by patents, with additional analysis of the patent subject categories—or classifications—in which the citations are made.
- Number of patents and patent applications based on NNI-funded research.
- Keynote and invited presentations on NNI-funded R&D at conferences throughout the various disciplines and sectors affected by nanotechnology. Such presentations are generally made by highly regarded researchers and so are a measure of research quality and a measure of diffusion of NNI research.
- Awards and prizes that recognize NNI-supported research that has had a substantial impact, such as awards by selected professional societies and agencies.
- Numbers of scientists, engineers, and technicians trained in nanotechnology, with additional analysis to show what jobs they have moved into. (See also Goal 3.)

As noted above, however, metrics like those are not an end in themselves. The most relevant numerical metrics must serve as the basis of a rational model of the evolution of the NNI R&D system that can be used to assess progress toward the NNI goals. Ideally, quantitative and qualitative metrics is combined with expert assessment whenever possible.

NATIONAL NANOTECHNOLOGY INITIATIVE GOAL 2: TO FOSTER THE TRANSFER OF NEW TECHNOLOGIES INTO PRODUCTS FOR COMMERCIAL AND PUBLIC BENEFIT

A definition of success that might be applied to NNI Goal 2 is the development in the United States of vibrant, competitive, and sustainable industry sectors that use nanotechnology to enable the creation of new products; skilled, high-paying jobs; and economic growth. The committee is keenly aware of the different time frames associated with the transition from discovery to products that are related to the missions of the NNI participating agencies. Some agencies (or offices in agencies) will pursue technologies that are closer to market to address mission-driven needs and goals, whereas others will develop knowledge that may well be many years from or not specific to commercialization. The NNI, like many federal R&D programs, funds primarily activities that are focused on discovery as opposed to commercialization. Commercialization requires private-sector investments over which the NNI has weak influence, so the NNI tends to focus on startups as opposed to large or multinational corporations. One example of an exception to that is the Nanoelectronics Research Initiative, a jointly funded venture between the National Science Foundation (NSF), the National Institute of Standards and

Technology (NIST), and the Semiconductor Research Corporation. Models and metrics for success require an understanding of the pathways and timelines for translation of discovery to commercial products.

Defining commercial benefits within the narrow confines of the U.S. economy is also challenging, given the highly interconnected global economy into which new nanotechnologies are launched. For example, it is extremely difficult to prepare sound economic-impact statements for a new technology that may be invented in the United States but then sold to a company that is headquartered elsewhere. The company may choose to manufacture the nanotechnology-enabled products in a third country but sell them in the United States, possibly yielding improvements in domestic productivity or quality of life, an increase in commercial activity, and financial benefits to U.S.-based shareholders in the company.

Because of such complexities, which are difficult to tease apart, the committee believes that the most robust indicator of commercial benefit to the United States may be the growth of U.S.-based jobs related to nanotechnology. Once that growth is defined and enumerated, pre-existing estimates of the economic good associated with each additional skilled technology worker could be used to extrapolate from the number of jobs to a direct impact on the U.S. economy.

Possible metrics of progress toward success as defined above in achieving NNI Goal 2 are listed below.

- Growth of nanotechnology-related jobs.
- Number of NNI-funded students who are hired for nanotechnology-related jobs.
- Number of published patents and applications (as reported by the U.S. Patent and Trademark Office) and patent licensing categorized according to
  - — Inventor affiliation (academe, industry, government, individual).
  - — Subject or sector (electronics, chemicals and materials, and so on).
  - — Inventor's country of origin.
- Number of Small Business Innovation Research (SBIR) awards related to nanotechnology, categorized by field of interest or topic.
- Number of nanotechnology-related companies partnering in specific ways with NNI-funded user centers, possibly weighted by funding levels.
- Number and economic health of companies started by NNI-funded SBIR and Small Business Technology Transfer (STTR) recipients.
- Nanotechnology-enabled products known to have been derived at least in part from NNI-funded activities.

Progress in fostering the transfer of technologies into products for commercial and public benefit is difficult to define, assess, and quantify throughout the NNI given the complexity of interactions. The translation of NNI research into products will require different metrics for different agencies because the products will differ considerably in their type and path to fruition. Translational entities and programs set up by such agencies as DOD, the Department of Energy (DOE), NIST, and NSF may be dedicated to nano-enabled products or have goals that include nano-enabled products. Products vary considerably; for example, the products of NSF-funded university research are typically graduates, publications, and, to a smaller extent, intellectual property, all of which contribute to the development of the nanotechnology workforce and to the body of knowledge. DOD research is generally aimed at developing technology that can be deployed for the national defense. Many companies are interested in products and services for public sale. Standards developed by various standards-development organizations with the participation of NIST and other federal agencies are a public good that supports industry while reducing technical barriers that favor a particular company's or country's agenda.

The pathways by which research results are translated into practical applications and commercial products are complex and numerous. Moreover, the time from research to product is typically measured in years or even decades. The NNI has existed for 10 years; nanotechnology-based products are emerging, and many more useful discoveries are in the innovation pipeline. At the agency or industry level, mechanisms exist for technology transfer and commercialization, and different metrics may be required to capture their effectiveness. Moreover, commercialization depends on various innovation activities, and hence various metrics, in the NNI: knowledge generation and dissemination, technology transfer, commercialization, and workforce creation in which NNI agencies and program managers and members of the international nanotechnology R&D community are prime actors. Metrics may be based, for example, on knowledge (publications, intellectual property, and citations), workforce training (graduates, employees, and meetings attended), private-sector engagement (patent licensing data, SBIR or STTR grant data and later venture funding acquisition, cooperative R&D agreements, and public-private partnerships), or revenue.

Desired outputs depend strongly on the agency involved; 26 agencies have widely different levels of engagement in the NNI as measured by funding for the research or staff involved. Outputs may even vary within a single agency. In DOE, for example, NNI-related output includes user centers, Advanced Research Projects Agency-Energy grants and contracts, SBIR funding, and the establishment of the Energy Frontier Research Centers program. In addition, outputs represent a broad range of technology readiness levels, and this has implications for the amount of funding, time, and effort required to convert a discovery or an invention into a useful product.

Encouraging inventors to take risks to commercialize their ideas is as much a cultural issue as it is a financial or a technical issue. Commercialization can be stifled in an environment in which risk-taking is not encouraged, mentors are not available, or licensing is difficult; some regions and institutions are good at off entrepreneurial activities, and others are not. Those cultural issues are common to universities, government laboratories, and other research institutions and can create a bottleneck in the innovation pipeline. Although that is not a nanotechnology-specific problem, addressing it is important for removing barriers to commercialization of results, given the substantial investment in the NNI.

Inventors and organizations may not be aware of the potential commercial value of technology if there is not an environment that encourages startups or spin-offs, and they may need a mechanism like a "preseed" workshop or NSF I-Corps[18] to foster commercialization concepts. Federal and local agencies have recognized that—the NSF I-Corps is an example of what can be done at the federal level to encourage and stimulate growth. It works to connect NSF-funded scientific research to the technologic, entrepreneurial, and business communities. The I-Corps curriculum is built on an accelerated version of Stanford University's Lean LaunchPad course and additional elements designed for I-Corps grantees. All I-Corps team members attend a kickoff workshop at Stanford University, the Georgia Institute of Technology, or the University of Michigan and then join a series of Web-based lectures and present their business pitches at a meeting of I-Corps grantees. Awards are for $50,000 with a duration of 6 months.

Many other excellent programs of this type may be available throughout the United States, but there is no current way to know how many and where they are. A measure of success for the NNI might be to expedite and facilitate connections for inventors in the nanotechnology-products realm to help them to identify agencies—federal, state, regional, and local—that can support them. The committee will examine such issues in its final report.

NATIONAL NANOTECHNOLOGY INITIATIVE GOAL 3: TO DEVELOP AND SUSTAIN EDUCATIONAL RESOURCES, A SKILLED WORKFORCE, AND THE SUPPORTING INFRASTRUCTURE AND TOOLS TO ADVANCE NANOTECHNOLOGY

The 2011 NNI Strategic Plan notes that the development and sustainment of the infrastructural elements addressed by NNI Goal 3 are essential for delivering commercial and public benefit from NNI efforts. The Strategic Plan supplements Goal 3 with three objectives that are paraphrased here as workforce development, informal education activities, and physical infrastructure development.

Definitions of success that might be applied to NNI Goal 3 include the following:

[18] See http://www.nsf.gov/news/special_reports/i-corps/.

- The supply matches the demand for U.S.-based skilled nanotechnology workers.[19]
- Public understanding of and interest in nanotechnology and how it may affect our lives are expanded.
- The amount and the type of infrastructure for nanotechnology advancement are appropriate, given the funding levels.
- Users' technical needs are met through NNI user facilities.
- Rates of use of NNI infrastructure are high.

Possible metrics of progress as defined above in achieving NNI Goal 3 are listed below.

- Evidence that U.S.-based skilled nanotechnology workers trained through the NNI are fully employed.
- Evidence that there is not unmet demand for skilled nanotechnology workers.
- Numbers of people beyond the NNI research community reached by specific agency-driven outreach activities, such as teacher-education activities and K-12 student activities.
- Mass-media stories about nanotechnology activities in or related to NNI participating agencies.
- Use of current infrastructure, according to numbers and types of users, and the outcomes of use of the infrastructure.
- Satisfaction among participants in user facilities, as established through surveys.
- Responsiveness to unmet needs for infrastructure signaled by unfulfilled requests for access to infrastructure.

The committee is impressed by the number and nature of programs targeting the training of a skilled nanotechnology workforce in the NNI environment. It is in the nation's interest that the supply of and demand for skilled workers be in balance. It is therefore desirable to collect reliable data on the supply of and demand for workers who have critical skills. Even the number of students who are receiving formal, career-oriented, "nanotechnology" education at various levels funded by NNI agencies is difficult to assess with the current system for collecting data from the agencies that participate in the NNI; only some agencies appear to collect such data, and the National Nanotechnology Coordination Office does not aggregate the data that are available as far as the committee can tell. The committee is considering ways in which data on the supply of workers at all levels of training and education

[19] A "nanotechnology worker" is, for example, a scientist or an engineer (such as a materials scientist, chemist, or physicist) who is trained to work on processes in the 1- to 100-nm range.

might be aggregated and compared with indicators of the workforce demand for skilled nanotechnology workers as a function of time.

At a minimum, the NNI-funded ecosystem should be graduating students at a rate sufficient to drive the nanotechnology innovation and commercialization process. Achieving that result, however, will require as a first step the collection and analysis of data. It may, however, be useful to collect and analyze the supply-side dataset. For NNI participating agencies, it may be possible to report where students work immediately after graduation. NNI-trained students moving to employment with U.S. firms, agencies or with institutions involved in nanotechnology could perhaps be fairly viewed as expanding the skilled nanotechnology workforce, whether or not job listings specify nanotechnology skills.

It is difficult to estimate the size of the current nanotechnology workforce, but the related issue of workforce growth in this segment, as estimated from periodic review of U.S. job listings, might provide a useful metric. The committee notes with interest the data on nanotechnology job openings collated by Freeman and Shukla for 2008 directly from the on-line job board SimplyHired.com.[20] The data are broken down into 18 categories, some of which are nanotechnology-specific (for example, scientist and engineer) and some of which might be considered support roles (information technology, human resources, and administration). Taken together, however, the data indicate the health of the U.S. nanotechnology economy. If tracked over a longer period, they might be considered a proxy indicator of the growth of the U.S. nanotechnology economy through the demand for a skilled nanotechnology workforce. The committee notes that many of the job listings represent workforce churn—skilled people changing jobs—rather than new positions, so it is the time-based growth in the number of listings that is of primary interest for NNI metrics, given the assumption that the churn rate might be taken as a somewhat constant fraction, other factors being equal.

The number of people receiving "nanotechnology" education at various levels through outreach and informal educational activities enabled by the NNI and the effectiveness of such activities will probably also be important to quantify. It will be difficult to measure efforts to expand public understanding of nanotechnology and all that it entails or to measure the effectiveness of such efforts. A possible metric is an estimate of the number of people reached by specific agency-driven outreach activities.

The NNI has created a substantial infrastructure that includes everything from laboratory equipment that is used by a single principal investigator to major facilities that are open to qualified researchers. The latter category includes the DOE nanoscale science research centers, the NIST Center for Nanoscale Science and

[20] R. Freeman and K. Shukla, Jobs in Nanotechnology—Creating a Measure of Job Growth, *Science and Engineering Workforce Project Digest*, National Bureau of Economic Research, June 2008.

Technology, the National Institutes of Health (NIH)-Food and Drug Administration (FDA)-NIST Nanotechnology Characterization Laboratory, and NSF centers and networks, including the National Nanotechnology Infrastructure Network and the Network for Computational Nanotechnology.[21]

The committee applauds the objective stated in the 2011 NNI Strategic Plan of taking an inventory of current infrastructure and estimating infrastructure needs out to 2020. The related issue of accessibility of that infrastructure should also be addressed. Metrics of progress toward that objective should track how useful the current infrastructure is (for example, on the basis of numbers and types of users, rates of use of key tools, and outcomes of using the infrastructure) and whether there are unmet infrastructure needs.

The committee is also interested in metrics that indicate the relative success of different models for operating the existing nanotechnology facilities in supporting innovation, such as papers written by academic and industry partners and related patent activity. Such metrics might reveal which operating models are most effective and thus provide direction to the management teams in new and existing facilities that are seeking to maximize impact. Some such data are given in the 2011 report *Assessment of Fifteen Nanotechnology Science and Engineering Centers' (NSECs) Outcomes and Impacts: Their Contribution to NNI Objectives and Goals.*[22]

NATIONAL NANOTECHNOLOGY INITIATIVE GOAL 4: TO SUPPORT THE RESPONSIBLE DEVELOPMENT OF NANOTECHNOLOGY

NNI Goal 4 attempts "to assure that nanotechnology-enabled products minimize adverse impacts and maximize benefits to humans and the environment." The NNI role in supporting responsible development includes investing in research on potential risks to health or the environment from nanomaterials and on societal aspects of the development of nanotechnology applications. Ensuring responsible development also entails communicating relevant information with various stakeholders, including business, international governance and other organizations, educators, and the public. It is notable that success in responsible nanotechnology development is considered necessary for the achievement of NNI Goals 1-3. Of the eight NNI program component areas, two in particular reflect the goals of responsible development of nanotechnology: Environmental Health and Safety (EHS), and Education and Societal Dimensions.

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[21] Information about each can be found on the nano.gov Web site by clicking on "Collaborations and Funding" and "User Facilities."

[22] Available at http://www.nsf.gov/crssprgm/nano/reports/Assessment_2011+May+12+of+NSEC+by+GaTech_ FinalReport_56p_web.pdf.

The *2011 NNI Environmental, Health, and Safety Research Strategy*[23] lays out the breadth and complexity of NNI Goal 4 and supplements it with a number of important, and in many cases concrete, objectives. In 2012, the funding for EHS is estimated to increase by about 20 percent over 2011 levels. The increase is in keeping with the perception that EHS will be critical for success in leveraging nanotechnology for societal benefit by identifying and addressing potential hazards of nanomaterials at an early stage. The primary agencies, by dollar value, that are supporting the EHS program component area are NSF, NIH, the Environmental Protection Agency, and the National Institute for Occupational Safety and Health, and FDA is playing an increasing role as new nanotechnology products come to market. Although the Consumer Product Safety Commission has been a member of the NNI since 2004, it contributed to the NNI budget for the first time in 2011; this shows the increasing importance of Goal 4 as nanotechnology matures.

Because of the complexity of NNI Goal 4, related definitions of success are particularly challenging to distill but may include the following:

- Development, updating, and implementation of a coordinated program of EHS research leads to development of tools and methods for risk characterization and risk assessment in general—including both hazards and the likelihood of exposure—and supports expanding understanding of potential risks posed by broad classes of nanomaterials.
- Results of EHS research worldwide are public and easily available to researchers and users of nanomaterials.
- Businesses of all sizes are aware of potential risks posed by nanomaterials and know where to obtain current information about their properties and best practices for handling them.
- To enable continued innovation, regulatory agencies have sufficient information to assess the risks posed by new nanomaterials.
- The NNI supports research to assess the societal effects of nanotechnology in parallel with technology development.
- K-12 students are exposed to nanotechnology as part of their education and are aware of the potential applications and opportunities available to those who go into STEM (science, technology, engineering, and mathematics) disciplines.
- The general public has access to information about nanotechnology and a growing percentage is familiar with the fundamental concepts.

[23] See http://www.nano.gov/sites/default/files/pub_resource/nni_2011_ehs_research_strategy.pdf. Accessed September 27, 2012.

- The NNI includes R&D aimed at applying nanotechnology to solve societal challenges, such as affordable access to clean water, safe food, and medical care.

Possible metrics of progress toward success as defined above in achieving NNI Goal 4 are listed below.

- EHS collaborations and projects or centers funded.
- Number of NNI EHS research results that are made easily accessible, for example, through an NNI-managed clearinghouse or in cooperation with international organizations.
- Guidance documents developed and made available to the public.
- Number of faculty and students supported for research in nanotechnology-related endeavors.
- Number of K-12 students and educators engaged by NNI-funded researchers, including DOE laboratory outreach and NSF-funded researchers, and the effects of such engagement.
- Evidence of public awareness and attitude regarding nanotechnology based on data on NNI-funded research.
- Availability of on-line information and news items related to nanotechnology.
- Evidence that NNI agencies are engaged in international forums discussing and developing standards, norms, and strategies for responsible development of nanotechnology.
- Number of NNI participating agency representatives at various international forums.
- Compilation of commercialized or commercializable technologies.
- Number of companies offering EHS, nanotoxicity, or nanotechnology safety services.
- Evolution of outcomes and impact of sustained funding in the EHS and societal dimensions of the NNI.

Progress toward Goal 4 requires collection of data and development of methods to assess potential risks associated with engineered nanomaterials. Integral to that effort is the design of methods and protocols for assessing properties of nanomaterials and their biologic effects on the environment and on human health and the creation of guidance documents, standards, or other regulatory approaches. The amount of information that is needed to make informed decisions is large (and expensive to collect and catalog). The committee applauds the NNI for its renewed commitment to addressing these hard problems and plans in its final report to suggest metrics for gauging progress or success without imposing undue reporting burdens on the participating agencies.

THE PATH FORWARD TO IMPROVED METRICS

The committee believes in the value of metrics—why we have them, what we hope to accomplish by using them, and how we can tailor them to yield the information desired—but will not recommend measuring something simply because it can be measured. Metrics should make clear what the desired outcomes are. That is, there must be a model that relates what is measured to the desired outcome and an accurate system for doing the measuring. Having both constitutes having a metric. Without both, measurements will have little value for program management.

The committee recognizes the difficulty of defining robust models and metrics for a field as diffuse as nanotechnology, for agencies as diverse as the 26 NNI participating agencies, and for goals as far-reaching as the four NNI goals. However, it emphasizes that any models and metrics applied must be rigorous and able to stand up fully to scientific scrutiny. If the data used are inaccurate or if the models linking data to desired outcomes have not been properly established, evaluation, rational decision-making, and allocation of resources become compromised. For example, the definitions by various stakeholders of what counts as nanotechnology are not consistent and make comparing or combining current analyses difficult or impossible.

The committee observes that data gathered by different agencies cannot now be usefully compared. The measurement systems are not the same. The agencies use different metrics for their R&D programs that are based on a given agency, its mission, and its historical way of doing things. The NNI is being asked to establish definitions of success and associated metrics for fulfilling the overarching NNI goals while meeting the needs and supporting the missions of the NNI participating agencies. To achieve those objectives, there must be both a model (or a set of models) that relates what is measured to the planned NNI outcomes and an accurate measurement system that operates throughout the NNI agencies. With respect to NNI R&D, some outcomes can be measured now; others may be measurable soon with the use of new data-collection and data-mining capabilities. In sum, what is needed to assess the NNI's progress and success are accurate measurement systems and valid models. In general, computational and data capacities have outrun the accuracy of measurement systems and understanding of the phenomena that relate metrics to desired outcomes. The result may be exciting graphical representations whose meaning remains uncertain. A key part of the solution is to get scientists together and to work with the NNI community to develop models that can be tested to validate the measures on the ground. In other words, the NNI could benefit from investing in research on indicators and processes to support the development and effective use of metrics.

The issue of metrics is not peculiar to the NNI. Other federal research programs and the international R&D community also are grappling with the issue of how to measure impact and return on investment. The committee views the present study as an opportunity to stimulate additional discussion on the question of metrics. It believes that metrics and models that relate metrics to outcomes of R&D can and should be developed for the NNI and other government programs. This interim report presents an overview of considerations related to the characteristics of good metrics. The committee's final report will provide specific recommendations on the topic that are based on the concepts presented here.