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Evaluation of the NNI Research Portfolio

BALANCE OF THE RESEARCH PORTFOLIO

Education and Training

The interdisciplinary[1] nature of nanoscale science and technology requires that we implement new paradigms for educating scientists and engineers. The new breed of student must have disciplinary depth but also be unafraid to cross disciplinary boundaries, must be energized by talking with colleagues in other fields, enjoy collaboration, and manage—when appropriate—to work in a team fashion. He or she must learn the languages and methods used by more than one field. While industry has long expected that its employees function well in an interdisciplinary environment, many government-sponsored training programs have only recently begun to address this need. Some of the training opportunities supported by NSF, NIH, DOE, other federal agencies, and private foundations now provide interdisciplinary and collaborative training for students and post-docs.

Research and training opportunities under the aegis of the NNI have been an excellent start for developing a cadre of interdisciplinary researchers. For example, all six of the recently funded NSF Nanoscale Science and Engineering Centers have strong educational components. Some of the centers require that graduate students take courses in fields other than their major field of study, and many have mechanisms to ensure that graduate students talk to their colleagues in other fields. Some centers support only projects in which people from two different disciplines collaborate. Other examples of multidisciplinary, multiuniversity centers include those supported by the Defense Advanced Research Projects Agency (DARPA) under its Bio/Info/Micro program, which focuses on neural processing and biological regulatory networks.

More must be done, however, to create the interdisciplinary and multidisciplinary culture that will be required to realize most of the anticipated advances in nanoscale science and technology, and these interdisciplinary interactions must be fostered and sustained over the long term. Universities must be given incentives to nurture research groups that combine disciplines such as biology, materials science, and engineering. Barriers to the funding of inter- and multidisciplinary research proposals must be removed, and interdisciplinary and multidisciplinary work must be readily publishable in all leading research journals and valued by tenure and promotion committees.

High-Risk vs. Low-Risk Research

Much good work in nanoscale science and engineering is evolutionary in nature—it extends known principles and techniques to smaller size scales but does not demonstrate fundamentally new scientific thinking. This work is valuable and a necessary part of the path to achievement in nanoscale science and technology. But one can anticipate that the biggest payoffs in nanoscale science and technology will come from revo-

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[1] It is important to distinguish *inter*disciplinary from *multi*-disciplinary. *Inter*disciplinary implies that both parties are conversant in multiple disciplines, in contrast to *multi*disciplinary, where parties remain firmly rooted within their own comfort zones but collaborate across the borders of these zones. Interdisciplinary research pushes existing boundaries and challenges the assumptions of each discipline.

lutionary work—work that engenders new paradigms in scientific thinking or fundamentally alters the boundaries between disciplines.

In the experience of the committee members, the current system of funding research proposals tends to favor evolutionary ideas and readily achieved research goals. With a limited pool of research dollars available, proposal review committees favor proposals with the greatest chance of achieving their goals within the funding period of the grant. In fact, early-career researchers often say that they cannot submit proposals for funding until they have already conducted enough experiments to have all but proved the expected result of the proposed investigation—which, of course, they do not have the funding to do.

The NNI has set aside some funds for truly exploratory research—for example, NSF has awarded modest (up to $100,000), 1-year Nanoscale Exploratory Research grants for proof of concept for early-stage ideas. However, the number of these grants is quite limited relative to the potential for fundamental breakthroughs in nanoscale work. The committee recommends that additional high-risk exploratory research should be supported through the NNI.

Short-Term vs. Long-Term Funding

As discussed throughout this report, realizing the potential of nanoscale science and engineering breakthroughs requires meeting several challenges. Establishing and nurturing a robust interdisciplinary culture in science and engineering is critical. Funding truly revolutionary and high-risk research is also necessary. Neither of these challenges can be met without a long-term commitment.

The interdisciplinary and multidisciplinary approaches that are essential for the success of NNI long-term objectives are already in place in some industrial labs. However, they are relatively new to universities and to many of the key funding agencies that support university work. It will therefore be necessary to encourage universities to nurture groups that combine the knowledge from disciplines such as biology, medicine, chemistry, physics, materials science, computer science, and engineering. It will also be important to develop realistic milestones as desirable goals for proposals. For example, although components (such as a transistor) have been shown to be scalable down to atomic dimensions, the integration of these molecular and nanocomponents into useful higher-order structures and devices is still a considerable technological challenge.

Reforms are required to create a scientific culture that better recognizes and rewards research at the interface of disciplines, particularly in universities. Successful fostering of interdisciplinary research groups is complex and difficult. Universities and their departments will have little incentive to begin this arduous process without the promise of support for their efforts for as long as it takes to achieve success. NSF-funded centers provide this incentive to some extent at the universities that host them, but mechanisms beyond centers are needed. Such a cultural transition is a complex undertaking that will take time, which implies the need for a commitment to sustained funding.

As for the funding agencies, a corresponding interdisciplinary knowledge base needs to be established in the program directorates with a long-term view. Also, there may be a need to change the perception that a long-term goal necessarily involves high risk. This may be particularly true for development of new nanomanufacturing processes, which may be technologically complex and difficult but which rest on a sound scientific base. Program directors will need knowledge and backgrounds that cross disciplines such as biology, materials science, and engineering. Only the most dedicated and visionary directors can tear down the barriers, quash the prejudice that exists, and provide the help and guidance their review panels and proposed referees need to make good choices and decisions.

As discussed above, the NSF Nanoscale Exploratory Research (NER) grant provides short-term funding for proof-of-concept for early-stage ideas. If an idea is truly revolutionary, however, or the technical problem being addressed is truly difficult, one year is often not long enough to produce results. Achieving the high-impact successes promised by nanoscale science and technology will require longer-term funding of extraordinarily challenging or revolutionary proposals, even though some proposals receiving such funding will inevitably fail to bear fruit. However, the breakthroughs achieved by even a few such projects can more than compensate for those projects that did not turn out as hoped.

The committee is not suggesting that successful short-term research efforts be abandoned. Indeed, some short-term successes, particularly developments that lead quickly to applications, can be key to garnering and maintaining public support for the initiative. However, the balance between short-term and long-term research needs to be carefully considered. In the committee's opinion, the current balance can and should be shifted more toward the longer term.

One reason for the committee's concern is DOD's FY 2002 and FY 2003 NNI budgets. While defense spending in nanoscale technology and research continues to rise, funding for basic research has declined below FY 2000 levels, in favor of applied research aimed at transitioning scientific discoveries into new technologies. The committee agrees with DOD's desire to transition technologies into defense applications, but this should not occur at the expense of fundamental research. This is particularly true in light of the fact that DOD has been designated as the lead agency for the recently established Grand Challenge CBRE: Detection and Protection.

PROGRAM MANAGEMENT AND EVALUATION

Interagency Partnerships

NSET member agencies have done a much better job of encouraging federal partnerships with industry, universities, and local government than they have of encouraging meaningful interagency partnerships. As it examined NNI activities at the various agencies, the committee recognized the strong and unapologetic focus of agencies on their respective missions. Each agency's response to and involvement in the NNI derives from its efforts to succeed in its mission. It is not inappropriate for federal agencies to focus on their own missions. Yet the breadth of NNI and its fields of interest—from new materials development to quantum computing and from cellular microbiology to national security—calls for agencies to cooperate more meaningfully in their nanoscale science and technology pursuits and to better leverage their investment for mutual benefit. While the NNI implementation plan lists major interagency collaborations, the committee has no sense that there is much common strategic planning in those areas, any significant interagency communication between researchers working in those areas, or any significant sharing of results before they are published in the open literature.

Those effective interagency partnerships that do exist can serve as an example for future partnerships. For example, a multiple agency partnership funded the conference Nanofabrication and Biosystems,[2] which led to some of the intellectual ideas that are currently driving research at the intersection of nanosystems and biology. Conference organizers secured joint funding from the Engineering Foundation, NSF, the Office of Naval Research, DARPA, and NIH. A visionary program manager at NIH worked from inside that organization to ensure that *almost every institute* at NIH contributed to the conference, because he could envision how every institute could benefit from advances in nanotechnology. Another example of an effective multiagency partnership is the support of the Cornell High Energy Synchrotron Source (CHESS), a public-access synchrotron facility. While NSF supports the core facility, NIH supports MacCHESS, which is devoted to biological macromolecular crystallography. This dual support began in 1983.

There are many opportunities for the NSET to develop interagency partnerships that will enhance the rate of nanoscale science and technology innovations. For example, partnerships between NIH and NSET agencies involved in physical science and engineering could greatly accelerate the development of instrumentation and research tools for probing nanoscale biological phenomena and engineering and developing nanoscale devices based on biological systems. NSET member agencies should increase their willingness to participate in interagency cofunding of large programs such as instrumentation centers and groups of investigators working at the interfaces of disciplines such as biology, engineering, and the physical sciences. The committee also recommends that the agencies pay particular attention to the hiring of program directors with an interdisciplinary background or understanding.

Interagency Coordination

The NNI is intended to be a coherent, government-wide effort to promote and accelerate the evolution of nanoscale science and technology through investments made by a federation of participating federal agencies. The success of the initiative to date is due in large part to the leadership of the NSF. Under this leadership, the NNI has organized the major research-sponsoring agencies into a coordinated body, the NSET, with regular meetings and information sharing. It has also attracted participation by other federal agencies that do not focus on research but that could advance their own missions by the applications anticipated from nanoscale science and technology.

NSET forms a solid foundation on which to build an NNI that adds up to more than the sum of its parts.

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[2] *Nanofabrication and Biosystems,* H.C. Hoch, L.W. Jelinski, and H. Craighead, eds. Cambridge University Press, New York, 1996.

However, more is needed to achieve meaningful interagency coordination and collaboration. Greater information sharing among agencies during strategic planning and program execution is called for. Even with increased interagency communication, however, it seems unlikely that NSET agencies, either individually or collectively, can reach outside the box of agency missions to achieve the larger vision required to identify cross-cutting research opportunities with the greatest potential payoff and broadest impact. To this end, the committee strongly recommends the establishment of an ongoing nanoscience and nanotechnology advisory board (NNAB), independent of the NSET agencies. NNAB, while having no formal oversight of NNI, would provide advice to NSET on research investment strategy, program goals, and coordination of strategy and program execution between agencies. It would be capable of identifying research opportunities that do not fit within any single agency's mission. NNAB should be composed of leaders from a broad representation of industry and academia. They should be leaders with scientific, technical, social science, or research management credentials relevant to advances in nanoscale science and technology.

One can envision several ways to set up such an advisory board. First, it could be set up by NSET itself, with each NSET agency nominating members. However, since the objective is for NSET to obtain fresh ideas and independent advice, such a mechanism might remained tied to individual agency perspectives and to sources of advice that are already available to the agencies. The advisory board could be established under the National Science Board; however, that organization is associated closely with the NSF, and an entity established under its aegis would be perceived as biased toward the needs of the NSF. The NRC is another possible means of obtaining such advice, and while certain aspects of the NNI might benefit from a continuation of the deliberative, consensus assessment that the NRC can provide, the committee envisions the NNAB as a more flexible body, capable of giving real-time, nonconsensus advice. On consideration of the possible alternatives for the NNAB, the committee believes OSTP might be the most appropriate home for such a body. An OSTP-administered board would be independent of the NSET agencies and thus would not be vested in the mission of any single agency. It would have sufficient cachet to attract the participation of the best, most forward-looking leaders. Being housed within the government, it would be an appropriate body to give the type of direct programmatic advice that the committee believes is needed. The President's Information Technology Advisory Committee (PITAC), administered by OSTP, provides an example of the type of advice mechanism the committee believes would benefit NNI and the NSET.

Evaluation of the NNI

So far, NNI has been funded for only 2 fiscal years, and it is not yet in the mature stages of program execution or evaluation. To date, the initiative programs have been evaluated as part of the Government Performance and Results Act (GPRA) procedures of the individual participating agencies. The committee notes that, while it was given much information on the NNI, its development, and its continuing programs, if established evaluation criteria for the NNI as a whole had been provided, along with information geared to those criteria, it could have been greatly helped in its assessment. The committee sees a need to measure the progress of the NNI as a whole and to consider the results of these measurements at the level of NSET and the proposed NNAB.

Despite a long history of efforts to define and improve evaluation criteria for research activities, the academic, industrial, and government sectors all continue to struggle with this problem. However, once program goals and objectives are established, exit criteria and related measurable factors can be developed to appropriately measure effectiveness or success against these goals and objectives. Possible measurable factors for NNI programs could be quality, relevance, productivity, resources, and movement of research concepts toward applications. Appropriate indicators and evaluation processes for these evaluation factors are indicated in Table 3.1.[3]

In developing evaluation criteria for the effectiveness of a research program or organization, the follow-

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[3] The Bush administration has requested that OMB, along with OSTP, establish criteria for selecting basic and applied research activities the federal government should support (prospective review), as well as metrics to measure the outcomes of basic and applied research (retrospective review). OMB is currently proposing preliminary criteria for quality, relevance, and performance to evaluate federal research activities. These criteria were adopted from Committee on Science, Engineering and Public Policy (COSEPUP), *Evaluating Federal Research Programs: Research and the Government Performance and Results Act, 1999,* and studies on developing research metrics supported by the Army Research Laboratory.

TABLE 3.1 Possible Evaluation Scheme for the NNI

Evaluation Factor	Key Indicators	Evaluation Process
Quality	Technical merit, originality, soundness of approach, innovation	Peer review
Relevance	Impact on mission or significant payoff; keyed to strategic or objective indicators	Board of directors, customers
Productivity	Documented progress or results as cited in publications, citations, patents, recognition awards, invited presentations	Peer review
Resources	Adequacy of personnel and resources, including students, equipment, and supporting facilities	Peer review
Transition	Handoff of concepts to applications domain. Concepts generated met exit criteria or strategic objectives, generated new projects, generated novel workshops and symposia, and educated or trained students/personnel	Board of directors, customers

ing caveats should be noted: (1) the research metrics should be consistent with the unique goals of the organization; (2) the metrics should build in risk, originality, and flexibility; (3) they should be drawn, used, and applied with consistency and with full consensus of the tech-base management; (4) in basic research, the customer is not always the best judge of long-term impact; and (5) metrics are designed not to initiate new programs, but to measure the effectiveness of evolving programs.

Strategic Plan

The NNI would benefit from a crisp, compelling, overarching strategic plan. The plan would articulate short- (1 to 5 years), mid- (6 to 10 years), and long-range (beyond 10 years) goals and objectives. It should emphasize the long-range goals that move results out of the laboratory and into the service of society.

The FY 2001 and FY 2002 implementation plan for the NNI is quite detailed and ambitious, and it covers a broad spectrum of good research and development opportunities. However, the plan appears to have been developed largely as pieces within individual agencies, each of which is driven by its own mission. While the outcomes of the NNI as a whole are articulated, the various themes of the NNI are overlapping and their goals are not specific.

For example, the NNI has established 12 Grand Challenges that are "essential for the advancement of this field"; together, they will receive $180 million in FY 2002. According to NNI documents, these challenges will be met through interdisciplinary research and education teams, including centers and networks that work on long-term goals. However, in reviewing two other NNI themes, (1) Long-Term Fundamental Nanoscience and Engineering Research and (2) Centers and Networks of Excellence, the committee found it difficult to distinguish the primary goals of these two themes from the goals of the Grand Challenges. While the two themes may be designed to help achieve the scientific and engineering goals of the Grand Challenges, it is not clear how the themes tie in to the Grand Challenges, or how the themes will be evaluated. Further, while potential scientific and technological breakthroughs associated with the Grand Challenges have been identified, it is not clear which challenge is associated with which breakthrough.

The committee recommends that, as part of the NNI strategic plan, the Grand Challenges be rewritten (each limited to one page). Each should focus on a current scientific problem, propose a research plan to address that problem, and offer metrics for measuring progress in solving the problem. The strategic plan should designate a lead agency for each Grand Challenge, as well as other agencies that will be involved in the research. However, designation as a lead agency should not be interpreted as giving an agency ownership, which could become a barrier to interagency cooperation, priority setting, and research participation. NSET should utilize the NNCO to facilitate interagency participation and coordination. The strategic plan should include anticipated outcomes and estimated time frames for achieving those outcomes. The committee also recommends that NSET try to prioritize the Grand Challenges in terms of their relative scientific and strategic importance. For example, given the recent change in our nation's domestic national security environment, it might be appropriate for the recently established Grand Challenge CBRE: Detection and Protection and the previously established Grand Challenge Bionanosensors for Communicable Disease and Biological Threat Detection to be given additional resources to meet near-term security needs.

The strategic plan should also address development of scientific instruments and infrastructure to support those instruments. Historically, many important advances in science came only after appropriate investigative instruments had become available. One must be able to measure and quantify a phenomenon in order to understand and use it. Thus, it is critical that we develop new tools that will allow quantitative investigations of nanoscale phenomena.

Simulation tools are also an essential part of infrastructure development. The formation of a network that encompasses nanostructure simulation from the atomic level to macroscopic fields and large systems would be desirable. Such a tool would allow researchers to test material characteristics and synthetic paths virtually, allowing the design of more efficient, less expensive experiments and bringing together researchers from various disciplines that use similar computational approaches—for example, chemists, physicists, and electrical engineers, of whom all use density functional theory. It would serve as a guide for the design of industrial applications and as a predictive tool for integrating larger and larger systems based on nanoscale components.

Congress recently approved the establishment of a new NIH institute, the National Institute of Bioimaging and Bioengineering. The new institute could offer a pivotal opportunity to advance facilities, instrumentation, and simulations in support of nanotechnology. Special attention should be paid in the planning of this new institute, which could provide a strong focus for equipment and infrastructure development at the interface between engineering, the physical sciences, and biology.

NATIONAL NANOTECHNOLOGY INITIATIVE PARTNERSHIPS

In developing nanoscale science and technology as a competence of the national scientific and industrial establishment, the federal government must promote, cooperate, seed, and leverage. The NNI has promoted an impressive array of research and technology development activities across numerous agencies and organizations. In addition, the U.S. initiative has been the impetus for initiatives in other countries and has brought inflows of private capital to emerging industrial applications of products deriving from nanotechnology. In essence, the NNI has leveraged the direct investment of the U.S. government by initiating a capital flow for nanoscale science and engineering that is several times as large.

There are important historical examples of leveraging government research funding. The initial investment by the United States government (through DARPA) that created the Arpanet and the initial investment by European governments (through the European Organization for Nuclear Research (CERN)) that created the World Wide Web have been leveraged over many orders of magnitude by private investment in the Internet. The government investment in biomedical research has been leveraged many times over by the investments of pharmaceutical companies.

A particularly successful example of leveraging by partnership is provided by Sematech, a highly successful public-private partnership in which federal funding encouraged billions of dollars of private investment, drove the microelectronic revolution forward, and ensured U.S. leadership. U.S. semiconductor manufacturers worked together on several highly specific problems, with assistance and funding from the DARPA. The partnership produced a semiconductor roadmap—a detailed chart of technological and manufacturing capabilities the industry needed to address in order to become and remain internationally competitive. This joint government-industry effort helped the United States to regain world leadership in an important industry. In the case of Sematech, demand-side input from industry sharpened the public sector research agenda. This input helped investigators to focus their energies on fundamental and applied issues that had the best potential for commercial outcomes. Although it may be too early to apply the Sematech model to nanotechnology, the committee suggests that one can learn from the successes of the past.

A broad array of institutions and nations are now investing in nanoscale science and technology. Given finite resources, remaining the leader in nanoscale science and engineering will require that the United States form judicious partnerships with these other entities to ensure that it has access to the latest developments. Partnerships offer a mechanism for leveraging investments in technology development and for accelerating the rate of technological advance. NNI partnerships could involve any mix of government, academic, industrial, or international participants.

University-Industry Partnerships

The experience of committee members indicates that university-industry collaborations in nanoscale science and technology are on the rise, many of them the result of collaborations between individual faculty members and their colleagues in industry. Others come about through faculty consulting agreements with individual firms. Many NSF-funded science and engineering centers at universities have industrial collaborations and outreach. Industrial collaboration is strongly encouraged in NSF's Nanoscale Interdisciplinary Research Teams (NIRT) program. In FY 2001, NSF spent $56 million for 43 separate NIRT awards, one-third of which included industry participation. In September of 2001, NSF announced the establishment of six large university-based nanoscale research and engineering centers, which will receive $65 million over 5 years.[4] Each of the six centers is required to have industrial partners collaborating in its research. Although these centers focus on producing basic scientific advances and successful graduates, their effectiveness in technology transfer is evaluated when the centers are reviewed for renewal of funding. NSF should also consider trying to use its well-respected and highly leveraged Industry/University Cooperative Research Centers (IUCRCs) program as a vehicle for supporting centers that focus more on industry.

State-Funded Partnerships

It is important to recognize that the states are also important partners in the commercialization of technology. Most states have an equivalent of New Jersey's Commission on Science and Technology, which invests in the commercialization of high-tech areas with the goal of job creation. Furthermore, most states are willing to become full partners by providing matching funds on major federal grants for science and technology to their state universities. Several states have efforts geared to developing local competence in nanoscale science and engineering. These efforts generally involve nucleating partnerships at research centers at state universities. These state-funded efforts have the goal of transforming basic research in the university into industrial products to create jobs for the local economy. The centers discussed below are examples of how states use their investments to attract matching funds from industry and the federal government.

The state of California has committed $100 million over 4 years to fund the California Nanosystems Institute (CNSI), which is colocated at the University of California at Los Angeles and at Santa Barbara. The state funding consists of $95 million for buildings on both campuses and $5 million for administration and is intended to attract federal research funding. In addition, CNSI has promises of funding from corporations for $46.7 million in the first year. The companies include large corporations such as Hewlett-Packard, Intel, and Sun Microsystems, as well as much smaller firms. CNSI plans dedicated "incubator" laboratories where industry researchers, faculty, and students can work together on precompetitive projects. Some results of this collaboration are shown in Box 3.1.

The Center for Nano- and Molecular Science and Technology (CNM) at the University of Texas at Austin comprises three multidisciplinary research groups studying bioelectronics materials, molecular nanoscale electronic materials, and quantum dot and quantum wire nanoscale materials. Faculty from departments as diverse as biomedical engineering, chemistry and biochemistry, physics, chemical engineering, and electrical and computer engineering are involved in research at the center. In addition to state support, CNM receives support from the Welch Foundation. The existence of CNM has galvanized local businesses in support of nanoscale development. The resulting Texas Nanotechnology Initiative (TNI), initially funded by Texas-based companies and venture capital investors, is developing a consortium of interested parties from industry, academia, and government. They hope to create a competitive cluster for nanodevelopment in Texas, much as a Silicon Valley is such a cluster for the computer and software industries. TNI hopes that by attracting sufficient state and national funding, Texas can also attract talented researchers, thereby then drawing major corporate facilities to the state.

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[4] The six centers are located at the following universities: Columbia, Cornell, Harvard, Northwestern, Rice, and Rensselaer Polytechnic Institute.

BOX 3.1
Circuits Smaller Than Cells

The DARPA Molecular Electronics Program has enabled a collaboration between Hewlett-Packard Laboratories and the University of California at Los Angeles. HP contributes over half the funding for this joint research, but without the catalyst of NNI funding no company would have the interdisciplinary resources, ranging from computer architecture to organic chemistry, required to create functioning electronics at the molecular scale. The HP-UCLA work is aimed at reinventing the integrated circuit at a molecular scale using chemistry to self-assemble very simple nanoscale circuits consisting of a layer one molecule thick sandwiched between two layers of perpendicular wires as in Figures 3.1.1 and 3.1.2. The complex integrated circuit design is then downloaded into the molecules through the nanowires. Such a system could eventually allow industry to overcome the fundamental limits to miniaturization imposed by current lithographic techniques.

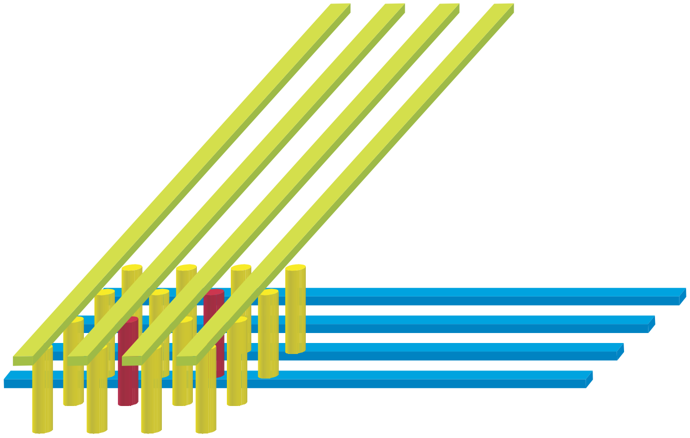

FIGURE 3.1.1 The architecture: Molecules trapped between nanowires act as memory bits.

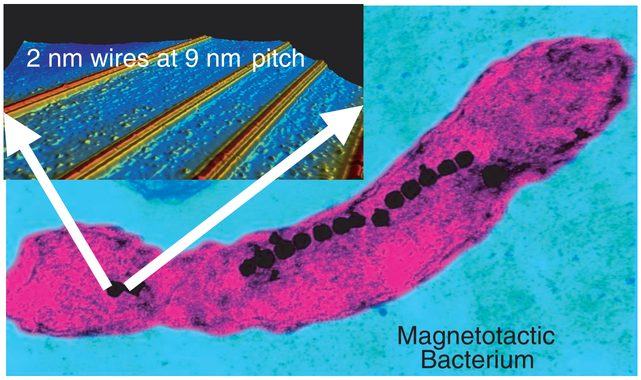

FIGURE 3.1.2 Hewlett-Packard's chemically formed nanowire array, showing the scale relative to 30 nm magnetic particles in a bacterium. Reprinted with permission of the American Association for the Advancement of Science from Frankel et al., *Science* 203, 1355 (1979). © 1979 by AAAS.

These two examples are only illustrative. Significant efforts exist in other states and even in regions (one example is the Center of Excellence in Nanoelectronics at the University of New York at Albany). All of these centers have firm objectives for putting in place local infrastructure for nanoscale science and technology and corresponding legislative support. They also demonstrate the impact that federal funds can have on achieving local objectives.

The NSET needs to monitor state and local investments in nanoscale science and engineering and coordinate its efforts with those of state and local agencies in order to leverage those investments.

Federal-Industry Partnerships

Nanoscale science and technology have seen several indicators that their fruits are moving toward commercialization. A number of new start-up companies have emerged in this area, and more than a dozen annual conferences have been organized to assist emerging nano players, from companies to investors to entrepreneurs, in assessing and evaluating potential business approaches. Venture investors are sponsoring conferences in nanoscale science and technology, and a number of these firms are infusing nanotech start-ups with needed capital. A limited number of venture firms are targeting nanoscale science and technology and related “small science” subjects such as microelectromechanical systems (MEMS), microfluidics, and nanomaterials as focus areas for their future investment. As a result, cumulative investment sums in such companies continue to grow, at least in part owing to the federal investment in the NNI. While such private capital investment is rarely being channeled into basic research and is not building infrastructure, it does fund new tools, applications, and innovations that utilize elements of nanoscale science and technology and it does contribute to the expanding fabric of nanoscale science and technology as a core industrial competence in the United States.

Overall, federal agencies need to establish mechanisms for leveraging federal assets and infrastructure through industrial partnerships while satisfying mission-based and program-based requirements. Several mechanisms are in place to foster these partnerships.

Small business innovation research (SBIR) and small business technology transfer (STTR) federal grants focus on providing support for science and technology developments in small firms. Within the NNI, DOD (including the four Services and DARPA), DOE, NASA, NIH, and NSF support both phase I and phase II SBIR and STTR activities.[5] Most of DOD’s SBIR/STTR activities have focused on material sciences and engineered biomolecular nanodevices. NSF has supported research on nanomaterials for electronics (functional nanostructures with at least one characteristic in the size range from molecular to 100 nanometers) and biotechnology fabrication involving biomolecules and/or biosystems for potential commercial applications. NASA SBIR/STTR efforts have supported work in the area of material fabrications, including nanopowder synthesis in a microgravity environment and lightweight, long-lasting power sources. DOE recently published an SBIRR/STTR program announcement on economical superplastic forming, with the goal of reducing the cost of manufacturing such materials.

Two additional types of industry-government partnerships, cooperative research and development agreements (CRADAs) and the Advanced Technology Program foster joint research in nanoscale science and technology in very different ways. CRADAs are used by federal agencies to advance mission-critical research and development activities through in-kind federal contributions to a project with an industrial partner. CRADAs also help transfer federally developed technology to the private sector for industrial development. In December 2001, the National Cancer Institute announced two CRADA opportunities specific to nanoscale science and technology.

The ATP funds high-risk research having potentially high economic payoff, granting federal funds but requiring matching funds from the industrial partner. In 2000 and 2001, ATP funded six projects involving nanoscale science and engineering. Note that this ATP funding is not managed as part of the NNI.

Moving nanoscale technologies into commercialization requires industrial players to have confidence in the ability of the emerging technology to provide a

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[5] Under SBIR, small companies (fewer than 500 employees) can apply for a 6-month award of $60,000 to $100,000 to test the scientific, technical, and commercial feasibility of a particular concept. If phase I proves successful, companies are encouraged to apply for a 2-year agency phase II award of between $500,000 and $750,000 to further develop the concept or a prototype. In phase III, small businesses are expected to obtain funding from a private sector firm or a non-SBIR government source to transfer the proven concept into commercial production. In 1992, Congress established the STTR pilot program. STTR is similar in structure to SBIR but funds cooperative R&D projects involving a small business and a research institution (i.e., a university, a federally funded R&D center, or a nonprofit research institution).

competitive advantage in the marketplace. That confidence is a function of both the scalability of the new technology and the strength of the intellectual property (IP) claims that a company can stake on it. Federal agencies should examine their intellectual property policies, particularly when partnering with industry, to ensure development of IP that will be conducive for commercialization.

To encourage technology that will have an economic impact, NSET should establish a procedure for evaluating competing nanoscale technologies. This evaluation should be used to ensure that government funding is available in critical areas in the early years of a technology's development.

Monitoring Partnerships

In its deliberations, the committee found it difficult to assess the number of partnerships encouraged by the NNI Working Group, the fraction of funds that involved partnerships, and the effectiveness of these partnerships.

NSET needs a long-term procedure for monitoring the success and effectiveness of partnerships in nanoscale science and technology, as well as the fraction of funds coming from sources other than the federal government. Properly monitored, these data will also help social scientists determine the role of partnerships in advancing this technology.

International Partnerships

The United States, while currently leading in nanoscale science and technology, is not the only country conducting research and development. Economically developed countries worldwide have initiated government-sponsored programs in nanoscale science and technology development in response to U.S. leadership in this area and have committed significant resources. Worldwide, investments in nanoscale science and technology development more than tripled between 1997 ($432 million) and 2001 ($1,619 million), with the highest rate of increase in 2001, as shown in Figure 3.1. More than 30 countries have national activities in nanoscale science and engineering. The scale of this funding is indicated in Table 3.2. The U.S. initiative, NNI, is the largest and broadest initiative in the world. The programs of other nations have generally been targeted at specific national interests, complementing existing industrial strengths and advancing their specific competency as a matter of choice. Many of these worldwide investments focus on developing local research networks that promote development.

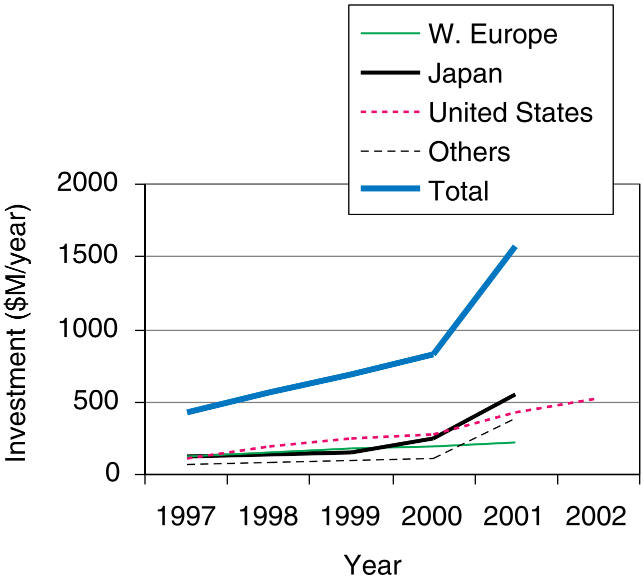

FIGURE 3.1 International government funding for nanotechnology R&D as of April 2002. Data are based on information collected from government programs by M. Roco, NSF. 2002 figures are estimates.

TABLE 3.2 Estimates for Government Nanotechnology R&D Budgets (million dollars)

Area	2000	2001	2002 Preliminary
Western Europe	200	225	400
Japan	245	465	750
United States	270	422	604
Others	110	380	520
Total	825	1,492	2,274
(% of 2000)	(100%)	(181%)	(276%)

NOTE: "Western Europe" includes the European Union and Switzerland; rate of exchange is $1 = 1.1 Euro. Japan rate of exchange $1 = 130 yen. "Others" includes Australia, Canada, China, Eastern Europe, countries of the former Soviet Union, Korea, Singapore, Taiwan, and other countries with nanotechnology R&D. A financial year begins October 1 in the United States and March 1 or April 1 in most other countries.

SOURCE: M. Roco, NSF. Estimates as of June 2002.

The number of such industrial-sector-oriented networks that exist worldwide is increasing. Moreover, regional alliances are increasingly important in maintaining globally competitive markets, which leads to increasing regional economic, trade, and technology cooperation. To maximize their national investments, countries are developing strategies that focus on areas that leverage local industry. In nanoscale science and technology development, the direct analogy is that regions are increasingly specific about the nanoscale science and technology topics they are supporting as a group, creating regional technology-specific competitive clusters. Box 3.2 provides a quick look at international activity in nanoscale science and technology.

Rationale for International Partnership

International collaboration in fundamental research; long-term technical challenges; education; and understanding of potential societal implications will play an important role in the growth of nanoscale science and

BOX 3.2
International Nano Activity

Nanotechnology will drive industrial competitiveness and manufacturing prowess in the 21st century. The implementation of the U.S. National Nanotechnology Initiative (NNI) has convinced governments and researchers around the world that nanotechnology will bring sea changes to whole industries. The United States has the broadest base of fundamental nanotechnology research, and its universities are training the next generation of nano scientists and engineers. While NNI builds strength in technology infrastructure at research centers and universities, numerous international programs focus on industrial competitiveness in other countries. U.S. NNI leadership in nanotechnology has continued as federal funding is proposed that will top $700 million in 2003, supporting more than 2,000 nanotechnology research projects. The effects of this initiative will be felt in virtually every industrial domain because nanoscale science and technology span fields from bioscience and chemistry to computing and medicine. At the same time, these novel technologies have led to a worldwide nanotechnology race, with countries in Europe and Asia targeting programs that are equivalent to those in the United States. Indeed, total foreign government funding has more than tripled over the last 5 years and now exceeds U.S. spending by a factor of more than 2.

At the end of 2001, at least 30 countries had initiated national nanotechnology programs (see Figure 3.2.1). The research base is particularly strong in technologically advanced countries, including Japan, Korea, Taiwan, China, Switzerland, Germany, France, Belgium, the Netherlands, and the Scandinavian countries. Funding for these programs supports competence centers as well as collaborations between academic institutions, national laboratories, and, many cases, corporations. European areas of application range from metrology and precision engineering to nanomaterial processing and nanorobotics. In the Asia-Pacific region, national programs range from a broad-based research program in Japan to Taiwan's targeting advances in nanoelectronics to China's program focused on nanomaterials and processing. Smaller initiatives are ongoing in countries ranging from Canada and Australia to the eastern European countries, including Russia and the Ukraine.

FIGURE 3.2.1 Countries with nanotechnology research programs.

technology. Many nanoscale scientific problems are complicated, and international collaboration will hasten their solution and the application of these solutions in commercial products. Countries developing nanoscale science and technology as a competence must build strong interdisciplinary collaborations. Government policies are already promoting this in many countries, particularly in Europe. As other countries aggressively pursue international partnering opportunities in nanoscale science and engineering, the United States will retain its world leadership in the field only if it is viewed as the collaborator of choice.

International collaboration can be in the best interests of national security. The CIA estimated that approximately one in four new technologies is likely to threaten U.S. political, economic, and military interests by 2015. Familiarity can breed friendliness rather than contempt, and U.S. participation in international collaborations can lessen the risk that nanoscale technologies are turned against us. Furthermore, by participating in open international collaborations and sharing research results, the United States will demonstrate that these technologies are not being developed for offensive purposes.

Opportunities for International Partnership

The exchange of ideas on a person-to-person basis is an important form of international collaborations. Collaborations are fostered through partnerships between individual investigators in different countries, through sabbaticals abroad for U.S. and foreign researchers, and through students who study abroad. About one-third of the individual investigator activities under the NSF Functional Nanostructures programs have international collaborations. NSF has also sponsored young researchers for group travel to Japan, Europe, and other areas to present their work and visit centers of excellence in the field. Bilateral and international activities with the European Union, Japan, Korea, India, Switzerland, Germany, and Latin America have been under way since 2000. U.S. universities also have many foreign science and engineering graduate students. These interactions, which reflect the international character of scientific research, are clearly valuable and should be encouraged. NSET should remain alert for additional opportunities to foster such interactions.

While single and small-group investigators perform most nanoscale R&D, large research centers play an essential role by nucleating interdisciplinary research and providing the facilities for experimentation and measurement. A large proportion of the worldwide investment in nanoscale science and technology has been devoted to the establishment of focused research centers (see Table 3.3). U.S. participation in international research centers devoted to nanoscale topics is one way of developing the international partnerships required to maintain a U.S. lead in this area. The United States has long participated in such partnerships, and the experience gained and successes achieved in past partnerships such as CERN can be used as models for nanoscale work.

The NNCO reports two important sources of information about international activities in nanotechnology. The London office of the Office of Naval Research attempts to track European R&D activities, while information on activities in Asia is gleaned from commercial sources, including the Asian Technology Information Program (ATIP) technical bulletin. This information is critically important for understanding the relative merits of U.S. programs, sponsored initiatives, and competitive position. NSET should consider sponsoring broader tracking, correlation, and dissemination of information on global nanoscale science and technology developments. This information should be used to develop a global strategy in nanoscale science and technology for the United States, determining priorities and opportunities for interactions with other nations.

RELEVANT SKILLS AND KNOWLEDGE

The data presented to the committee on the current NNI research portfolio indicate that projects being funded are indeed relevant to the continued development of nanoscale science and technology. Many world-class university researchers in a variety of disciplines are being funded under the auspices of this initiative. Federal laboratories have directed monies toward mission-relevant programs involving nanoscale research. Current programs appear appropriate. However, the committee is concerned that certain key areas of training may not be receiving sufficient attention from the NNI. To realize the potential benefit of nanoscale science and engineering requires greatly improving the environment for interdisciplinary training and research, along with attention to future generations of workers through K-12 education.

Interdisciplinary Culture

Nanoscale science and technology are leading researchers along pathways where many different dis-

TABLE 3.3 Examples of Nationally Sponsored Nanoscale Technology Development Centers

Country	Nanotechnology Networks/Centers	Country	Nanotechnology Networks/Centers	Country	Nanotechnology Networks/Centers
Americas		Asia		Europe	
United States	Nanoscale science and engineering centers: RPI, Northwestern, Cornell, Harvard, Columbia, Rice University	Taiwan	Industrial Technology Research Institute	European Commission	European Consortium on Nanomaterials, Network on Nanoelectronics, Information Society Technologies Nanoelectronics Network (PHANTOMS)
	DOE nanoscience laboratories: Los Alamos, Lawrence Berkeley, Sandia, and Oak Ridge national laboratories	Korea	Seoul National University, Photonics Technology Institute, Nanodevice R&D Network	Belgium	Microelectronics Center, Leuven
	Distributed Center for Advanced Electronic Simulation (DESCARTES): University of Illinois at Urbana, Purdue, Stanford, Arizona State University	China	National Nanotechnology Research Center	Italy	Milan, Rome, Lecce, and others
	National Nanofabrication User Network: Cornell, Penn State, Stanford, Howard, University of California at Santa Barbara	Australia	CSIRO Nanotechnology Group, University of Technology at Sydney, University of New South Wales	United Kingdom	Universities of Birmingham, Leeds, Greenwich, Liverpool, Newcastle, Sheffield, Sussex, Surrey; Cambridge, Cranfield, Durham, Nottingham, Oxford, Southampton, Warwick University
	NASA science laboratories: Langley, Ames, Jet Propulsion Laboratory	Japan	Silicon Nanotechnology Center, Institute of Nanomaterials, Nanotechnology Research Center–RIKEN, National Institute of Materials Science, Tohuko, Osaka, Kyushu, Tokyo University, Himeji, and Tokyo Institute of Technology	France	University of Paris, French National Scientific Research Center (CNRS), Electronics and Information Technology Laboratory (LETI), Institute for Micro and Nanotechnologies (MINATECH), Materials Elaboration and Structural Studies Center (CEMES)
	Materials research science and engineering centers: Columbia, Cornell, Harvard, Johns Hopkins, Massachusetts Institute of Technology, Northwestern, Universities of Kentucky, Oklahoma, Arkansas, Pennsylvania, and Wisconsin			Netherlands	Technical University of Delft, University of Twente, STT Netherlands Study Center for Technology Trends
	Nanobiotechnology Science and Technology Center: Cornell University			Germany	Advanced Microelectronics Center, Technical University of Berlin, Franhofer Institute, Institute for New Materials, Physikalisch-Technische Bundesanstalt Braunschweig, Institute for Solid State & Materials Research, Forschungszentrum Karlsruhe, Center for Advanced European Studies and Research, Institute for Carbon Reinforced Materials, Universities of Munich, Hamburg, Tuebingen

continued

TABLE 3.3 Continued

Country	Nanotechnology Networks/Centers	Country	Nanotechnology Networks/Centers	Country	Nanotechnology Networks/Centers
Americas		Eastern Europe and Middle East		Europe	
	Centers/laboratories at Clemson, Princeton, Rice, Rutgers, Dartmouth, Yale, Georgia Tech, New Jersey Institute of Technology, North Carolina State, Universities of Michigan, Cincinnati, Nebraska, North Carolina at Chapel Hill, Notre Dame, Washington; Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, California NanoSystems Institute	Israel	Tel Aviv, Technion, Hebrew, Ben Gurion Universities	Denmark	Technical University of Denmark, University of Copenhagen
		Romania	Nanotechnology Center, National Institute of Microsystems, National Institute of Physics, Nanostructured Materials Center	Switzerland	University of Basel, Swiss Center of Electronics and Microtechnologies (CSEM), Institute of Experimental Physics (IPE), Swiss Federal Institute of Technology, Zurich (ETHZ), Swiss Federal Institute of Technology, Lausanne (EPFL), Paul Scherrer Institute

ciplines converge—biology, physics, chemistry, materials science, mechanical engineering, and electrical engineering, to name several. Such a convergence was unimaginable to most researchers and educators only 15 years ago. Indeed, each discipline still has its own set of required knowledge and skills that must be transmitted to the next generation of researchers, nor are the prescribed courses of study generally designed to expose students to concepts outside the discipline. While some efforts have been made by the scientific and engineering community to broaden the exposure of students to other fields—chemists to biology, for example—most of our educational system is not producing researchers who are capable of engaging in research that crosses disciplinary boundaries. Even now, the standard training pathway for biologists does not provide them with quantitative skills, despite the fact that the highly quantitative areas of genomics and bioinformatics are transforming the practice of molecular biology. Students in the physical sciences and engineering can generally obtain an advanced degree without exposure to the life sciences. Furthermore, in some traditional disciplines, tenure and promotion can be difficult to obtain for those who work across departmental and field boundaries. The overall value system used by the community to judge scientific quality continues to discourage interdisciplinary research, with negative consequences for tenure, promotion, and the awarding of research grants. These situations conspire to make it difficult to ensure that we will have a cadre of highly trained people to push the frontiers of nanoscale science and technology.

However, as happened with biology in the early 1970s, it is likely that the excitement of nanoscale science and technology will pull more students into the field. This is likely to result in federal agencies funding more graduate students and post-doctoral fellows, which is likely, in turn, to result in the creation of additional loci of interdisciplinary competence at the nation's research universities.

K-12 Education

Many reports produced by various institutions have pointed to the need to improve K-12 science and mathematics education in order to ensure that the next generation will have the skills necessary not only to continue advances in science and technology, but also to be able to fill the jobs in the manufacturing and services sectors that advances in nanotechnology will create. The potential of nanoscale science and technology to bring about major advances in medicine, computer science, manufacturing, and many other fields makes this need more urgent.

Almost all of the NSF-funded nanoscale science and engineering centers have a component that reaches out to children in grades K-12. However, the NNI could develop a much more coherent program for K-12 outreach and education. These activities should include programs to introduce K-12 science and math teachers to nanoscale science and technology.

SOCIETAL IMPLICATIONS AND THE NATIONAL NANOTECHNOLOGY INITIATIVE

The fifth NNI funding theme deals with the social implications of nanoscale science and technology, including education and training issues, and provides a mechanism for using social science methods to gain a better understanding of the social processes that might affect or be affected by nanoscale science and technology. The committee was charged with assessing whether "NNI gives sufficient consideration to the societal impact of developments in nanotechnology."

On balance, the rationales for addressing societal implications within NNI seem particularly compelling:[6]

• *The development of radically new nanotechnologies will challenge how we educate our scientists and engineers, prepare our workforce, and plan and manage R&D.* As other parts of this report have pointed out, the ability of the United States to produce the scientific and technical breakthroughs needed for a nanorevolution will require significant changes in the country's R&D system. Many, if not most, of the really important scientific breakthroughs in nanoscale science and technology and supporting areas will occur at the intersection of different disciplines and fields, and some may result in the creation of new disciplines. This will require truly interdisciplinary collaborations between fields like biology and physics at a scale and intensity that may be unprecedented. It will also require significant changes to the curricula and training experiences offered to our undergraduate and graduate students, to the preparation received in K-12, and to the way we train our workforce. In addition, timely and successful commercialization of the breakthroughs that come from our scientific work will require effective, ongoing communication and collaboration between the public and private sectors. As a consequence, the nation needs to develop education-, training-, and partnership-based initiatives to meet these challenges.

• *The social and economic consequences of nanoscale science and technology promise to be diverse, difficult to anticipate, and sometimes disruptive.* The title of the IWGN report *National Nanotechnology Initiative: Leading to the Next Industrial Revolution* reveals many of the expectations the United States has for nanoscale science and technology. However, if the nanorevolution lives up to the hype comparing it to the industrial revolution, it will also transform and perturb labor and the workplace, introduce new worker safety issues, affect the distribution of wealth within and between nations, and change a variety of social institutions, including our medical system and the military. While these kinds of transformations occurred with other technological advances and were managed reasonably well, there are reasons to believe the transformation propagated by a nanorevolution may be particularly challenging. Nanoscale science and technology are likely to affect and transform multiple industries and affect significant numbers of workers and parts of the economy. "Technological acceleration," the increasing rate of discovery in some disciplines, most notably biology, and the synergy provided by improvements in information and computing technologies have the potential to compress the time from discovery to full deployment for nanoscale science and technology, thereby shortening the time society has to adjust to these changes.[7] Speculation about unintended consequences of nanotechnology, some of it informed but a lot of it wildly uninformed, has already captured the imagination and, to some extent, the fear of the general public.

Some technologists, such as those in the nuclear power and genetically modified foods industries, have ignored these kinds of challenges and suffered the consequences. Others, most notably those in the molecular biology community, have attempted to address the issues and to use their understanding to stimulate an informed and objective dialogue about the choices that can be made and the directions taken.

• *Nanoscale science and technology provides a unique opportunity for developing a fuller understand-*

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[6] In preparing this section the committee drew heavily on material included in the recent NSET-sponsored workshop "Societal Implications of Nanoscience and Nanotechnology," September 2000.

[7] Newt Gingrich, presentation at the NSET-sponsored workshop "Societal Implications of Nanoscience and Nanotechnology," September 29, 2000.

ing of how technical and social systems affect each other. As the NSET-sponsored workshop on societal implications[8] concluded, we currently do not have a comprehensive and well established knowledge base on how social and technical systems affect each other in general, let alone for the specific case of nanoscale science and technology. This state of affairs is a byproduct of not having a chance to examine these interactions until the systems are well established and of simply not investing sufficient resources in these activities. However, nanoscale science and technology are still in their infancy. Thus, a relatively small investment now in examining societal implications has the potential for a big payoff.

Societal Implications Activity Within the Initiative

A variety of documents containing budget information on NNI and social implications were made available to the committee. Unfortunately, the documents mixed budget requests with actual expenditures. Moreover, reports of expenditures differed from source to source and sometimes did not reconcile within a source. According to these sources, the funding committed to societal implications for FY 2001 appears to range between $16 million and $28 million. To understand actual funding commitments, the committee contacted agencies and asked them to provide data on resources expended and efforts undertaken in this area for FY 2001. Two agencies, NIST and NIH, reported no activity or expenditures in the area. DOD indicated that it had made 46 awards under a nano-focused fellowship program within the Defense University Research Initiative on Nanotechnology. NSF reported committing roughly $8 million to activities in this area. While it is possible that some agencies are underreporting their efforts in this area, depending on the value of DOD fellowship support, there appears to be a gap of somewhere between $8 million and $20 million in support budgeted and support expended for NNI societal implications activities during FY 2001. NSF appears to be the only agency to have engaged in major efforts to study societal implications during 2001.

NSF was relatively proactive in soliciting nano-focused proposals: It carried out two NSF-wide solicitations (NSF 00-119, FY 2001, and NSF 01-157, FY 2002). These solicitations mentioned all NNI themes, including societal implications, and requested proposals for nanoscale science and engineering centers (NSEC), nanoscale interdisciplinary research teams (NIRT), and nanoscale exploratory research (NER) modes of support. To encourage proposals dealing with societal implications, NSF supported and/or participated in a number of invited and grantee-focused workshops.[9] However, it is worth noting that since most of these efforts took place during or after the FY 2001 competition, their impact is unlikely to be seen until FY 2002 proposals have been evaluated.

Education and Training

The education, training, and outreach component of NSF's societal implications work has been extensive and has involved a diverse collection of funding mechanisms (both existing and new) and a variety of target populations. For example, the NSF supported course and curriculum development at universities around the country and used its combined research and curriculum development (CRCD) and its research experiences for undergradautes (REU) programs to strengthen undergraduate and graduate education in nanoscale science and technology.

A major focus of NSF's educational efforts in this area involves the integration of research and education. A number of universities have received interdisciplinary graduate education and research and teaching (IGERT) awards that focus on nano-related topics.

Because of the team-based and interdisciplinary approach used in research groups, centers, and networks, these funding mechanisms have also played a central role in NSF's educational strategy. This kind of training experience has been provided through the national nanotechnology user network (NNUN) and a variety of nano-focused materials research science and engineering centers (MRSECs), engineering research centers (ERCs), and science and technology centers

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[8] Societal Implications of Nanoscience and Nanotechnology, Report of NSET-sponsored workshop of the same name, Mihail C. Roco and William Sims Bainbridge eds., Kluwer Academic Publishers and National Science Foundation, Arlington, Va., March 2001.

[9] These included the NSET-sponsored workshop "Societal Implications of Nanoscience and Nanotechnology," September 2000, a report published by NSF and Kluwer Academic Publishers based on this workshop (see footnote 10); "Nanotechnology—Revolutionary Opportunities and Societal Implications," NSF-EC workshop, January 2002; "Converging Technologies (nano-bio-info-cogno) for Improving Human Performance," December 2001, at NSF; and "Partnership in Nanotechnology," NSF Grantees Conference, January 2001, at NSF.

(STCs).[10] These efforts appear to have been significantly enhanced by the creation of six new NSECs during 2001. Graduate and undergraduate students trained in these centers appear to be involved in exactly the kind of interdisciplinary, team-based, and multisector research environment that nanoscientists and nanoengineers must learn to thrive in.

NSF's efforts have also begun to target more immediate technology workforce education needs. These activities include the Nanotechnology Research and Teaching Facility at the University of Texas at Arlington and the Regional Center for Nanofabrication Manufacturing Education at Pennsylvannia State University. Box 3.3 discusses the Pennsylvania program as an example of activities in workforce education.

Finally, some of NSF's educational efforts have included an international dimension. For instance, roughly one-third of its small group awards have involved international collaborations. In addition, NSF has sponsored international trips by groups of young researchers and developed bilateral and multilateral activities with a number of countries having advanced nano programs.

Outreach and Public Education

NSECs also serve as a vehicle for a variety of more nontraditional outreach efforts to K-12 students and teachers, to academic institutions without strong infrastructures, to underserved populations, and to the public at large. For instance, the Nanoscale Systems in Information Technologies program at Cornell University has been partnering with industry to support a K-12 teachers' institute and a nanotechnology teaching laboratory. The Center for Science of Nanoscale Systems and their Device Applications at Harvard University has been fostering nano-focused public education activities in partnership with the Boston Science Museum. Finally, the Center for Directed Assembly Nanostructures at Rensselaer Polytechnic Institute has developed a partnership with industry and several smaller universities, some with large underrepresented populations. Outreach efforts have also been carried out through initiatives like the NanoManipulator at the University of North Carolina at Chapel Hill; Molecular Modeling and Simulation; the Web-based network at the University of Tennessee, and the Interactive Nano-Visualization in Science and Engineering Education program at Arizona State University. Traditional NSF outreach programs like Research Experiences for Teachers (RET) have also targeted nanoscale science and technology.

BOX 3.3
Nanotechnology Manufacturing

As one of the five nodes in NSF's national nanotechnology user network (NNUN), Penn State University and other institutions of higher education in Pennsylvania have formed a partnership with the Commonwealth of Pennsylvania to established a unique and comprehensive program in nanofabrication manufacturing technology (NMT). The NMT program seeks to develop a technical 2-year degree and a science-based 4-year degree, both intended to prepare the future workforce for nano-related industries such as MEMS, pharmaceuticals, biomedicine, information storage, power devices, opto-electronics, and microelectronics. The NMT program has also developed activities to increase the awareness of nanotechnology for K-12 students and teachers.

A key element of the NMT program is the sharing of a $23 million nanofabrication facility by educational institutions across Pennsylvania. By sharing this manufacturing facility, colleges across the state can offer their students some of the most current training available in nanofabrication manufacturing technology.

Clearly, as the international use of nanofabrication manufacturing technologies increases in high-tech industries, demand for individuals with nanofabrication manufacturing skills will increase dramatically. However, the global competitive position of the United States in this area could be jeopardized if the nation is unable to prepare enough technicians and scientists for these new nanomanufacturing fields. Initiatives like NMT, with its nanofabrication facility, are examples of how NNI funding is being used to meet these needs.

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[10] The MRSECs were established in 1994. They are supported by NSF to undertake materials research of a scope and complexity that would not be feasible under traditional funding of individual research projects. The ERCs are a group of engineered systems-focused, interdisciplinary centers at universities across the United States, each in close partnership with industry. They provide an environment in which academe and industry can collaborate in pursuing strategic advances in complex engineered systems and systems-level technologies important for the nation's future. NSF established the science and technology centers (STC) program in 1987. The objective, in response to rising global competition, was to mount an innovative, interdisciplinary attack in important areas of basic research. The first STCs were established in 1989; more were added in 1991.

NSF has also sponsored a number of outreach efforts specifically targeted at the general public. These include "Making the Nanoworld Comprehensible," an exhibit with the University of Wisconsin and Discovery World Science Museum in Milwaukee; "Internships for Creating Presentations on Nanotechnology Topics," at the Arizona Science Center; and "Small Wonders: Exploring the Vast Potential of Nanoscience," a traveling education program.

Social Science Research on Societal Implications

While at least one NSEC focuses on an area of great societal concern, the environment, NSF did not support any social science projects focused on nano-related societal implications during FY 2001. According to NSF, some nano-related social science activities were included in several NSEC proposals, but these activities were not at centers judged meritorious enough to warrant funding. Further, very few social science projects were received in the individual investigator and small group competitions, and none were funded. Thus, although NSF explicitly included societal implications in its NNI solicitations, nothing came of those efforts. Given the compelling reasons for including this kind of work within NNI and the strong endorsement activities such as those received from the diverse group of participants attending the NSET-sponsored societal implications workshop, this is a disappointing outcome.

There appear to be a number of reasons for the lack of activity in this area. First and foremost, while a portion of the NNI support was allocated to the various traditional disciplinary directorates, no funding was allocated directly to the Directorate of Social and Behavioral and Economic Sciences, the most capable and logical directorate to lead these efforts. As a consequence, social science work on societal implications could be funded in one of two ways: (1) it could compete directly for funding with physical science and engineering projects through a solicitation that was primarily targeted at that audience or (2) it could be integrated within a nanoscience and engineering center.

There are a number of reasons both funding strategies failed to promote a strong response from the social science community. First, given the differences in goals, knowledge bases, and methodologies, it was probably very difficult for social science group and individual proposals to compete with nanoscience and engineering projects in the NIRT and NER competitions. In addition, while proposals for NIRT and NSEC awards were *required* to include an educational component and/or a component aimed at the development of a skilled workforce or an informed public, "studies of societal implications" was only *one of six optional activities* (including international collaboration; shared experimental facilities; systems-level focus; proof-of-concept testbeds; and connection to design and development activities) that individual proposals could include. Not surprisingly, while essentially every proposal included an educational component, and many included familiar practices like testbeds, very few included a social science component.[11] Finally, NSEC review committees and site visit teams did not include social scientists.[12]

Thus, although NSF appears to have made a good faith effort to include social science proposals in its agency-wide solicitation, its internal funding strategy and the way the solicitation was framed probably undermined its attempts to support work in this area.

Evaluation of Activities That Explore Social Implications

Although some progress has been made, particularly with respect to educational initiatives, the amount of attention devoted to societal implications within NNI is disappointing. As one indication that this is the case, the original NNI request budgeted approximately 5.6 percent of its funding to this area. The committee's best estimate is that for FY 2001 less than half that amount was spent on these activities. While it is merely speculation that this outcome may have been caused by

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[11] It is worth noting that the NSEC guidelines did not solicit proposals for centers focused on societal implications. Development of a virtual social science center was one of the major recommendations of the NSET-sponsored workshop on societal implications.

[12] If social science efforts are handled correctly, there is reason to believe they can be integrated within broad-based science and engineering projects or centers. The NSF IUCRC program has included a mandatory social science component for most of the past 20 years. This effort helped the IUCRC program win a Technology Transfer Society Justin Morril Award. In addition, the Center for Environmentally Responsible Solvents and Processes at the University of North Carolina at Chapel Hill, at the University of Texas at Austin, and at North Carolina Agricultural and Technical State University, an NSF science and technology center, includes a social science research group that addresses collaboration and technology transfer issues. NSF had the wisdom to include social scientists on the review panels for this center.

agencies that reduced or eliminated their commitment to addressing societal implications in order to protect funding for other thrust areas after receiving cuts in their NNI budget request, the fact that only two agencies, NSF and DOD, appear to have committed support to activities in this area, although six requested funds, seems consistent with such speculation.

On a more positive note, NSF and DOD should be commended for committing the time and resources to some nano-focused educational and training activities. In contrast, the lack of any educational activity within NIH, which—like NSF—has a significant educational mission, is particularly disappointing. NSF should also be recognized for using a variety of new and existing funding modes to support a diverse collection of educational and outreach strategies targeted at different populations. These efforts are the one bright spot in this theme and show that motivated agencies can respond to the societal challenges posed by the development of nanoscale science and technology. On a more cautious note, it is worth noting that it is premature to evaluate the balance and effectiveness of these educational, outreach, and training efforts.

NSF also appears to have taken some positive steps to increase the quantity and quality of the nano-focused social science proposals it receives by sponsoring workshops on this topic and being more proactive in soliciting proposals.[13] However, it is not clear whether NSF is addressing the root causes of the shortfall—namely, the decision to not allocate funds directly to the directorate that traditionally develops and supports these kinds of activities and shortcomings in its proposal solicitation strategy.

In spite of indications of significant progress in developing educational initiatives, the information provided to this committee suggests that NSET agencies have generally not given sufficient consideration to the societal impact of developments in nanoscale science and technology. Since funding for this theme is supposed to reach $35 million for FY 2003, NSET clearly needs to rethink the way it funds and implements activities for this activity.

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[13] NSF believes it has received some higher quality individual and group proposals for "societal and educational implications" for FY 2002 and expects to make some awards in this area.