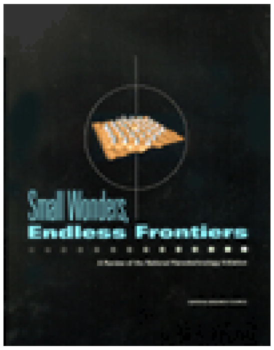

Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative

Committee for the Review of the National Nanotechnology Initiative, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Small Wonders, Endless Frontiers

A Review of the
National Nanotechnology Initiative

Committee for the Review of the National Nanotechnology Initiative
Division on Engineering and Physical Sciences
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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Back cover: A nanoscale motor created by attaching a synthetic rotor to an ATP synthase. Reprinted with permission of the American Association for the Advancement of Science from Soong et al., *Science* 290, 1555 (2000). © 2000 by AAAS.

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COMMITTEE FOR THE REVIEW OF THE NATIONAL NANOTECHNOLOGY INITIATIVE

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Preface

Not only did microtechnology during the second half of the 20th century lead to computers and the Internet, but it also brought us to the beginning of an exciting scientific revolution we now call nanotechnology. In addition to the information technologies currently enjoyed throughout the world, microtechnology has helped develop scientific instruments that make it possible for the first time to image, manipulate, and probe objects that can be more than 1,000 times smaller than the microcircuits of the most advanced computers. These objects have dimensions on the scale of nanometers, 1/100,000 the width of a human hair, hence the term "nanotechnology." In recent work it has been discovered that these tiny objects can have electrical, mechanical, magnetic, and optical properties completely different from those of the same material in bulk form. These discoveries could lead to powerful devices with new capabilities and also new materials that will impact all sectors of technology, from advanced electronics to advanced medicine.

Scientists have recently gained the understanding that biology works through highly synchronized interactions among nanoscale objects. For this reason, nanoscale science and technology offer the opportunity to understand life processes at a deeper level, cure and prevent disease, heal injured bodies, and protect society against chemical and biological weapons. At the same time, nanotechnology will point the way to the design of synthetic devices with some of the amazing capabilities of living systems. This prospect is nothing short of astounding, and it places the importance of nanoscale science and technology research into the right perspective.

Science and engineering at the nanoscale demand interdisciplinary research. To make, manipulate, and probe matter on this size scale requires chemical knowledge and also a deep understanding of physical phenomena. Furthermore, the organization of nanoobjects into useful products is a monumental task for engineers. To realize the potential of nanoscale science and technology in advanced medicine will require research at the interface between engineering, the physical sciences, and biology. For all these reasons, the development of nanoscale science and technology will require generations of interdisciplinary scientists and engineers who can learn and operate across traditional boundaries.

How should the country respond to the scientific and societal challenges posed by nanoscale science and technology? All parts of our government—the White House, Congress, federal agencies, and state and local governments—need collectively to implement an effective plan to galvanize the development of nanoscale science and technology in the United States, with advice from experts in our nation's universities, industries, and national laboratories. This plan must also foster strategic alliances with other countries engaged in nanoscale science and technology development.

This review of the National Nanotechnology Initiative (NNI) was initiated by the National Research

Council (NRC) at the request of officials at the White House National Economic Council during the Clinton administration and of agencies participating in the NNI. In reviewing the NNI, the NRC agreed to consider the following questions:

- Does the NNI research portfolio address the skills and knowledge that will allow the United States to fully benefit from the new technology? Is the balance of the research portfolio appropriate?
- Are the available U.S. resources (people, infrastructure, and funding) being applied appropriately within the portfolio? Are the correct seed investments being made now to provide needed infrastructure for future years (to 2005 and beyond)? Are partnerships (government-industry-university, international) being used appropriately to leverage the public investment in this area?
- Is the portfolio of programs being coordinated in such a way as to maximize the effectiveness of the investment? (Is the whole greater than the sum of the parts?)
- Does NNI give sufficient consideration to the societal impact of advances in nanotechnology?
- Are the processes for evaluating the effectiveness of the NNI (determination of metrics, milestones, etc.) appropriate and meaningful? How should the program be evaluated in light of the long-term (10- to 20-year) nature of many of its research goals?
- What are some important areas for future investment in nanotechnology?

The committee offers the following report in response to these questions, and in the hope that its efforts will help the United States to capture the enormous potential benefits of advances at the nanoscale.

Samuel I. Stupp, *Chair*
Committee for the Review of the National
Nanotechnology Initiative

Acknowledgment of Reviewers

This report has been reviewed by individuals 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 wish to thank the following individuals for their review of this report:

Andreas Acrivos, City College, City University of New York,
A. Paul Alivisatos, University of California, Berkeley,
Louis Brus, Columbia University,
Michael M. Crow, Columbia University,
Alan B. Fowler, IBM Corporation,
Yury Gogotsi, Drexel University,
Evelyn L. Hu, University of California, Santa Barbara,
Royce W. Murray, University of North Carolina,
Mark A. Ratner, Northwestern University, and
J. Fraser Stoddard, University of California, Los Angeles.

Although the individuals 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 this report was overseen by Alan Fowler, IBM Thomas J. Watson Research Center (emeritus). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Executive Summary

Nanoscale science and technology, often referred to as "nanoscience" or "nanotechnology," are science and engineering enabled by our relatively new ability to manipulate and characterize matter at the level of single atoms and small groups of atoms. This capability is the result of many developments in the last two decades of the 20th century, including inventions of scientific instruments like the scanning tunneling microscope. Using such tools, scientists and engineers have begun controlling the structure and properties of materials and systems at the scale of 10^{-9} meters, or 1/100,000 the width of a human hair. Scientists and engineers anticipate that nanoscale work will enable the development of materials and systems with dramatic new properties relevant to virtually every sector of the economy, such as medicine, telecommunications, and computers, and to areas of national interest such as homeland security. Indeed, early products based on nanoscale technology have already found their way into the marketplace and into defense applications.

In 1996, as the tremendous scientific and economic potential of nanoscale science and technology was beginning to be recognized, a federal interagency working group formed to consider creation of a national nanotechnology initiative (NNI). As a result of this effort, around $1 billion has been directed toward NNI research since the start of FY 2001. At the request of officials in the White House National Economic Council and agencies that are participating in NNI, the National Research Council (NRC) agreed to review the NNI. The Committee for the Review of the National Nanotechnology Initiative was formed by the NRC and asked to consider topics such as the current research portfolio of the NNI, the suitability of federal investments, and interagency coordination efforts in this area.

During the course of its evaluation, the committee was impressed with the leadership and level of multiagency involvement in the NNI. Specifically, the committee commends the leadership of the National Science Foundation (NSF) in the establishment of the multiagency Nanoscale Science, Engineering and Technology (NSET) subcommittee as the primary coordinating mechanism for the NNI. NSET has played a key role in establishing research priorities, identifying Grand Challenges, and involving the United States scientific community in the NNI. It has also helped to sponsor a number of symposiums and workshops on advances in nanoscale science and technology, as well as the potential ethical, legal, and social issues of those advances.

In short, the committee finds that the leadership and investment strategy established by NSET has set a positive tone for the NNI. The initial success of the NNI can also be measured by the number of foreign governments that have established similar nanoscale science and technology research programs in response. Nevertheless, the committee has formulated a limited number of recommendations to further strengthen the implementation of NNI. Using information provided by the federal agencies involved in the initiative, the committee considered structure and made 10 recommendations:

Recommendation 1: The committee recommends that the Office of Science and Technology Policy (OSTB) establish an independent standing nano-

science and nanotechnology advisory board (NNAB) to provide advice to NSET members on research investment policy, strategy, program goals, and management processes. With potential applications in virtually every existing industry and new applications yet to be discovered, nanoscale science and technology will no doubt emerge as one of the major drivers of economic growth in the first part of the new millennium. An advisory board could identify and champion research opportunities that do not conveniently fit within any single agency's mission. It should be composed of leaders from industry and academia with scientific, technical, social science, or research management credentials.

Recommendation 2: The committee recommends that NSET develop a crisp, compelling, overarching strategic plan. The plan would articulate short- (1 to 5 years), medium- (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. It should also include mechanisms for accelerating ideas into applications and identify applications for pilot projects. It should include a consistent set of anticipated outcomes for each theme and Grand Challenge and should estimate time frames and metrics for achieving those outcomes.

Recommendation 3: The committee recommends that NNI support long-term funding in nanoscale science and technology so that they can achieve their potential and promise. Establishing a proper balance between the short-term and long-term funding of nanoscale science and technology will be critical to realizing their full potential. Truly revolutionary ideas will need sustained funding to achieve results and produce important breakthroughs.

Recommendation 4: The committee recommends that NSET increase multiagency investments in research at the intersection of nanoscale technology and biology. The relevance of the NNI to biology, biotechnology, and the life sciences cannot be overstated. Cellular processes are inherently nanoscale phenomena. Our developing ability to manipulate matter at the nanoscale challenges us to construct nanodevices and systems capable of complex functioning similar to that of a cell. While we are far from achieving such complexity, we can already see applications of nanoscale science and technology that will have significant impacts in biotechnology and medicine. Barriers to interagency and interdisciplinary work must be overcome to enable such developments.

Recommendation 5: The committee recommends that NSET create programs for the invention and development of new instruments for nanoscience. Historically, many important advances in science come only after the appropriate investigative instruments became available. The NSET program should include analytical instruments for modeling, manipulating, tailoring, characterizing, and probing at the nanoscale.

Recommendation 6: The committee recommends the creation of a special fund for Presidential grants, under OSTP management, to support interagency research programs relevant to nanoscale science and technology. These grants should be used exclusively to fund meaningful interagency collaborations that cross mission boundaries, particularly among the National Institutes of Health, the Department of Energy, and the National Science Foundation. While it is appropriate for a federal agency to focus on its own particular mission, the breadth of NNI and its fields of impact—from new materials development to quantum computing and from cellular microbiology to national security—should compel agencies to form more meaningful cooperation in their nanoscale science and technology pursuits.

Recommendation 7: The committee recommends that NSET provide strong support for the development of an interdisciplinary culture for nanoscale science and technology within the NNI. Nanoscale science and technology are leading researchers along pathways formed by the convergence of many different disciplines, such as biology, physics, chemistry, materials science, mechanical engineering, and electrical engineering. To date, NSET member agencies have encouraged multidisciplinary collaborations, but creative programs are needed that encourage the development of self-contained interdisciplinary groups as well.

Recommendation 8: The committee recommends that industrial partnerships be stimulated and nurtured, both domestically and internationally, to help accelerate the commercialization of NNI developments. NSET should create support mechanisms for coordinating and leveraging state initiatives to

organize regional competitive clusters for the development of nanoscale science and technology. Nanoscale science and technology are ultimately about industrial competitive position, and the defining benefit is economic, as new technologies and products move from laboratories to commercial reality. The key to commercial success is to have processes that accelerate nanotechnology ideas into the commercial mainstream, thereby providing a timely return on the national investment in nanoscale science and technology.

Recommendation 9: The committee recommends that NSET develop a new funding strategy to ensure that the societal implications of nanoscale science and technology become an integral and vital component of the NNI. This is critical, because our success in developing, deploying, and exploiting nanotechnologies will require synchronous innovation in how we educate and train our workforce, manage our R&D system, and prepare for and adjust to the expected and unexpected social and economic impacts of the new technologies. Activities supported by the societal implications thrust area will help to ensure that this "second industrial revolution" produces social and economic as well as technical benefits.

Recommendation 10: The committee recommends that NSET develop performance metrics to assess the effectiveness of the NNI in meeting its objectives and goals. This should be done under the aegis of the OSTP. Measurable factors include quality, relevance, productivity, resources, and movement of research concepts toward applications. These factors should be developed with the advice of an appropriate advisory council, perhaps the suggested NNAB, in conjunction with the various agencies involved in the NNI.

1

The Importance of Nanoscale Science and Technology

Nanoscale science and technology, often spoken of as "nanoscience" or "nanotechnology," are simply science and engineering carried out on the nanometer scale, that is, 10^{-9} meters. Figure 1.1 provides some sense of how this scale relates to more familiar, everyday scales. In the last two decades, researchers began developing the ability to manipulate matter at the level of single atoms and small groups of atoms and to characterize the properties of materials and systems at that scale. This capability has led to the astonishing discovery that clusters of small numbers of atoms or molecules—nanoscale clusters—often have properties (such as strength, electrical resistivity and conductivity, and optical absorption) that are significantly different from the properties of the same matter at either the single-molecule scale or the bulk scale. For example, carbon nanotubes are much less chemically reactive than carbon atoms and combine the characteristics of the two naturally occurring bulk forms of carbon, strength (diamond) and electrical conductivity (graphite). Furthermore, carbon nanotubes conduct electricity in only one spatial dimension, that is, along one axis, rather than in three dimensions, as is the case for graphite. Nanoscale science and engineering also seek to discover, describe, and manipulate those unique properties of matter at the nanoscale in order to develop new capabilities with potential applications across all fields of science, engineering, technology, and medicine.

The National Nanotechnology Initiative (NNI) was established primarily because nanoscale science and technology are predicted to have an enormous potential economic impact. Many potential applications of nanoscale science and technology have been touted in both the scientific and the popular press, and there has been no shortage of promises made for the ability of nanoscale technology to revolutionize life as we know it. Beyond any speculation or hype, the committee can point to current applications of nanoscale materials and to devices that are already impacting our nation's commerce, as well as advances that are mature enough to promise impacts in the near future**.** Figure 1.2 is a time line for anticipated impacts. Some of the current impacts, as well as anticipated longer-term impacts, of the technical revolution that will be ushered in by nanoscale science and technology are discussed in more detail below.

PRESENT APPLICATIONS OF NANOSCALE MATERIALS AND PHENOMENA

The earliest application of nanoscale materials occurred in systems where nanoscale powders could be used in their free form, without consolidation or blending. For example, nanoscale titanium dioxide and zinc oxide powders are now commonly used by cosmetics manufacturers for facial base creams and sunscreen lotions. Nanoscale iron oxide powder is now being used as a base material for rouge and lipstick. Paints with reflective properties are also being manufactured using nanoscale titanium dioxide particles. Nanostructured wear-resistant coatings for cutting tools and wear-resistant components have been in use for several years. Nanostructured cemented carbide coatings are used on some Navy ships for their increased durability.

More recently, more sophisticated uses of nanoscale materials have been realized. Nanostructured materials are in wide use in information technology, integrated into complex products such as the hard disk drives that

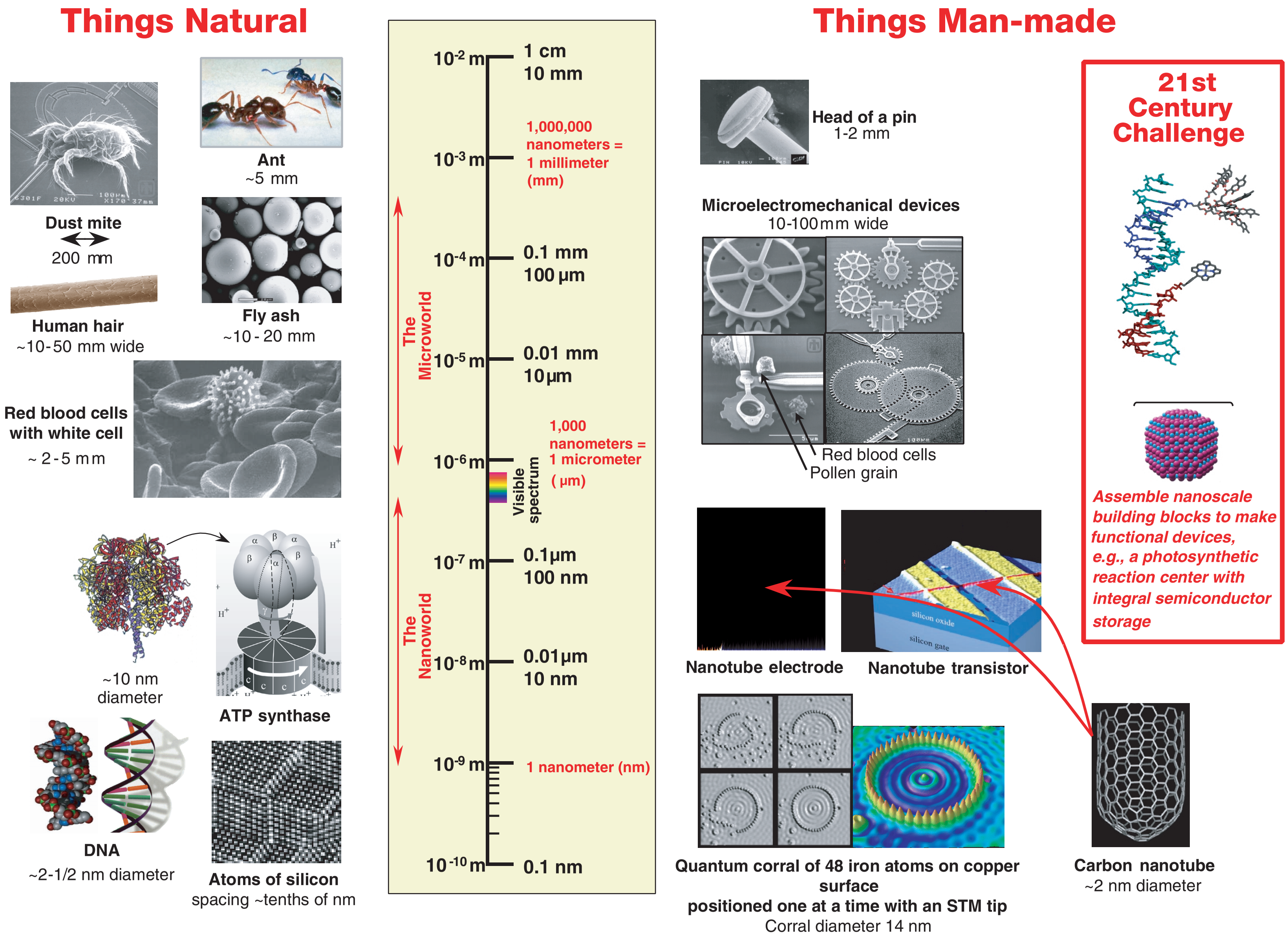

FIGURE 1.1 The size of nanoscale objects and phenomena compared with the size of small everyday objects. Courtesy of Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy.

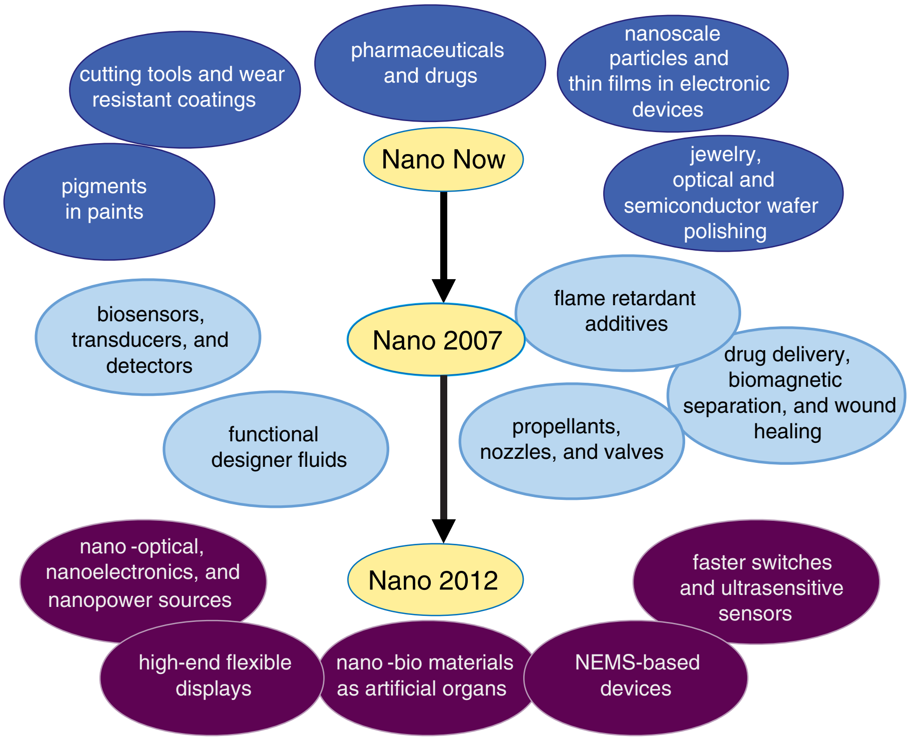

FIGURE 1.2 Current applications of nanotechnology and time line for anticipated advances.

store information and the silicon integrated circuit chips that process information in every Internet server and personal computer. The manufacture of silicon transistors already requires the controlled deposition of layered structures just a few atoms thick (about 1 nanometer). Lateral dimensions are as small as 180 nanometers for the critical gate length, and semiconductor industry roadmaps call for them to get even smaller. With shorter gate lengths come smaller, faster, more power-efficient transistors and corresponding improvements in the cost and performance of every digital appliance. Similar processes are required for the manufacture of information storage devices. The giant magnetoresistive (GMR) read heads in computer industry standard hard disk drives are composed of carefully designed layered structures, where each layer is just a few atoms thick. The magnetic thin film on the spinning disk is also a nanostructured material. Last year IBM announced the introduction of an atomically thin layer of ruthenium (humorously referred to as "pixie dust") to substantially increase the information storage density of its products. Greater storage density translates directly to the less expensive storage of information. Incorporating nanostructured materials and nanoscale components into complex systems, both magnetic data storage and silicon microelectronics provide a glimpse of the future of nanoscale science and technology. Box 1.1 provides a look at the history of miniaturization in computing and the potential impact of nanoscale science and technology on that sector.

In biomedical areas, structures called liposomes have been synthesized for improved delivery of therapeutic agents. Liposomes are lipid spheres about 100 nanometers in diameter. They have been used to encapsulate anticancer drugs for the treatment of AIDS-related Kaposi's sarcoma. Several companies are using magnetic nanoparticles in the analyses of blood, urine, and other body fluids to speed up separation and improve selectivity. Other companies have developed derivatized fluorescent nanospheres and nanoparticles that form the basis for new detection technologies. These reagent nanoparticles are used in new devices and systems for infectious and genetic disease analysis and for drug discovery.

Many uses of nanoscale particles have appeared in specialty markets, such as defense applications, and in markets for scientific and technical equipment. Producers of optical materials and electronics substrates such as silicon and gallium arsenide have embraced the use of nanosize particles for chemomechanical polish-

BOX 1.1
Nanotechnology and Computers

The history of information technology has been largely a history of miniaturization based on a succession of switching devices, each smaller, faster, and cheaper to manufacture than its predecessor (Figure 1.1.1). The first general-purpose computers used vacuum tubes, but the tubes were replaced by the newly invented transistor in the early 1950s, and the discrete transistor soon gave way to the integrated circuit approach. Engineers and scientists believe that the silicon transistor will run up against fundamental physical limits to further miniaturization in perhaps as little as 10 to 15 years, when the channel length, a key transistor dimension, reaches something like 10 to 20 nm. Microelectronics will have become nanoelectronics, and information systems will be far more capable, less expensive, and more pervasive than they are today. Nevertheless, it is disquieting to think that today's rapid progress in information technology may soon come to an end. Fortunately, the fundamental physical limits of the silicon transistor are not the fundamental limits of information technology. The smallest possible silicon transistor will probably still contain several million atoms, far more than the molecular-scale switches that are now being investigated in laboratories around the world.

But building one or a few molecular-scale devices in a laboratory does not constitute a revolution in information technology. To replace the silicon transistor, these new devices must be integrated into complex information processing systems with billions and eventually trillions of parts, all at low cost. Fortunately, molecular-scale components lend themselves to manufacturing processes based on chemical synthesis and self-assembly. By taking increasing advantage of these key tools of nanotechnology, it may be possible to put a cap on the amount of lithographic information required to specify a complex system, and thus a cap on the exponentially rising cost of semiconductor manufacturing tools. Thus, nanotechnology is probably the future of information processing, whether that processing is based on a nanoscale silicon transistor manufactured to tolerances partially determined by processes of chemical self-assembly or on one or more of the new molecular devices now emerging from the laboratory.

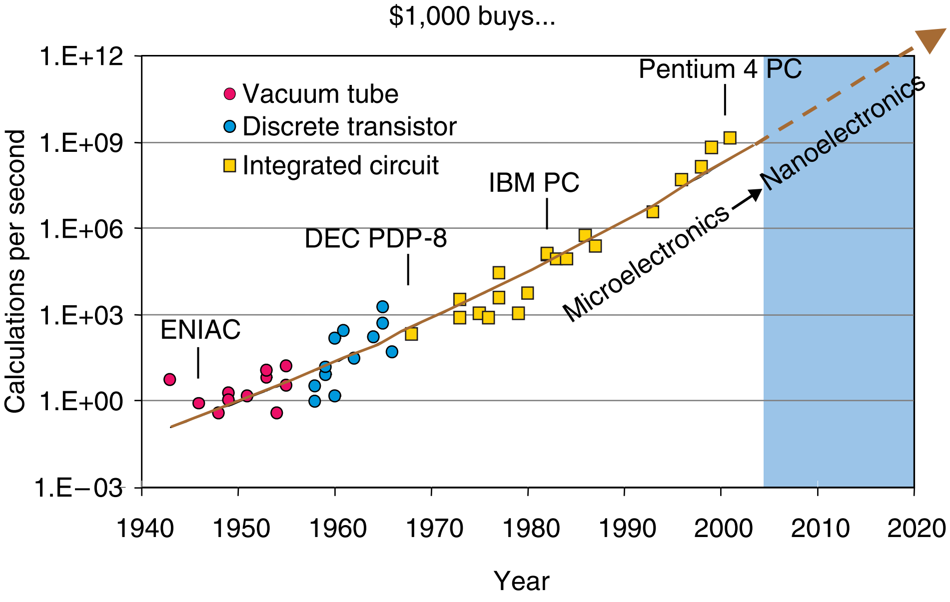

FIGURE 1.1.1 The increasing miniaturization of components in computing and information technology. Adapted from R. Kurzweil, *The Age of Spiritual Machines,* Penguin Books, 1999.

ing of these substrates. Nanosize particles of silicon carbide, diamond, and boron carbide are used as lapping compounds to reduce the waviness of finished surfaces from corner to corner and produce surface finishes to 1-2 nm smoothness. The ability to produce such high-quality components is significant for scientific applications and could become even more important as electric devices shrink and optical communications systems become a larger part of the nation's communications infrastructure.

DEVELOPING APPLICATIONS OF NANOSCALE TECHNOLOGY

Several nanoscale technologies appear to be 3 to 5 years away from producing practical products. For example, specially prepared nanosized semiconductor crystals (quantum dots) are being tested as a tool for the analysis of biological systems. Upon irradiation, these dots fluoresce specific colors of light based on their size. Quantum dots of different sizes can be attached to the different molecules in a biological reaction, allowing researchers to follow all the molecules simultaneously during biological processes with only one screening tool. These quantum dots can also be used as a screening tool for quicker, less laborious DNA and antibody screening than is possible with more traditional methods.[1]

Also promising are advances in feeding nanopowders into commercial sprayer systems, which should soon make it possible to coat plastics with nanopowders for improved wear and corrosion resistance. One can imagine scenarios in which plastic parts replace heavier ceramic or metal pieces in weight-sensitive applications. The automotive industry is researching the use of nanosized powders in so-called nanocomposite materials. Several companies have demonstrated injection-molded parts or composite parts with increased impact strength. Full-scale prototypes of such parts are now in field evaluation, and use in the vehicle fleet is possible within 3 to 5 years. Several aerospace firms have programs under way for the use of nanosized particles of aluminum or hafnium for rocket propulsion applications. The improved burn and the speed of ignition of such particles are significant factors for this market.

A number of other near-term potential applications are also emerging. The use of nanomaterials for coating surfaces to give improved corrosion and wear resistance is being examined on different substrates. Several manufacturers have plans to use nanomaterials in the surfaces of catalysts. The ability of nanomaterials such as titania and zirconia to facilitate the trapping of heavy metals and their ability to attract biorganisms makes them excellent candidates for filters that can be used in liquid separations for industrial processes or waste stream purification. Similarly, new ceramic nanomaterials can be used for water jet nozzles, injectors, armor tiles, lasers, lightweight mirrors for telescopes, and anodes and cathodes in energy-related equipment.

Advances in photonic crystals, which are photonic bandgap devices based on nanoscale phenomena, lead us closer and closer to the use of such materials for multiplexing and all-optical switching in optical networks. Small, low-cost, all-optical switches are key to realizing the full potential for speed and bandwidth of optical communication networks. Use of nanoscale particles and coatings is also being pursued for drug delivery systems to achieve improved timed release of the active ingredients or delivery to specific organs or cell types.

As mentioned above, information technology has been, and will continue to be, one of the prime beneficiaries of advances in nanoscale science and technology. Many of these advances will improve the cost and performance of established products such as silicon microelectronic chips and hard disk drives. On a longer time scale, exploratory nanodevices being studied in laboratories around the world may supplant these current technologies. Carbon nanotube transistors might eventually be built smaller and faster than any conceivable silicon transistor. Molecular switches hold the promise of very dense (and therefore cheap) memory, and according to some, may eventually be used for general-purpose computing. Single-electron transistors (SETs)[2] have been demonstrated and are

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[1] Mingyon Han, Xiaohu Gao, Jack G. Su, and Shuming Nie, 2001, "Quantum-Dot-Tagged Microbeads for Multiplexed Optical Coding of Biomaterials," *Nature Biotechnology* 19:631-635.

[2] The single-electron transistor, or SET, is a switching device that uses controlled electron tunneling to amplify current. The only way for electrons in one of the metal electrodes to travel to the other electrode is to tunnel through the insulator. Since tunneling is a discrete process, the electric charge that flows through the tunnel junction flows in multiples of e, the charge of a single electron. Definition from Michael S. Montemerlo, MITRE Nanosystems Group, and the Electrical and Computer Engineering Department, Carnegie Mellon University.

being explored as exquisitely sensitive sensors of electronic charge for a variety of applications, from detectors of biological molecules to components of quantum computers. (Quantum computing is a recently proposed and potentially powerful approach to computation that seeks to harness the laws of quantum mechanics to solve some problems much more efficiently than conventional computers.) Quantum dots, discussed above as a marker for DNA diagnostics, are also of interest as a possible component of quantum computers. Meanwhile, new methods for the synthesis of semiconductor nanowires are being explored as an efficient way to fabricate nanosensors for chemical detection. Rather than quickly supplanting the highly developed and still rapidly advancing silicon technology, these exploratory devices are more likely to find initial success in new markets and product niches not already well-served by the current technology. Sensors for industrial process control, chemical and biological hazard detection, environmental monitoring, and a wide variety of scientific instruments may be the market niches in which nanodevices become established in the next few years.

THE FUTURE OF NANOSCALE SCIENCE AND TECHNOLOGY

As efforts in the various areas of nanoscale science and technology continue to grow, it is certain that many new materials, properties, and applications will be discovered. Research in areas related to nanofabrication is needed to develop manufacturing techniques, in particular, a synergy of top-down with bottom-up processes. Such manufacturing techniques would combine the best aspects of top-down processes, such as microlithography, with those of bottom-up processes based on self-assembly and self-organization. Additionally, such new processes would allow the fabrication of highly integrated two- and three-dimensional devices and structures to form diverse molecular and nanoscale components. They would allow many of the new and promising nanostructures, such as carbon nanotubes, organic molecular electronic components, and quantum dots, to be rapidly assembled into more complex circuitry to form useful logic and memory devices. Such new devices would have computational performance characteristics and data storage capacities many orders of magnitude higher than present devices and would come in even smaller packages.

Nanomaterials and their performance properties will also continue to improve. Thus, even better and cheaper nanopowders, nanoparticles, and nanocomposites should be available for more widespread applications. Another important application for future nanomaterials will be as highly selective and efficient catalysts for chemical and energy conversion processes. This will be important economically not only for energy and chemical production but also for conservation and environmental applications. Thus, nanomaterial-based catalysis may play an important role in photoconversion devices, fuel cell devices, bioconversion (energy) and bioprocessing (food and agriculture) systems, and waste and pollution control systems.

Nanoscale science and technology could have a continuing impact on biomedical areas such as therapeutics, diagnostic devices, and biocompatible materials for implants and prostheses. There will continue to be opportunities for the use of nanomaterials in drug delivery systems. Combining the new nanosensors with nanoelectronic components should lead to a further reduction in size and improved performance for many diagnostic devices and systems. Ultimately, it may be possible to make implantable, in vivo diagnostic and monitoring devices that approach the size of cells. New biocompatible nanomaterials and nanomechanical components should lead to the creation of new materials and components for implants, artificial organs, and greatly improved mechanical, visual, auditory, and other prosthetic devices.

Exciting predictions aside, these advances will not be realized without considerable research and development. For example, the present state of nanodevices and nanotechnology resembles that of semiconductor and electronics technology in 1947, when the first point contact transistor was realized, ushering in the Information Age, which blossomed only in the 1990s. We can learn from the past of the semiconductor industry that the invention of individual manufacturable and reliable devices does not immediately unleash the power of technology—that happens only when the individual devices have low fabrication costs, when they are connected together into an organized network, when the network can be connected to the outside world, and when it can be programmed and controlled to perform a certain function. The full power of the transistor was not really unleashed until the invention of the integrated circuit, with the reliable processing techniques that produce numerous uniform devices and connect them across a large wafer, and the computerized design, wafer-scale packaging, and interconnection techniques for very-large-scale integrated circuits themselves. Similarly, it will require an era of spectacular advances in the development of processes to integrate nanoscale components into devices, both with other nanoscale components and with microscale and larger components, accompanied by the ability to do so reliably at low cost. New techniques for manufacturing massively parallel and fault-tolerant devices will have to be invented. Since nanoscale technology spans a much broader range of scientific disciplines and potential applications than does solid state electronics, its societal impact may be many times greater than that of the microelectronics and computing revolution.

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The National Nanotechnology Initiative

BRIEF HISTORY

Attempts to coordinate federal work on the nanoscale began in November 1996, when staff members from several agencies decided to meet regularly to discuss their plans and programs in nanoscale science and technology. This group continued informally until September 1998, when it was designated as the Interagency Working Group on Nanotechnology (IWGN) under the National Science and Technology Council (NSTC) of the OSTP.[1]

The IWGN laid the groundwork for the National Nanotechnology Initiative (NNI). It sponsored numerous workshops and studies to define the state of the art in nanoscale science and technology and to forecast possible future developments. Two relevant background publications were produced by the group between July and September 1999: *Nanostructure Science and Technology: A Worldwide Study*,[2] a report based on the findings of an expert panel that visited nanoscale science and technology laboratories around the world; and *Nanotechnology Research Directions,*[3] a workshop report with input from academic, private sector, and government participants. These documents laid the groundwork and provided the justification for seeking to raise nanoscale science and technology to the level of a national initiative. In August 1999, IGWN completed its first draft of a plan for an initiative in nanoscale science and technology. The plan went through an approval process involving the President's Council of Advisors on Science and Technology (PCAST)[4] and OSTP; subsequently, in its 2001 budget submission to Congress, the Clinton administration raised nanoscale science and technology to the level of a federal initiative, officially referring to it as the National Nanotechnology Initiative.

ADMINISTRATION OF THE INITIATIVE

Once the NNI had been set up, the IWGN was disbanded and Nanoscale Science, Engineering and Technology (NSET) was established as a subcommittee of the National Science and Technology Council's (NSTC) Committee on Technology (CT). CT, which is composed of senior-level representatives from the federal government's research and development departments and agencies, provides policy leadership and budget guidance for this and other multiagency technology programs.

NSET is responsible for coordinating the federal government's nanoscale research and development programs. NSET membership includes representatives of departments and agencies currently involved in the NNI and OSTP officials. The National Nanotechnology Coordination Office (NNCO) was established to serve as the secretariat for NSET, providing day-to-day technical and administrative support. The NNCO supports

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[1] M.C. Roco, National Science Foundation, presentation to the committee, August 16, 2001.

[2] *Nanostructure Science and Technology: A Worldwide Study,* R.W. Siegel, E. Hu, and M.C. Roco, eds. Kluwer Academic Publishers, 1999. Available at <http://itri.loyola.edu/nano/final/>.

[3] *Nanotechnology Research Directions, IWGN Workshop Report, Vision for Nanotechnology Research in the Next Decade,* M.C. Roco, S. Williams, and P. Alivisatos, eds. Kluwer Academic Publishers, 2000.

[4] PCAST consists of nongovernmental experts who provide advice to the President on science and technology issues.

TABLE 2.1 Estimated Funding for Nanotechnology from FY 1999 to FY 2003 (million dollars)

Organization[a]	FY 1999	FY 2000	FY 2001	FY 2002 Estimate	FY 2003 Request
NSF	85	97	150	199	221
DOD	70	70	123	180	201
DOE	58	58	88	91	139
DOJ			1	1.4	1.4
DOT				2	2
NIH[b]	21	32	40	41	43
NASA	5	5	22	46	51
NIST[c]	16	8	33	38	44
EPA			5	5	5
USDA			2	1.5	2.5
Total	255	270	464	604.9	709.9

[a] Funding figures for four additional entities (the Departments of State and Treasury, the CIA, and the Nuclear Regulatory Commission) that are also joining the NNI are not yet available.
[b] In the Department of Health and Human Services.
[c] In the Department of Commerce.

NSET in multiagency planning and the preparation of budgets and program assessment documents. It also assists NSET with the collection and dissemination of information on industry, state, and international nanoscale science and technology research, development, and commercialization activities. Currently represented on NSET are the Departments of Defense (DOD), Energy (DOE), Justice (DOJ), Transportation (DOT), Agriculture (USDA), State, and Treasury; the Environmental Protection Agency (EPA); the National Aeronautics and Space Administration (NASA); the National Institutes of Health (NIH); the National Institute of Standards and Technology (NIST); the National Science Foundation (NSF); the Nuclear Regulatory Commission (USNRC); the Central Intelligence Agency (CIA); and two White House offices (the Office of Management and Budget (OMB) and OSTP).

According to the NNI implementation plan,[5] each agency invests in projects that support its own mission and retains control over how it will allocate resources against its NNI proposals based on the availability of funding. Each agency evaluates its own research activities within the NNI according to its own Government Performance and Results Act (GPRA) procedures. NNI coordination should result from NSET activities, direct interactions among program officers from the participating agencies, periodic management meetings and program reviews, and joint scientific and engineering workshops. OSTP works with the NSET and with individual agencies to establish NNI priorities, budgets, and metrics for evaluating various research activities.

STATUS OF FUNDING

The NNI has received strong Presidential and congressional support. Table 2.1 presents funding for nanoscale science and technology from 1999 to the present. For the purposes of determining which programs are to be included in the tally of federal "nanotechnology" funding, the OMB has developed a definition of nanotechnology to guide federal agencies in the reporting of their respective research efforts.[6] While

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[5] *NNI: Leading to the Next Industrial Revolution. The Initiative and Its Implementation Plan*, NSTC, July 2000, pp. 38-40.

[6] Contained in Circular A-11, 1465-xx, NNI research activities are defined as follows:

> . . . research and technology development at the atomic, molecular, or macromolecular levels, in the length scale of approximately 1-100 nanometer range, to provide a fundamental understanding of phenomena and materials properties at the nanoscale and to model, create, characterize, manipulate, and use structures, devices, and systems that have novel properties and functions because of their small or intermediate size. The novel and differentiating properties and function are developed at a critical length scale of matter typically under 100 nanometers. Nanotechnology research and development includes integration of nanoscale structure into larger material components, systems, and architectures. Within these larger scale assemblies, the control and construction of their structures and components devices remain at the nanometer scale.

the Bush administration's FY 2002 budget included a request for $485 million for the NNI, almost a 15 percent increase over FY 2001, Congress approved an estimated $604.9 million, a 30 percent increase over FY 2001 (see Table 2.1). However, according to some NSET representatives, 25 to 30 percent of the $140 million increase can be attributed to the reclassification or reallocation of existing agency research expenditures into the NNI program. Three agencies, NSF, DOD, and NASA, accounted for the majority of additional federal expenditures for the NNI in FY 2002. Since FY 1999, federal support for the NNI has received average annual increases of 33 percent.

The FY 2002 Department of Veterans Affairs subcommittee appropriations bill (which contains annual appropriations for the NSF, NASA, EPA, and other federal agencies) noted the Senate Appropriations Committee's strong support for "the interagency nanoscience and technology initiative." The report's language requests that OSTP and the NSET update the FY 2001 NNI Implementation Plan as a supplemental report to the President's FY 2003 budget request. The Appropriations Committee specifically requested that the report include a detailed discussion on "agency efforts to transfer nanotechnology research efforts into applications."[7] It requested an update of the NNI implementation plan because the plan had not been significantly revised since 1999. Further, the Appropriations Committee wanted to know if OSTP and NSET representatives are working together to establish mechanisms that will enhance the transfer of NNI research results from the laboratory into commercial applications.

The NNI implementation plan, as currently drafted, incorporates a series of primary themes that are described in this report and highlights a number of Grand Challenges facing the successful development and deployment of nanoscale science and technology in general and the NNI in particular. The existing Grand Challenges (11 in number in the FY 2001 NNI summary) are meant to spur the development required to meet the goal of economic growth through nanotechnology and to form a basis for examining program support for specific initiatives.

For FY 2003, the Bush administration has designated the NNI as a multiagency research initiative that will benefit from improved coordination across multiple agencies. As indicated in Table 2.1 and mentioned previously, the administration has proposed $709.9 million for the NNI, a 17 percent increase over the FY 2002 estimated level of $604.9 million. Three agencies—DOE, DOD, and NSF—account for over 90 percent of the proposed FY 2003 increase. However, according to NSET officials, the NSF and the NIH are the only agencies whose FY 2003 increases included new funding.

For FY 2003 the initiative will continue to focus on fundamental nanoscale science and technology research, centers and networks of excellence, and support of new research infrastructure. The NSET has approved the creation of a twelfth Grand Challenge, which will focus on homeland defense: Chemical, Biological, Radiological, and Explosive (CBRE) Detection and Protection.

BRIEF DESCRIPTION OF THE INITIATIVE

The NNI is built around five funding themes distributed among the agencies currently funding nanoscale science and technology research.[8] These themes are described below, with estimated FY 2002 funding and requested increases for FY 2003. Table 2.2 details the distribution of funds between these five themes for FY 2001.

- *Long-term fundamental nanoscience and engineering research ($201 million, +$31 million).* Long-term basic nanoscience and engineering research will focus on fundamental understanding and synthesis of nanometer-size building blocks aimed at potential breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and health care, environment and energy, the chemical and pharmaceuticals industries, biotechnology and agriculture, computation and information technology, and national security. This investment is intended to provide sustained support for individual investigators and small groups doing fundamental research, to promote university-industry-federal laboratory partnerships, and to foster interagency collaboration.
- *Grand Challenges ($180 million, +$24 million).* The second theme includes support for interdisciplinary research and education teams, including centers and networks, that work on key long-term objectives.

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[7] Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriations Bill, 2002. S. 1216, Senate Report 107-43, page 89.

[8] *NNI: Leading to the Next Industrial Revolution: The Initiative and Its Implementation Plan,* NSTC, July 2000.

TABLE 2.2 Distribution of Funds Between the Five NNI Funding Themes for FY 2001, the First Year of the Initiative (million dollars)

Agency	Fundamental Research	Grand Challenges	Centers and Networks of Excellence	Research Infrastructure	Societal Implications	Agency Total
NSF	84	8	26	17	15	150
DOD	20	58	24	21	0	123
DOE	25	34	14	15	0	88
NIH	9	19	1	9	2	40
NASA	4	11	2	5	0	22
NIST	0	16	9	8	0	33
EPA	0	2	2	1	0	5
DOJ	0	1	0	0	0	1
DOT	0	0	0	0	0	0
USDA	2	0	0	0	0	2
Total	144	149	78	76	17	464

NOTE: FY 2002 funding data were incomplete at the time of this report's publication.

The Bush administration has identified a dozen Grand Challenges that are essential for the advancement of nanoscale science and technology. They include the design and manufacture of nanostructured materials that are correct at the atomic and single-molecule level. These advances are aimed at applications such as cost-effective manufacture of nanoscale microelectronics, more efficient and cost-effective energy conservation and storage devices, and biological sensors with applications to both health care and chemical and biological threat detection. Many of the Grand Challenges are aligned with the mission of the various agencies participating in the NNI.

- *Centers and networks of excellence ($96 million, +$23 million).* The third theme is the establishment of 10 centers and networks of excellence, each of which would be funded at about $3 million a year for 5 years. Pending a successful interim progress review, each center could receive a one-time 5-year renewal. The centers will play a key role in achieving top NNI priorities (fundamental research, grand challenges, educating future scientists and engineers), in developing and utilizing specific nanoscale research tools, and in promoting research partnerships. The administration anticipates that the establishment of centers and networks will spawn the integration of research and education in nanoscale science and technology across disciplines and by various research sectors, including universities, federal laboratories, and the private sector. It anticipates that interdisciplinary research activities by government, university, and industrial performers will create a vertical integration arrangement that includes activities from basic research to the development of specific nanotechnology devices and applications.

- *Research infrastructure ($97 million, +$23 million).* The fourth theme supports the creation of a research infrastructure for metrology, instrumentation, modeling and simulation, and facilities. To work at the nanoscale, new research tools—for example, new forms of lithography, computational capabilities, and instruments for manipulation—will have to be developed. New research centers possessing such instrumentation will be built and made available to researchers from universities, industry, and government laboratories. The ultimate objective is new innovations that can be rapidly commercialized by U.S. industry. According to NSET representatives, if the need for instrumentation and the ability to make the transition from knowledge-driven to product-driven efforts are not addressed satisfactorily, the United States will not remain internationally competitive in this field.

- *Ethical, legal, and social implications and workforce education and training ($30 million, +$5 million).* The societal implications of nanotechnology and workforce education and training constitute the fifth theme of the NNI. In concert with the initiative's university-based research activities, this effort is designed to educate and train skilled workers, giving them the interdisciplinary perspective necessary for rapid progress in nanoscale science and technology. Researchers will also examine the potential ethical, legal, social, and workforce implications of nanoscale science and technology.

As part of the FY 2002 budget submission, key outcomes expected from the NNI in fiscal years 2002-2006 were outlined; these are given in Table 2.3. However, because Congress did not pass most of its FY 2002 appropriations bills until December 2001, the agencies involved in the NNI are not yet in a position to assess their FY 2002 activities for this report.

The NSET, working with the National Nanotechnology Coordination Office (NNCO), has tried to identify the most promising complementary and synergistic fields of research being carried out by the various NNI agencies in order to develop collaborations that will advance nanoscience and engineering. According to NNI documents, an important goal of these multiagency collaborative efforts is to coordinate funding activities for centers and networks of excellence, to share the costs of expensive research initiatives, and to study potential societal implications surrounding the adoption of nano-related capabilities, while reducing the probability of duplicative research efforts. Table 2.4 provides an overview of major collaborations planned by the NNI member agencies, as listed in the NNI implementation plan.

TABLE 2.3 Key Outcomes Planned for NNI from FY 2002 to 2006

Outcome	Target Date
Provide augmented research and development in fundamental research, grand challenges, infrastructure, education, and nanotechnology societal impacts in response to open competitive solicitations and regular program reviews.	FY 2002
Increase work on teams and centers for pursuing agency mission objectives.	FY 2002
Establish 10 new centers and networks with full range of nanoscale measurement and fabrication facilities.	FY 2002
Establish three distributed consortia for nanotechnology research and applications in transportation.	FY 2002
Begin focused research on nanoscale experimental tools and manufacturing at the nanoscale.	FY 2002
Develop new standard reference materials for semiconductor nanostructures, lab-on-a-chip technologies, nanomagnetics, and calibration and quality assurance analysis for nanosystems.	FY 2003
Leverage NNI funds by 25% by working with states, universities, and the private sector to increase funding and synergism in R&D, to nucleate new clusters of industries.	FY 2003
Develop standardized, reproducible, microfabricated approaches to nanocharacterization, nanomanipulation, and nanodevices.	FY 2004
Develop quantitative measurement methods for nanodevices, nanomanipulation, nanocharacterization, and nanomagnetics.	FY 2004
Develop 3D measurement methods for the analysis of physical and chemical properties at or near atomic spatial resolution.	FY 2004
Ensure that 50% of research institutions' faculty and students have access to full range of nanoscale research facilities.	FY 2005
Enable access to nanoscience and engineering education for students in at least 25% of research universities.	FY 2005
Catalyze creation of several new commercial markets that depend on 3D nanostructures.	FY 2005
Develop 3D modeling of nanostructures with increased speed and accuracy to allow practical system and architecture design.	FY 2005
Nanoelectronics: first terabit memory chip demonstrated in the laboratory.	FY 2006
Introduce manufacturing at nanoscale for three new technologies.	FY 2006
Monitor contaminants in air, water, and soils with increased accuracy for better environmental quality and reduced emissions.	FY 2006
Integrate facilities for nanoscale and microscale testing and manufacturing at 10 R&D centers.	FY 2006
Develop methods, tools, and computational tools for structure analysis for the extraction of information from nature's nanoscale materials and machines.	After 2006
Incorporate biological molecules into otherwise electronic devices, mimic biological structures in fabricated devices, and incorporate lessons learned from biological signal processing into the logic of electronic systems.	After 2006
Conduct nanoscale measurements on microsecond time scales to provide a blueprint for the development of nanomachines and synthetic molecular processors that carry out complex functions.	After 2006
Use photovoltaic proteins in plants that extract electronic energy from light energy, or insect hearing organs 1 mm apart that have highly directional sound source localization sensitivity, as models for, or components of, nanosystems that accomplish other functions.	After 2006

NOTE: NNI implementation plan, FY 2002 update, January 15, 2001, draft, pp. 13-14. The plan states as follows: "Out-year deliverables depend on regular increases in funding for this initiative."

TABLE 2.4 Examples of Major Collaborations Planned by NNI Participating Agencies

Area of Investment	DOD	DOE	DOJ	DOT	Treasury	EPA	NASA	NIH	NIST	NSF	USDA
Fundamental research	X	X		X	X		X	X		X	
Nanostructured materials	X	X		X	X	X	X	X	X	X	X
Molecular electronics	X						X		X	X	
Spin electronics	X						X			X	
Lab-on-a-chip	X	X	X	X	X		X	X	X	X	X
Biosensors, bioinformatics			X				X	X		X	
Bioengineering	X	X						X		X	
Quantum computing	X	X					X		X	X	
Measurements and standards for tools	X	X		X		X		X	X	X	X
Nanoscale theory, modeling, simulation	X	X					X			X	X
Environmental modeling		X				X	X			X	
Nanorobotics		X					X			X	
Unmanned missions	X						X				
International collaborations	X	X	X	X	X	X	X	X	X	X	X
Nanofabrication user facilities		X		X		X	X	X	X	X	X

3

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 Bio-nanosensors 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 nano-development 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.

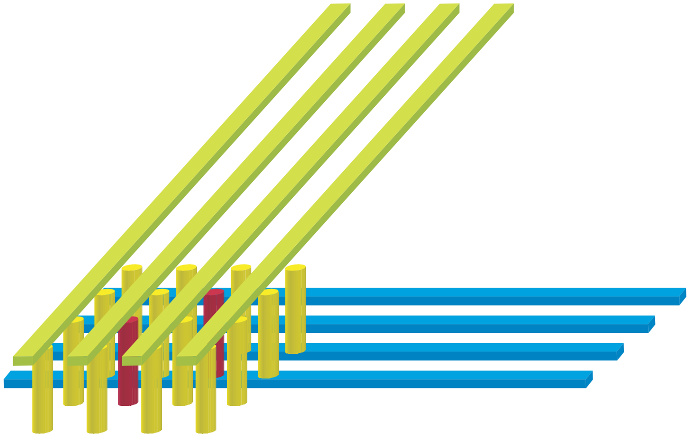

FIGURE 3.1.1 The architecture: Molecules trapped between nanowires act as memory bits.

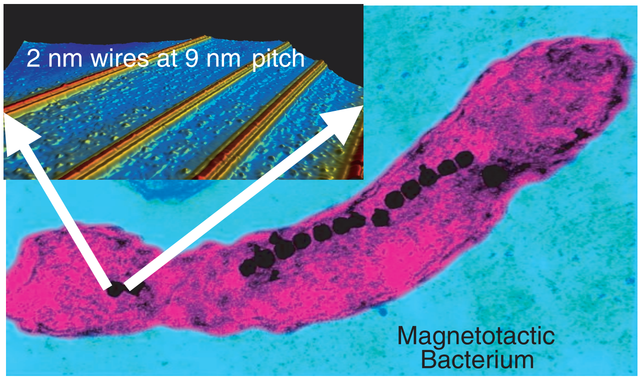

FIGURE 3.1.2 Hewlett-Packard's chemically formed nanowire array, showing the scale relative to 30 nm magnetic particles in a bacterium. Reprinted with permission of the American Association for the Advancement of Science from Frankel et al., *Science* 203, 1355 (1979). © 1979 by AAAS.

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.

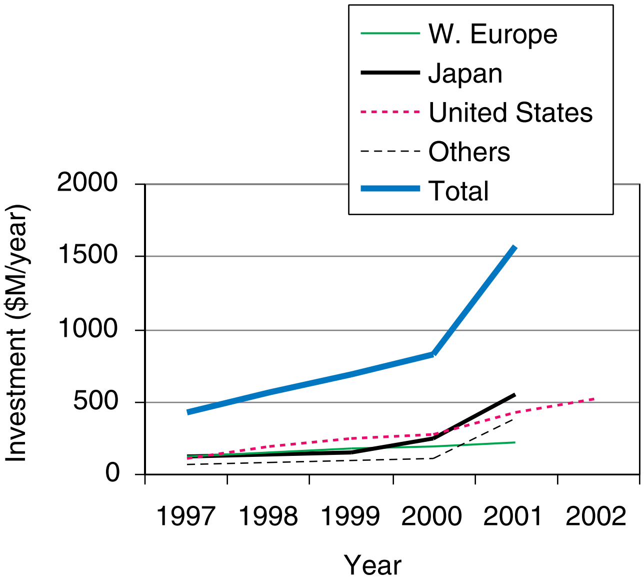

FIGURE 3.1 International government funding for nanotechnology R&D as of April 2002. Data are based on information collected from government programs by M. Roco, NSF. 2002 figures are estimates.

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.

4

Important Areas for Investment

The committee's charge calls for it to point to important areas for future investment in nanoscale science and engineering. Below, the committee discusses those areas that are most critical for realizing benefits from nanoscale advances and for future leadership in nanoscale science and technology. Although many of them are already in the current portfolio, their critical importance means they will require sustained investment to reach fruition.

The important areas for investment outlined below all have in common the theme of interdisciplinary science. The promise of nanoscale science and technology is dependent on research spanning many scientific cultures and disciplines, and the last two decades have seen an increasing awareness of the need to foster interdisciplinary work at the intersection of chemistry, physics, biological sciences, molecular biology, engineering, materials science, and surface science. Box 4.1 uses tissue engineering to demonstrate the advances that may come from such interdisciplinary work.

In considering investments in the areas outlined below, it is important that NSET base its decisions on the promise of the science involved and not on rigid definitions of the nanoscale. For example, microscale technology will clearly be critical to the realization of nanoscale science, so NSET must think broadly when defining NNI mission and portfolio investments.

NANOMATERIALS

Nanomaterials are nanoscale materials that exhibit new phenomena or behavior or that can be controlled at the nanometer scale. Such materials will probably feature in the first big successes for nanoscale technology. Nanomaterials are also the building blocks upon which complex two- and three-dimensional functional nanoscale systems will be built, enabling new devices and new functionalities. Box 4.2 discusses the importance of materials advances in achieving the potential payoff of nanoscale science and technology.

Broad markets for early nanoscale materials are expected in the near future. Several manufacturers have plans to use nanomaterials in catalytic surfaces. Nanomaterials are also excellent candidates for filters for liquid separations of various sorts—from water purification to chemical waste separation—because nanoscale titania and zirconia materials can facilitate the trapping of heavy metals and attract and retain bioorganisms. Nanoparticles have already been used in timed-release drug delivery systems, and their pharmaceutical uses will probably expand. Enzymes are being attached to nanoparticles that can be steered internally or externally to kill diseased cells. Future advances in nanofluidics, including lab-on-a-chip, may lead to faster diagnosis of distance and new procedures for delivering medications. Nanoparticles have also been used in creating novel optical films and in producing materials having optical or magnetic properties that enable new performance levels. For example, magnetic nanoparticles and quantum dots will be used to produce ultrasmall disk drives with 10 times the current capacity and memory chips with speeds of several hundred gigahertz.

NSET has done an excellent job supporting and coordinating research and development for nanoscale science and technology and materials science. The current NNI investment in materials science should be

BOX 4.1
Nanotissue Engineering

All tissues of the human body, including brain, heart, bone, skin, muscle, and cartilage, contain differentiated cells living in an extracellular matrix exquisitely designed by nature (Figure 4.1.1). These matrices contain nanofibers, microfibers, sheaths of material, mineral nanocrystals, proteins, and other biopolymers. The nanoscale architecture of these matrices is critical for the proper functioning of each tissue. Advances in cell biology and nanotechnology are expected to enable the fabrication of structurally and functionally designed synthetic matrices that will provide cells with all the necessary cues to regenerate structural tissues, organs, and body parts.

In one vision of this future, liquids will be delivered to parts of the body in noninvasive ways, and through self-assembly at the nanoscale, fully biodegradable matrices will form to serve as templates for regeneration. Nanoscale science and technology are needed to bring human capabilities to the scale at which nature designs the matrices for function. To make this happen, chemists, biologists, engineers, and physicists will have to work together to create the necessary strategies to synthesize matrices with nanosized features. The targets include the regeneration of spinal cord to reverse paralysis, and the regeneration of the retina to reverse blindness.

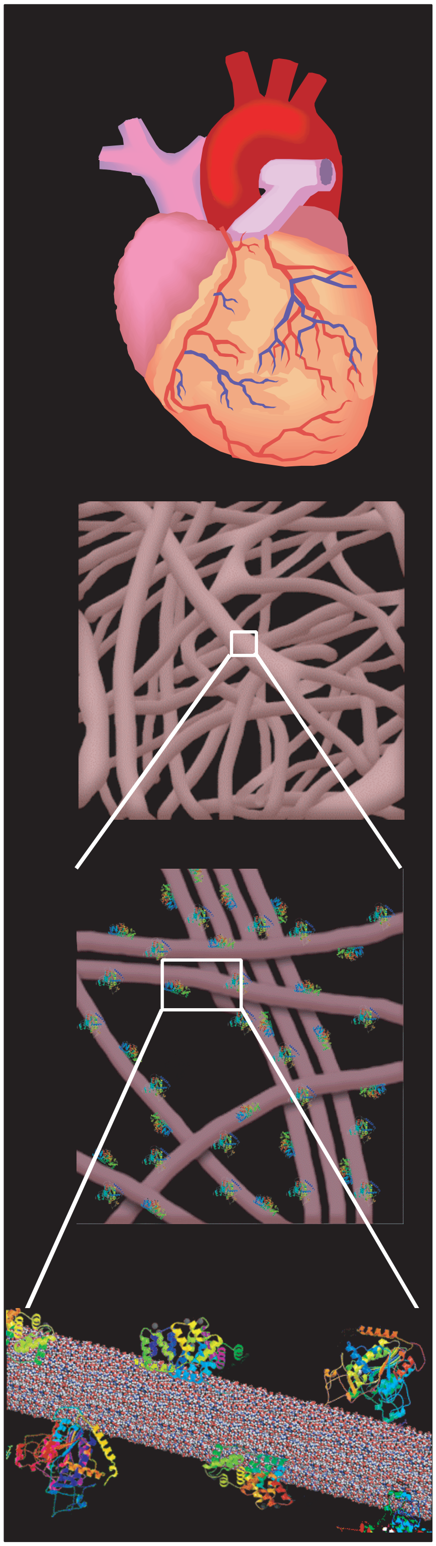

FIGURE 4.1.1

BOX 4.2
Nanotechnology in Advanced Materials

All technologies utilize materials, whether they are linked to information, energy, transportation, consumer products, or medicine. In the second half of the 20th century, the field of materials science and engineering emerged as a discipline. This field seeks to understand how the structure of materials is connected to their properties and thereby enable “materials by design,” with special properties required for particular applications. Important connections have been established between microscale properties such as the structure of metals or the molecular weight of polymers and their respective properties. As a result, materials available today are stronger, lighter, more durable, or have other unique properties that enable applications such as high-speed integrated circuits.

The world of designed materials should be significantly impacted by nanotechnology, leading to materials and devices with significantly advanced properties. Imagine organic, inorganic, and hybrid materials made up of nanostructures that can have prescribed shapes, as proteins do in biology. There have already been some previews in the scientific literature of what these new capabilities may bring. Inorganic nanostructures measuring only a few nanometers (quantum dots) (Figure 4.2.1) have unique optical properties. Recently discovered organic nanofibers mimic collagen fibrils found in our tissues (Figure 4.2.2). These structures may help us create materials that resemble bone for medical applications, but they could also produce bone-inspired hybrid materials in which organic nanofibers guide the organization of quantum dots or other inorganic nanocrystals (Figure 4.2.3). Such hybrid materials, and others such as carbon nanotubes, may someday be part of computers with memories and speeds that are thousands or millions of times greater than the ones we know today or be part of materials that help us improve the energy efficiency of the systems we use everyday.

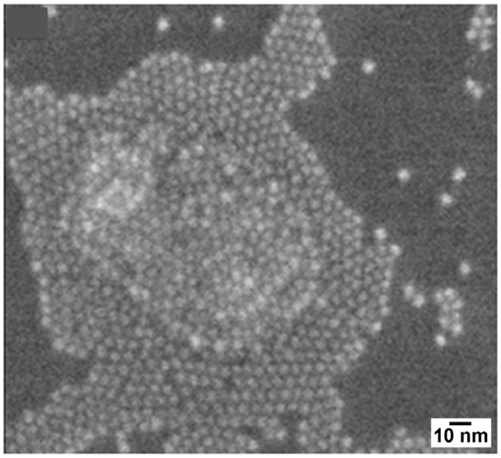

Figure 4.2.1 Quantum dots.

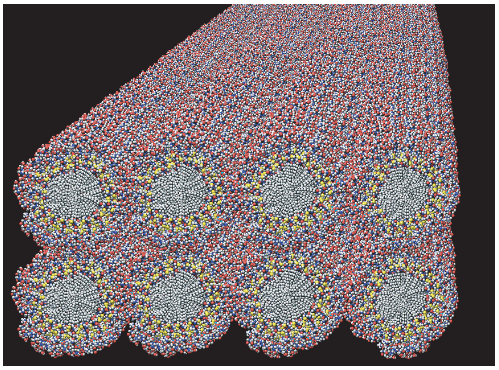

Figure 4.2.2 Organic nanofibers that mimic collagen fibers.

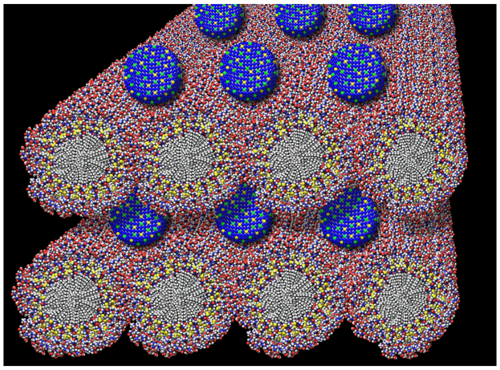

Figure 4.2.3 Organic nanofibers used to guide the organization of inorganic nanocrystals. SOURCE: All three figures in this box are from *Annual Review of Materials Science,* Volume 30, 2000. Used by the permission of Annual Reviews, <www.AnnualReviews.org>.

continued, with a special focus on developing and characterizng materials with novel properties.

INTERFACE OF NANOSCALE TECHNOLOGY WITH BIOLOGY

The relevance of the NNI to biology, biotechnology, and the life sciences cannot be overstated. Cellular processes and molecular biology techniques are inherently nanoscale phenomena. By elucidating cellular mechanisms, molecular biology provides us with a good textbook on nanoscale technology. However, the true challenge is to (create ways to) construct nanodevices and systems capable of complex functions. Nature integrates biological molecules into functioning three-dimensional macrostructures. Nevertheless, while we already have a good understanding of how nature works, we are not yet able to create synthetic systems that rival nature's elegance.

At the nanoscale, cells record information, process information, carry out a set of instructions, transform energy from one form to another, replicate themselves, and adapt to changing environments in ways that allow optimal performance of necessary tasks. Biological systems provide great inspiration for the design of functional nanoscale structures and can also help us learn how to organize nanostructures into much larger systems. Understanding biological phenomena at the nanoscale will be central to our continuing drive to understand cell function. It may also lead to biomimetic models for harnessing and duplicating organic-based functional systems for nonbiological applications, which is the idea behind such concepts as DNA computing. Box 4.3 provides an elegant example

BOX 4.3
Nanotechnology and Biology: Molecular-Scale Manipulation

Sensing and actuation in living systems are based on nanometer-scale mechanisms (protein-protein interactions). As nanotechnology advances, the merging of natural and synthetic modalities will provide novel approaches to nanoscale system design and application.

One ubiquitous natural actuator is the ATPase motor, a few hundred nanometers in size, that utilizes naturally occurring substances to provide actuation in living systems. Nanotechnology is allowing scientists to fabricate inorganic materials at the same scale. By merging the two (natural and synthetic), researchers have attached a nanopropeller to a natural ATPase motor (Figure 4.3.1). The propeller rotated at approximately 10 revolutions per second for several hours (Ricky K. Soong et al., "Powering an Inorganic Nanodevice with a Biomolecular Motor," *Science* 290: 1555-1558). Such hybrid nanodevices lay the foundation for building complex nanosystems capable of performing complex functions useful in medical and environmental applications.

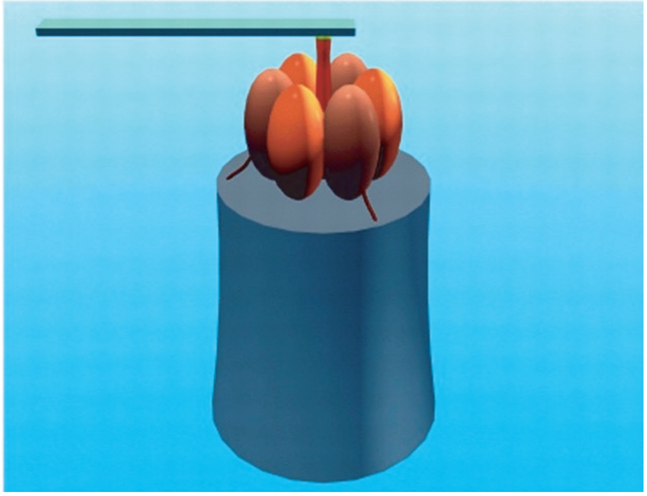

FIGURE 4.3.1 A nanoscale motor created by attaching a synthetic rotor to an ATP synthase. Reprinted with permission of the American Association for the Advancement of Science from Soong et al., *Science* 290, 1555 (2000). © 2000 by AAAS.

of the use of biological phenomena as the basis for nanoscale mechanical systems. Box 4.4 details an example in which the ability to mimic biological systems would greatly improve the capabilities of existing devices.

Many of the most readily foreseen applications of nanoscale science and technology are in biomedical technologies, including some that may be useful to counter bioterrorism. For example, one can envision the military use of nanostrucures to produce smart protective textiles such as high-efficiency particle air (HEPA) filters that are effective against particulates or biological toxins that might be dispersed as aerosols. Nanoscale technology might also enable the development of ultrasensitive detectors of biological or chemical threats. Box 4.5 discusses a new Army initiative to utilize nanoscale technology in defense applications. Potential early breakthroughs in medicine include regeneration of functional biomaterials such as bone or skin using nanostructured materials as a template for

BOX 4.4

The Nanofabrication Challenge: A Biological Light Conversion Device Versus a Man-made Photovoltaic Device (Solar Cell)

Green plants have structures called chloroplasts that carry out the highly efficient conversion of light into energy and biomass. Chloroplasts are self-organized structures that contain hundreds of nanometer-size structures called thylakoids (Figure 4.4.1). Within the thylakoids are numerous antenna nanostructures that capture light with high efficiency and convert it into chemical energy. A solar cell is a man-made photovoltaic device that converts light energy into electrical energy (Figure 4.4.2). A solar cell is relatively expensive compared with plant material and does not have the same overall efficiency. Photovoltaic devices and other microelectronic devices are made with so-called top-down fabrication processes. All biological systems use a bottom-up process to self-assemble molecules into nanostructures, then into larger structures, and finally into macroscopic structures (plants and animals). A Grand Challenge for nanotechnology will be the merger of top-down and bottom-up fabrication processes, which will allow us to self-assemble a whole new generation of inexpensive electronic and photonic devices with efficiencies closer to those achieved in nature.

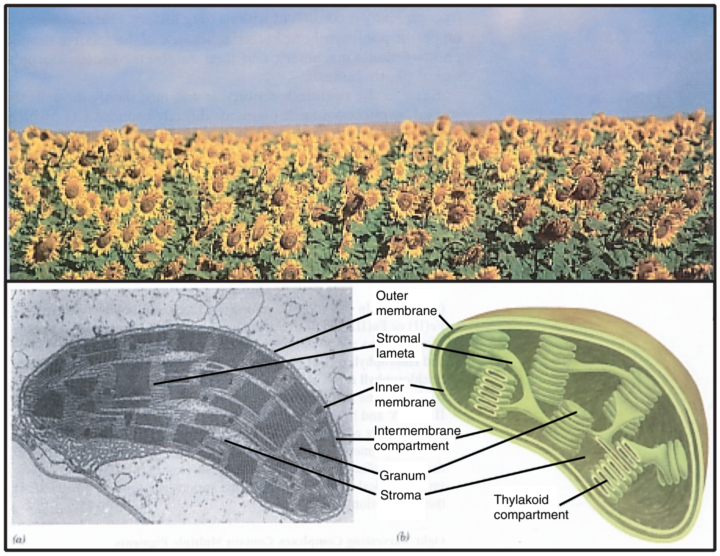

FIGURE 4.4.1 Plant chloroplast. SOURCE: *Fundamentals of Biochemistry,* Donald Voet, Judith G. Voet, and Charlotte W. Pratt, 1998. This material is used by permission of John Wiley & Sons, Inc.

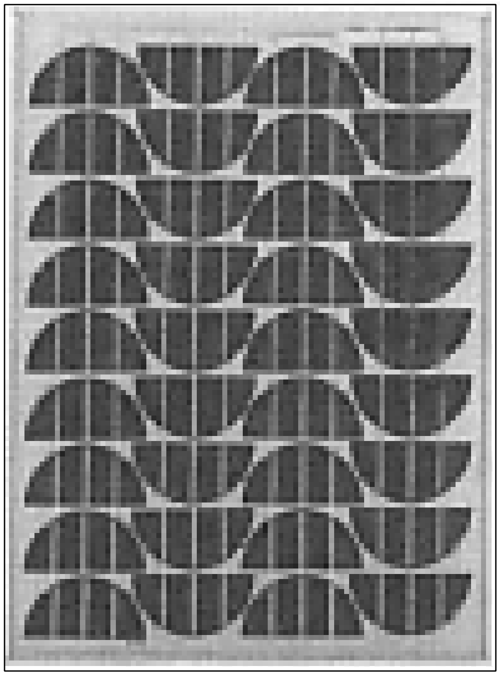

FIGURE 4.4.2 Solar cell array.

BOX 4.5
Nanotechnology and the Soldier

The Department of the Army has selected the Massachusetts Institute of Technology (MIT) to develop a variety of nanomaterials that will allow equipping future soldiers with uniforms and gear that can “heal them, shield them, and protect them against chemical and biological warfare.” The Institute for Soldier Nanotechnologies (ISN), as it will be known, will receive $50 million over 5 years, with industry partners providing an additional $40 million in funds and equipment. The ISN will focus on six key soldier capabilities: threat detection, threat neutralization (such as bulletproof clothing), concealment, enhanced human performance, real-time automated medical treatment, and reducing the weight load of the fully equipped soldier from 125-140 pounds to 45 pounds.

The primary role of ISN is to support basic and applied research. These innovations will lead to an array of innovations in nanoscience and nanotechnology in a variety of survivability-related areas. They will be transferred to industrial partners for future Army requirements and eventually civilian applications. Current and future DOD-sponsored nanoscience research is expected to lead to a variety of near-term (1-5 years) and long-term (5-15 years) advances in uniforms and equipment. These advances could include such capabilities as a semipermeable membrane with molecular-scale pores that open to allow passage of water but remain closed to other molecules. Such a membrane could be used in water filtration and purification systems or for chemical/biological protective clothing. Another possible outcome is engineering of molecular-scale rotors on a three-dimensional grid array so that they can pivot and block off high-intensity laser light—a molecular-scale Venetian blind—to protect soldier eyes from laser blinding or to act as high-speed switches in opto-electronic circuits. Nanoparticles of gold in solution, linked together by strands of DNA that are specifically encoded to respond to the DNA of biological agents, may produce reliable field detection of biological warfare agents at very low sample sizes or rapid, reliable screening for such diseases as influenza or strep throat. Materials are also sought that could react to a wound by becoming, for example, a tourniquet or to a fractured bone by becoming a hard cast.

growth and novel cancer or gene therapy strategies using nanoscale particles to deliver treatment to specific cell or gene types.

The scientific community currently recognizes the importance of nanoscale biological and biomedical research. In particular, NSF and NIH report increased numbers of proposals submitted in nano-bio areas. NSET has done a fair job of responding to this pressure and of promoting investment at the intersection of nanoscale science and technology and biology and biomedicine. For example, NIH has implemented a new interdisciplinary review system based on special emphasis panels (SEPs). SEPs are formed on an ad hoc basis to review research proposals requiring special expertise not found on any one standing review panel. The ability to convene SEPs means that interdisciplinary proposals are less likely to fall through the cracks of the NIH review system because no one standing panel can comprehend all aspects of the proposal. Nevertheless, NIH’s support of nanoscale science and technology R&D funding is small ($39 million in FY 2001) considering the size of its overall budget ($21 billion) and the potential impact that such research could have on the human condition.

NSET should examine means to increase the NNI investment in research at the intersection between nanoscale technology and biology and biomedicine. One could envision a multiagency research program in bio-nano areas for which an interagency review mechanism is established, as it may not be reasonable to expect single agencies to bear the very high cost of bio-based research. Examples include research on single-molecule detection, nanofabrication processes for biocompatible materials, and novel sensors. It is clear that understanding the cell is the next major challenge in biological science. Nanoscale science and technology will be critical both to achieving this understanding and to leveraging the understanding to achieve novel nanoscale devices.

INTEGRATION OF NANOSYSTEMS

Revolutionary change will come from integrating molecular and nanoscale components into higher order structures. The integration of nanoscale components with larger-scale components and the integration of large numbers of nanoscale components with one another are challenges that need to be overcome to achieve practical devices based on nanoscale phenomena. At present, the best techniques to produce large numbers of nanoscale systems are self-assembly techniques, which are only likely to produce fairly regular structures with low information content. These simple structures contrast to the components found in today's computers, which derive their capabilities from the great complexity that has been imposed by human designers. To achieve improvements over today's systems, chemically or biologically assembled machines must combine the best features of top-down and bottom-up approaches. Integration at the nanoscale is inherently complex and must be approached stepwise, and solutions to these problems will require a sustained investment and long-term commitment.

Research investments in molecular electronics and quantum and molecular computing could be critical for realizing this goal of integration. Real breakthroughs require fully integrated systems capable of manipulating the molecules, efficiently reading the code, and allowing for parallelism and diversity. One strategy toward for achieving three-dimensional assembly and complex functionality is to use self-organizing ideas and mechanisms gleaned from biology. Efficient self-assembly mechanisms will lead to advances in numerous areas, including decreases in the size of instrumentation and the ability to integrate multiple sensing devices on a chip.

INFRASTRUCTURE AND INSTRUMENTATION

The committee echoes the recommendations made at the culmination of the Bioengineering Consortium symposium—namely, that one of the most important areas for investment is the development of instrumentation, computation, and facilities to support research at the nano-bio interface.[1] The sophisticated and expensive equipment and facilities required for a multifaceted initiative such as the NNI can be shared among many investigators, and the specialized facilities can employ highly trained individuals to assist researchers in the optimum use of such equipment.

NSET has done an outstanding job of developing, supporting, and encouraging multiuser instrumentation and facilities. For example, DOE is proposing three new nanoscale science and technology centers. A "molecular foundry" is proposed for its Lawrence Berkeley National Laboratory that will focus on the connection of "soft" and "hard" materials, multicomponent functional assemblies, and multidisciplinary research. This facility is used in Box 4.6 to illustrate some of the features important to such centers. The Center for Integrated Nanotechnologies at Sandia National Laboratory and Los Alamos National Laboratory will concentrate on nanoelectronics and photonics, nanomechanics, complex materials, and the nano-bio-micro interface. At Oak Ridge National Laboratory, the Center for Nanophase Materials Sciences will focus on soft materials and complex nanophase materials. As another example, the national nanofabrication user network (NNUN) supported by NSF involves four primary sites and one secondary site at universities. The sites at Cornell, Penn State, and Stanford have personnel with biological expertise.[2] The NNUN is accessible to academic and industrial researchers and is particularly useful to start-up companies, which will be able demonstrate proof-of-principle without major capital outlay.

However, most of the equipment in these user facilities is for traditional use. For instance, Stanford's semiconductor wafer fabrication center was created for complementary metal-oxide semiconductor (CMOS) processes and developments. Materials that deviate from those used in CMOS technology cannot be used in the etchers, evaporators, and other equipment. Many of the interdisciplinary techniques researchers wish to utilize require nonstandard materials, so no user facilities are available for them. This issue must be addressed if NNUN is to truly serve the needs of researchers working at the interface between biology, chemistry, and materials science at the nanoscale. If it is to realize the research gains that it seeks, especially in the area of nanoscale studies of biological systems and the creation and characterization of nanoscale devices based on biological systems, NSET must encourage and support the development of multiuser facilities, particularly those that can tolerate the introduction of biological samples and saline solutions. This might be accomplished in partnership with the new National Institute of Bioimaging and Bioengineering, part of NIH.

In addition to supporting large user facilities, NNI must invest heavily in new instrument development if

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[1] NIH, *Nanoscience and Nanotechnology: Shaping Biomedical Research,* Bioengineering Consortium (BECON) Conference Center, June 25-26, 2000.

[2] The other primary site is at the University of California, Santa Barbara, while the secondary site is at Howard University.

BOX 4.6
Infrastructure for Interdisciplinary Nanoscience: DOE Nanoscale Science

The Department of Energy (DOE) has funded nanoscale science since the 1980s. Recently, DOE Basic Energy Sciences decided to fund nanoscale science research centers (NSRCs) at three national laboratories: the “molecular foundry” at Lawrence Berkeley National Laboratory, the Center for Integrated Nanotechnologies at Los Alamos and Sandia National Laboratories, and the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory. These centers will house specialized facilities for the synthesis, processing, fabrication, and characterization of nanoscale materials. They will all be scientific user facilities, with successful proposals selected by peer review. They will be located at existing DOE laboratories that have experience in operating such user facilities. By providing large-scale facilities that would be too expensive for individual universities, together with an interdisciplinary support staff, they will foster the interdisciplinary environment necessary for studying materials at the nanoscale. Figure 4.6.1 is an artist’s rendition of the new building for the molecular foundry at Lawrence Berkeley National Laboratory.

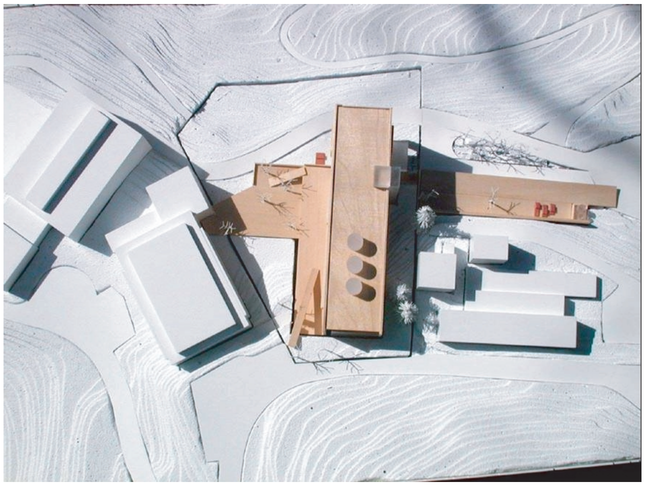

FIGURE 4.6.1 Artist’s rendition of the molecular foundry at Lawrence Berkeley. Courtesy of Lawrence Berkeley National Laboratory.

it wishes to accelerate breakthroughs in nanoscale science and technology. Many important advances in science came after the appropriate investigative instruments, such as the scanning tunneling microscope, were made available (see Box 4.7). One must be able to measure and quantify phenomena in order to understand and use them, which is true also for nanoscale phenomena.

Metrology at the nanoscale will also be critical. Most metrological tools currently available and in use in both laboratory and industrial settings do not provide the capability to perform measurements on the nanoscale. The ability to measure nanoscale dimensions in real systems such as integrated circuits is important to verify nanoscale advances.

LONG-TERM INVESTMENTS

Applications based on nanoscale technology are predicted to have profound impacts on society and the economy over the next several decades. Government and private science and technology funding sources and those responsible for determining industrial R&D funding will need a long-term view and patience in the development of a roadmap for nanoscale technology.

It was impossible in 1947 to predict the cost of producing an individual transistor on an integrated circuit in the year 2001, nor are we now able to predict what the real costs of manufacturing circuits and networks of devices fabricated at the nanoscale will be several decades from now, but like the transistor, it seems

BOX 4.7
Imaging and Manipulating Atoms

The invention of the scanning tunneling microscope (STM) in 1982 by Gerd Binnig and Heinrich Rohrer at the IBM Zurich Research Laboratory revolutionized our ability to image atoms on a solid surface. Binning and Rohrer shared the 1986 Nobel Prize in physics for their invention. This instrument and related ones based on scanning a sharp probe tip near a surface have continued to enhance our ability to measure and make pictures of atoms, molecules, and even biological cells on the nanoscale. This has already had significant impacts on the fields of physics, chemistry, and biology and in applications such as magnetic disc memory.

Not only can the STM be used to make images of individual atoms on a surface, but its sharp tip can also be used to pick atoms up from the surface and reposition them into desired arrangements. A striking example of this ability to manipulate atoms and make ordered man-made atomic structures is given in Figure 4.7.1, which demonstrates that man can manipulate matter and fabricate structures on the nanoscale. Such techniques may lead to the ability to make smaller memory, storage, and computational devices.

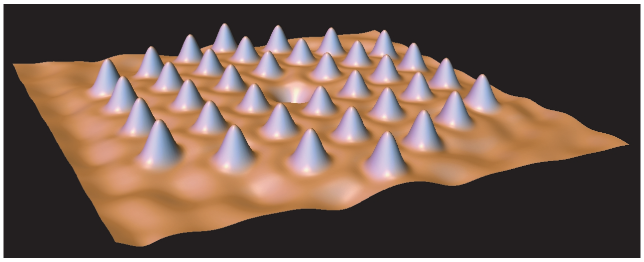

FIGURE 4.7.1 Three-dimensional STM image of man-made lattice of cobalt atoms on a copper (111) surface. Note that the center atom was deliberately omitted from the array, and the dip there is a result of the quantum mechanical standing wave field of the surface electrons. The image width is 14 nm. Courtesy of Don Eigler, IBM Almaden Research Center.

likely that eventual production costs will be low enough for mass production. However, two to three decades of research may be necessary to achieve reliable, low-cost interconnected networks of nanoscale devices, either for electronics, materials, or health-care applications. Since very few small start-ups or even large companies can afford to spend decades pursuing dreams without near-term economic payback, extended research in universities and national laboratories is needed to establish much of the groundwork for the most profound breakthroughs in nanoscale technology. This research will need to be far more interdisciplinary than that which most universities currently foster.

To develop nanoscale technologies into products with the greatest socioeconomic benefit, it is important that NNI create the best partnerships between those entities with present and future applications and those with technology vision, and sustain funding for decades of research and development. New ways will have to be found for the government to encourage industry research and offer long-term support of the industry-university-national laboratory partnerships needed to achieve the required breakthroughs.

SPECIAL TECHNOLOGICAL CHALLENGES

Many present technological paths to nanofabrication are safe paths—for example, integrated circuit producers will follow Moore’s law using modifications of established lithographic processes that will produce nanometer-scale silicon and complementary metal-oxide semiconductor (CMOS)[3] devices within the next 10 or 15 years. Industry will fully utilize and exploit present lithography-based manufacturing processes to produce devices with nanometer dimensions. Nevertheless the production of these devices will be dependent on billion-dollar fabrication facilities.

A significant challenge for nanoscale science and technology is the development of truly revolutionary nanofabrication processes. These new processes might utilize aspects of synthesis and self-assembly to allow for the heterogeneous integration of a diversity of molecular components, nanocomponents, and micron-scale components into a new generation of three-dimensional structures, devices, and systems. Basically, these new nanofabrication processes would eliminate the need for prohibitively expensive fabrication facilities.

There exists as well a large number of special challenges in nanostructures having to do with regard to their electrical, mechanical, optical, materials, and chemical properties. A few of these challenges are described next.

One outstanding challenge was posed by Feynman:[4] the use of the third dimension for electronic storage and processing of data. Current chips do use the third dimension for electrical interconnects. It is an open question, however, whether the tyranny of large systems would prevent effective use of the third dimension for layers of devices. Feynman maintained that only this use would provide plenty of room for future development. Integration in two dimensions has not made use of molecular precision and dimensions. In fact, not even the densities typical for solids can be achieved, since current technology is based on the existence of dilute (relative to the atomic densities of solids) donors and acceptors of electrons. Devices need to be found that can be based on solid-state densities. These devices will require control of pattern generation and perfection on a molecular scale.

New massively parallel schemes such as cellular automata or nanostructures integrated to perform quantum computing are ripe for exploration, including demonstrating in principle their potential functionality. The current state of the art has not demonstrated the feasibility of executing even a greatly simplified computational task. Once feasibility is determined, an assessment needs to be made of those circumstances in which the advantages of these approaches would outweigh their disadvantages (e.g., the requirement of low temperature).

Biological systems such as ionic channels have great advantages over current transistors, such as an infinite on/off current ratio. However, all biological systems work on a time scale much shorter than the switching times of current silicon technology. A challenge is to find material systems and implementations that have the advantages of the biological materials and designs and that also operate at high speed.

All of these challenges will require the development of computational tools that permit the simulation of these devices from their atomistic structure to their connections to macroscopic components and their integration into large systems.

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[3] In complementary metal-oxide semiconductor (CMOS) technology, both N-type and P-type transistors are used to realize logic functions. Today, CMOS technology is the dominant semiconductor technology for microprocessors, memories, and application-specific integrated circuits. The main advantage of CMOS over negative-channel metal oxide semiconductor (NMOS) and bipolar technology is the much smaller power dissipation. Unlike NMOS or bipolar circuits, a CMOS circuit has almost no static power dissipation. Power is only dissipated in case the circuit actually switches. This allows integrating many more CMOS gates on an IC than in NMOS or bipolar technology, resulting in much better performance.

[4] Richard P. Feynman, "There's Plenty of Room at the Bottom," Lecture at the annual meeting of the American Physical Society, California Institute of Technology, December 29, 1959.

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Recommendations

Overall, the leadership and investment strategy for the first several years of NNI have been appropriate. The committee has formulated a number of recommendations to further strengthen the implementation and goals of NNI. The following recommendations represent the committee's highest with respect to the current state of the NNI.

Recommendation 1: The committee recommends that the Office of Science and Technology Policy establish an independent standing nanoscience and nanotechnology advisory board (NNAB) to provide advice to NSET members on research investment policy, strategy, program goals, and management processes.

The rapidly changing political and economic climate poses significant challenges for the continued priority of the federal investment in the NNI. With potential applications in virtually every existing industry and new applications yet to be discovered, there is no doubt that nanoscale science and technology will emerge as an important driver of economic growth in the first years of the new millennium. An independent advisory board could provide advice to NSET members on research investment strategy, program goals, and management processes. It could identify and champion research opportunities, particularly ones that do not conveniently fit within any single agency's mission, to ensure that nanoscale science and engineering continue to progress toward their ultimate potential. Such a board should be composed of leaders from industry and academia with scientific, technical, social science, or research management credentials. It might be appointed by and overseen by the Office of Science and Technology Policy.

Recommendation 2: The committee recommends that NSET develop a crisp, compelling, overarching strategic plan. The plan would articulate short- (1 to 5 years), medium- (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.

While the FY 2001 and FY 2002 implementation plans for the NNI are quite detailed and ambitious and cover a broad spectrum of good research and development opportunities, they appear to have been developed largely as pieces within individual agencies, each driven by its own mission. While the outcomes of the NNI as a whole have been articulated, the various themes of the NNI are overlapping, and their strategies and goals have not been consistently described.

The strategic plan should include a consistent set of anticipated outcomes for each theme and each Grand Challenge, along with estimated time frames and metrics for achieving those outcomes. The plan should include mechanisms for accelerating ideas into applications. Appropriate mechanisms include pilot projects, the strategic infusion of new dollars into the NNI budget for engineering applications, the development of dedicated SBIR/STTR budgets for nanoscale science and technology in participating agencies, and the development of incentives for university projects in alliance with industrial partners and state and regional incubators. The committee also urges that the NSET, with the advice of the proposed NNAB, prioritize the Grand

Challenges in terms of their relative scientific and strategic importance.

Recommendation 3: The committee recommends that NNI support long-term funding in nanoscale science and technology so they can achieve their potential and promise.

Nanoscale science and technology will have continued and growing impact, with benefits seen in both the short and long-term. Establishing a proper balance between the short-term and long-term funding of nanoscale science and technology will be critical to realizing its potential. If an idea is truly revolutionary and promises higher impact successes, a longer period—and longer-term funding—is needed to demonstrate results. While funding some of these extraordinary ideas for a long time may be risky, achieving success in even a small number of them would produce breakthroughs that more than compensate for those that did not succeed.

Recommendation 4: The committee recommends that NSET increase multiagency investments in research at the intersection between nanoscale technology and biology.

The relevant scientific community currently recognizes the importance of nanoscale biological and biomedical research. NSET, with the advice of the proposed NNAB, must further encourage and promote investment at the intersection between nanoscale technology and biology if it wishes to lead in this area. NSF and NIH report an increase in the number of proposals in nano-bio areas. Since many of these proposals cross the boundaries of individual agency expertise and missions, the creation of multiagency research programs and review mechanisms is critical. The role of NSET, with the advice of NNAB, is to overcome agency barriers that might otherwise prevent the allocation of resources to research that cuts across disciplines and missions.

Recommendation 5: The committee recommends that NSET create programs for the invention and development of new instruments for nanoscience.

NSET must invest heavily in the development of new instruments if it wishes to substantially accelerate breakthroughs in nanoscale science and technology. Historically, many important advances in science happened only after the appropriate investigative instruments became available. Since one must be able to measure and quantify a phenomenon in order to understand and use it, it is critical that we develop tools that allow for more quantitative investigations of nanoscale phenomena. These should include analytical instruments capable of manipulating, tailoring characterizing, and probing at the nanoscale.

Recommendation 6: The committee recommends the creation of a special fund for Presidential grants, under OSTP management, to support interagency research programs relevant to nanoscale science and technology. These grants should be used exclusively to fund meaningful interagency collaborations that cross mission boundaries, particularly among the National Institutes of Health, the Department of Energy, and the National Science Foundation.

The breadth of NNI and its fields of interest—from new materials development, to quantum computing, to cellular microbiology, and to national security—compels agencies to form more meaningful cooperation in their nanotecnology pursuits and to better leverage their investments for mutual benefit. While the NNI Implementation Plan lists major interagency collaborations, the committee has no sense that there is any common strategic planning occurring 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. All NNI funds are currently directed by each individual agency to the projects and programs of that agency's choice. Currently, NSET agencies have an incentive to collaborate on research only where they do not have and cannot acquire all the necessary skills in-house. This incentive has not been sufficient to develop any meaningful interagency research collaboration. Creation of a special fund strictly for meaningful interagency collaboration should motivate the best possible collaboration and leveraging of resources.

Recommendation 7: The committee recommends that NSET provide strong support for the development of an interdisciplinary culture for nanoscale science and technology within the NNI.

Nanoscale science and technology are leading researchers along pathways formed by the convergence of many different disciplines—biology, physics, chemistry, materials science, mechanical engineering, electrical engineering, and others. A critical factor in enhancing interdisciplinary research is the establishment of more academic laboratories in which interdisciplinary science is practiced. The agencies have done a good job of structuring multidisciplinary collaborations through their funding opportunities, but these collaborations do not necessarily lead to self-contained interdisciplinary groups in academia. Further, the overall value system used by the community to judge scientific quality continues to discourage interdisciplinary research, with negative impact on tenure, promotion, and the awarding of research grants. It is expected that the number of interdisciplinary groups will grow as it becomes evident that an interdisciplinary approach is necessary to tackle the interesting and complex problems that are part of nanoscale science and technology. However, creative programs that encourage such groups will accelerate this growth and must be part of NSET's agenda.

Recommendation 8: The committee recommends that industrial partnerships be stimulated and nurtured, both domestically and internationally to help accelerate the commercialization of NNI developments. NSET should create support mechanisms for coordinating and leveraging state initiatives to organize regional competitive clusters for the development of nanoscale science and technology.

Nanoscale science and technology promise to bring about important changes in industries based in biology, medicine, chemistry, and information technology during the next decade and beyond. Governments around the world have followed the lead of NNI by creating their own nanoscale science and technology programs, generally aligned with the industries in their countries and targeting specific advances in nanoscale science and technology that will improve the competitiveness and technological capability of those industries. Governments are fostering nanoscale science and technology mainly to enhance the competitive position of their industries, and the defining benefit is economic, as new capabilities in technologies and products move from laboratories to commercial reality.

As other countries aggressively pursue international partnering opportunities in nanoscale science and engineering, the United States should continually be positioning itself as the collaborator of choice in order to retain its world leadership not only in nanoscale science and technology development but also in commercial deployment. NNI must embrace efforts that fully engage industrial partnerships both here and abroad, rapidly moving developments from laboratories to novel applications, through product design and into the marketplace. The United States is most likely to realize economic benefits from nanoscale science and technology developments when the technology and its underlying intellectual property comes from U.S.-based laboratories, institutions, and corporations.

Coordinating and leveraging state-level initiatives with national funding is critical to the rapid deployment of nanotechnology advances. States are willing to match large federal research grants to their state universities. Several states already have efforts specifically targeting nanoscale science and engineering. NSET should establish appropriate mechanisms for monitoring state and local investments in nanoscale science and engineering in order to form partnerships that would leverage federal assets and infrastructure.

Recommendation 9: The committee recommends that NSET develop a new funding strategy to ensure that the societal implications of nanoscale science and technology become an integral and vital component of the NNI.

Our nation's success in developing, deploying, and exploiting new nanotechnologies will require synchronous innovation in how we educate and train our workforce, manage our R&D system, and prepare for and adjust to the expected and unexpected social and economic impacts of these new technologies. Activities supported by the societal implications theme are supposed to help ensure that this "second industrial revolution" produces social, economic, and technical benefits. Although some progress has been made, particularly with respect to educational initiatives, the disappointing level and diversity of efforts within this theme leads the committee to conclude that NSET has not given sufficient consideration to the societal impact and developments in nanoscale science and technology.

Agencies *willing* to engage in assessing societal implications must be given a budgetary incentive to do so. The committee believes that NSET should develop a funding strategy that treats societal implications as a supplement or set-aside to agency core budget requests.[1] In this vein, the committee suggests that

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[1] Such a funding strategy is not new. For example, most federal agencies resisted involvement in the SBIR program until Congress required agencies to set aside a certain percentage of their budget for the program.

NSET should request funding for societal implications activities and then award that funding directly to agencies willing to do this kind of work and capable of doing it.

The societal implications theme has three components: educational, outreach, and social science. However, unless things change dramatically during FY 2002, the social implications theme will simply be a fancy title for a relatively straightforward educational initiative targeted at graduate and undergraduate students. While not every agency may want to address all three components, they should all be required to budget for, or at least report about, these areas separately.

Agencies willing to engage in outreach or social impact studies should allocate funds directly to the office or division that typically engages in or supports these kinds of activities. These divisions could then pursue focused intramural studies or develop solicitations targeted at the appropriate social science community. These NNI agencies should also be encouraged to consider focusing on the topics and funding strategies highlighted in NSF and NSET-sponsored workshops on societal implications.

Recommendation 10: The committee recommends that NSET develop performance metrics to assess the effectiveness of the NNI in meeting its objectives and goals.

The committee sees a need to measure the progress of the NNI as a whole, under the aegis of the OSTP, with measurable factors including quality, relevance, productivity, resources, and progress in moving research concepts toward applications. To date, NNI programs have been evaluated as part of the Government Performance and Results Act (GPRA) procedures of the individual participating agencies.

Despite a long history of efforts to define and improve evaluation criteria, the academic, industrial, and government sectors continue to struggle with the problem of measuring the effectiveness of research activities. The challenge of evaluation is compounded in the case of the NNI, since the program spans multiple agencies with varying missions. However, once the participating agencies have agreed upon program goals, evaluation and exit criteria can be developed to appropriately measure effectiveness or success in achieving the goals. These criteria should be developed jointly by an appropriate council and with the various agencies under NSET. One possibility for such council could be the suggested NNAB.

Appendixes

A

Meeting Agendas

AUGUST 30-31, 2001
WASHINGTON, D.C.

Thursday, August 30

7:30 a.m. Continental breakfast

CLOSED SESSION

8:00 Executive session: Discussion of committee balance and composition, review agenda

9:30 Break

OPEN SESSION

9:45 Presentation of charge to committee/discussion. Mike Roco, senior advisor, National Science Foundation

10:15 NNI Organization, Mike Roco, chair, National Science, Engineering and Technology Council's subcommittee on Nanoscale Science, Engineering and Technology (NSET)

10:45 National Nanotechnology Coordinating Office (NNCO), Jim Murday, part-time director, NNCO

11:15 National Science Foundation Role in NNI, Mike Roco

11:45 Department of Defense Role in NNI, Jim Murday, superintendent, Chemistry Division, Naval Research Laboratory

12:15 p.m. Lunch

1:00 National Institutes of Health Role in NNI, Jeffrey Schloss, program director, Technology Development Coordination, National Human Genome Research Institute, NIH

1:30 National Aeronautics and Space Administration Role in NNI, Murray Hirschbein, senior advisor to the chief technologist, NASA

2:00 National Institute of Standards and Technology Role in NNI, Chad Snyder, program analyst, NIST

2:30 Department of Energy Role in NNI, Pat Dehmer, associate director for basic energy science, DOE

3:00 Break

3:15 Environmental Protection Agency Role in NNI, Stephen Lingle, director, Environmental Engineering Division, EPA

3:30 Department of Justice Role in NNI, Trent DePersia, director, R&T Development Division, National Institute of Justice

3:45	Department of Commerce, Office of International Technology and Programs, Technology Administration Role in NNI, Cathleen Campbell, director, Office of International Technology, DOC
4:00	Department of Transportation Role in NNI, Annalynn Lacombe, program analyst, Transportation Strategic Planning and Analysis Office, Volpe National Transportation System Center, DOT
4:15	Central Intelligence Agency Role in NNI, Frank Gac, Directorate of Science & Technology, CIA
4:30	Follow-up and general discussion
5:15	Cocktails, committee and speakers
	CLOSED SESSION
7:00	Committee dinner

Friday, August 31

	CLOSED SESSION
7:30 a.m.	Continental breakfast
8:00	Executive session
	Discussion of presentations Committee work plan Plan for future meetings
12 noon	Adjourn

OCTOBER 29-30, 2001
WASHINGTON, D.C.

Monday, October 29

7:30 a.m.	Continental breakfast
	CLOSED SESSION
8:00	Executive session: Discussion of Monday agenda and other committee business
8:45	Break
	OPEN SESSION
9:00	NSET and Agency Roles in Developing the FY2003 NNI Budget, James Murday, part-time director, NNCO (30 minutes for presentation, 30 minutes for Q&A)
10:00	Office of Management and Budget Role in Developing FY2003 NNI Budget, David Radzanowski, program examiner, OMB (30 minutes for presentation, 30 minutes for Q&A)
11:00	National Science Foundation, Establishment of Six NSF Centers for Nanoscale Research, Ulrich Strom, program director, Materials Research Science and Engineering Centers (30 minutes for presentation, 30 minutes for Q&A)
12 noon	Lunch
1 p.m.	Panel discussion: Agency Program Manager's Perspectives on NNI
	National Science Foundation—Ulrich Strom, program director, Materials Research Science and Engineering Centers
.	Department of Energy—Jerry Smith, program manager, Condensed Matter Physics; Dick Kelley, program manager, Materials Science
	National Institutes of Health—Jeffrey Schloss, director, Technology Development Coordination, National Human Genome Research Institute
	Department of Defense, Gernot S. Pomrenke, program manager, Optoelectronics and Nanotechnology, Air Force Office of Scientific Research
3:00	Break
3:15	Nanotechnology and National Security Research, Defense Advanced Research Projects Agency (DARPA), Robert F. Leheny, Director, Microsystems Technology Office

4:15	Break
4:30	Follow-up and general discussion
	CLOSED SESSION
6:30	Committee dinner

Tuesday, October 30

	CLOSED SESSION
7:30 a.m.	Continental breakfast
8:00	Executive session
	Discussion of presentations Discussion of committee topical drafts
12 noon	Lunch
1 p.m.	Executive session
	Discussion of committee topical drafts Develop outline for final report Next meeting
4:30	Adjourn

JANUARY 30-31, 2002
LA JOLLA, CALIFORNIA

Wednesday, January 30

7:30 a.m.	Continental breakfast
	CLOSED WORKING SESSION
8:00	Review of meeting agenda and objectives
8:20	Discussion of draft sections Short synopsis of team draft (5-7 minutes) followed by committee discussion introduction—Sam Stupp
8:45	Evaluation of Critical Program Areas—Mike Heller
9:15	Important Areas for Investment—Lynn Jelinski
9:45	Break
10:00	Social Science and the NNI—Denis Gray
10:30	NNI Partnerships—Tim Jenks
11:00	Program Management and Evaluation—Tom Theis
11:30	Overall draft observations Inclusion of sidebars in the report?
12 noon	Lunch Title of the report Teams work on individual drafts
5 p.m.	Committee reconvenes Discussion of revisions
5:30	Draft revisions to staff for duplication
6:30	Dinner—on your own

Thursday, January 31

7:30 a.m.	Continental breakfast
	CLOSED WORKING SESSION
8:00	Review agenda Discussion of revisions
8:15	Introduction–Sam Stupp
8:30	Evaluation of Critical Program Areas—Mike Heller
8:45	Important Areas for Investment—Lynn Jelinski
9:00	Social Science and the NNI—Denis Gray
9:15	NNI Partnerships—Tim Jenks
9:30	Program Management and Evaluation—Tom Theis
9:45	Sidebar recommendations
10:30	Break

10:45	What is missing?
11:30	Next meeting—March 4 and 5 Additional information? All revisions to staff by February 15
11:30	Strategy for report dissemination Who, what, where, and when?
12 noon	Adjourn

MARCH 4-5, 2002
WASHINGTON, D.C.

Monday, March 4

	CLOSED SESSION
7:30 a.m.	Continental breakfast
8:00	Overview of meeting OSTP visit
	OPEN SESSION
9:00	Mike Roco, senior advisor, National Science Foundation
	CLOSED SESSION
10:00	Break
10:15	Discussion
12 noon	Lunch
1 p.m.	Recommendations
1:30	Executive summary
2:00	Work on draft changes
6:00	Committee dinner

Tuesday, March 5

	CLOSED SESSION
7:30 a.m.	Continental breakfast
8:00	Discussion
10:00	Break
10:15	Discussion
11:15	Recommendations—executive summary
12:15 p.m.	Lunch
1:00	Recommendations—executive summary
2:00	Title of report—cover design
3:00	Break
3:15	Report distribution
3:45	Role of committee—final review process

B

Acronyms

ATP	Advanced Technology Program
CBRE	chemical, biological, radiological, and explosive
CIA	Central Intelligence Agency
CRADAs	cooperative research and development agreements
DARPA	Defense Advanced Research Projects Agency
DNA	deoxyribonucleic acid
DOD	Department of Defense
DOE	Department of Energy
DOJ	Department of Justice
DOT	Department of Transportation
EPA	Environmental Protection Agency
GMR	giant magnetoresistive
GPRA	Government Performance and Results Act
IWGN	Interagency Working Group on Nanotechnology
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NNAB	nanoscience and nanotechnology advisory board
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NNUN	national nanotechnology user network
NRC	National Research Council
NSET	Nanoscale Science, Engineering and Technology (subcommittee)
NSF	National Science Foundation
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PCAST	President’s Council of Advisors on Science and Technology
PITAC	President’s Information Technology Advisory Committee
SBIR	small business innovation research
SET	single electron transistor
State	Department of State
STTR	small business technology transfer
Treasury	Department of the Treasury
USDA	Department of Agriculture