Chapter 12

AGENCY FUNDING STRATEGIES

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12.1 VISION

There is no question that nanotechnology in its broadest sense will be a dominant force in our society in the early decades of the next century. The primary questions are how soon this destiny will arrive, what benefits and risks it presents, and how the United States can be in the best position to guide and capitalize on the development of nanotechnology for the benefit of Americans and for the world. U.S. funding agencies have both the opportunity and the obligation to seed the scientific efforts that will nurture nanotechnology to the point where they can realize their beneficial intellectual, economic, and societal potentials. The challenge for the funding agencies is to formulate a long-term and sustainable strategy that promotes the healthy development of nanotechnology within the constraints imposed by the annual cycle of the Federal budget. It is strongly recommended that this process begin with the creation of a high profile National Nanotechnology Initiative, which will have the short-term goal of doubling the Federal Government's present investment in nanotechnology research in fiscal year 2001.

12.2 CURRENT FUNDING PRACTICES

Nanotechnology research in the United States has developed thus far in open competition with other research topics within various disciplines. This is one reason that U.S. nanotechnology research efforts tend to be fragmented and overlap among disciplines, areas of relevance, and sources of funding (Roco 1999). This situation has advantages in establishing competitive paths in the emerging nanotechnology field and in promoting innovative ideas, and some disadvantages for developing systems applications. As the far-reaching consequences of nanotechnology R&D has begun to be appreciated within the scientific community and various Government agencies, interest has grown in focusing national resources on stimulating cooperation, avoiding unwanted duplication of efforts, and building a supporting infrastructure that will better position the United States to lead and benefit from the revolution that is coming. Twelve funding/research agencies established an informal group in 1997 in order to enhance communication and develop partnerships. The National Science and Technology Council (NSTC) formally established the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN) on September 23, 1998.

An inventory of current activities and R&D future needs was assembled at the workshop held by the IWGN on January 27-29, 1999. This inventory is presented herein. The agencies participating in the working group are the departments of Commerce, Defense, Energy, and Transportation (DOC, DOD, DOE, DOT), the National Aeronautics and Space Administration (NASA), the National Institutes of Health (NIH), and the National

Science Foundation (NSF), with NSF, DOD and DOE making the largest investment in nanotechnology in fiscal year 1999. Other agencies with nanotechnology-related activities that may be added in the future include the Department of Justice (DOJ) (with interest in forensic research, high-performance computing and database management), the Environmental Protection Agency (EPA) (with interest in measurement and remediation of nanoparticles in air, water, and soil), the Treasury Department (with interest in special colloidal suspensions at the Bureau of Engraving and Printing).

Section 12.7.1 outlines the main R&D themes, current focused programs and initiatives, as well as research opportunities at the seven major Government funding departments and agencies. The estimated total funding from the U.S. Federal agencies in fiscal year 1999 is approximately $255 million (based on the IWGN survey in June 1999, see Section 12.7.2). The projected nanotechnology-related needs of all participating departments and agencies for fiscal year 2001 total roughly double the amount of the current budget. For each of the seven major funding departments and agencies, this section provides a concise summary of the agency's current major interests in nanotechnology, and the themes and modes of R&D support proposed for increased funding in fiscal year 2001.

Department of Commerce (DOC, including the National Institute of Science and Technology, NIST)

1. *Current major interests in nanotechnology:* Measurement science and standards, including methods, materials, and data; development and acceleration of enabling commercial technologies through industry-led joint ventures (Advanced Technology Program—ATP). The current budget for nanotechnology is divided between measurement and standards research, and ATP cost-shared awards to U.S. industry.
2. *Themes and modes of proposed R&D support for fiscal year 2001:* Develop the measurement and standards infrastructure to support U.S. industry development and commercialization of nanotechnology; and perform economic and foreign assessment studies. Major themes in fiscal year 2001 include nanodevices and biotechnology for quantum level measurement and calibration; magnetic measurements and standards research; nanoscale characterization—measurement systems, approaches, and algorithms; standard data and materials; and nanoscale manipulation for synthesis and fabrication.

Department of Defense (DOD)

1. *Current major interests in nanotechnology:* Information acquisition, processing, storage, and display; high performance, affordable materials; and bioengineering for chemical and biological warfare defense, casualty care, and human performance monitors.
2. *Themes and modes of proposed R&D support for fiscal year 2001:* Investigator projects; focused programs and initiatives (e.g., the Multidisciplinary University Research Institute—MURI program, instrumentation grants, Defense Advanced Research Projects Agency—DARPA programs); DOD service laboratory programs; and cooperative research and development agreements between laboratories and commercial ventures. Major themes and new programs include advanced processes and tools; nanoelectromechanical systems (NEMS), with focus at DARPA; biocentric

research, where nano is part of the Office of Naval Research (ONR) overall program; and MURI topics focused on nanotechnology.

Department of Energy (DOE)

1. *Current major interests in nanotechnology:* Basic energy science and engineering, including experiments, diagnostics, fabrication and modeling, energy efficiency, defense, environment, and nonproliferation. The largest expenditures in the current budget include materials, chemistry, defense-related projects, and engineering.
2. *Themes and modes of proposed R&D support for fiscal year 2001:* Capital development at national labs; secondary funding of universities for collaboration with DOE labs; programs to encourage national labs to work with other Government agencies and industry; and 2-3 laboratory user facilities. Increased funding is needed to support both a network of research user facilities at four national laboratories and academic research for energy- and environment-related topics.

Department of Transportation (DOT)

1. *Current major interests in nanotechnology:* Nanostructured coatings; sensors for physical transportation infrastructure; and smart materials. DOT incorporates the results of nanotechnology R&D into its more focused R&D programs, without having specialized departments for nanotechnology R&D.
2. *Themes and modes of proposed R&D support for fiscal year 2001:* Efficient incorporation of research results into more focused DOT research and technology activities: nanostructured coatings for metallic surfaces to achieve super-hardening, low friction, and enhanced corrosion protection; "tailored" high-performance materials with reduced life-cycle costs, greater strength-to-weight, and longer service life for vehicles and infrastructure; "smart" materials that monitor and assess their own status and health and that of systems and subsystems; monitoring and remediation of oil spills and other hazardous materials incidents; studies of the implication of advances in nanotechnology for the next-generation of transportation professionals.

National Aeronautics and Space Administration (NASA)

1. *Current major interests in nanotechnology:* Lighter and smaller spacecraft; biomedical sensors and medical devices; powerful, small, lower power consumption computers; radiation hard electronics; and thin film materials for solar sails.
2. *Themes and modes of proposed R&D support for fiscal year 2001:* Three laboratories—Jet Propulsion Lab (Pasadena), Ames Research Center, and Johnson Space Center (Houston)—and academic research on space exploration topics. Research needs have been identified in the following areas: techniques for manufacturing of single-walled carbon nanotubes for structural reinforcement, electronic, magnetic, lubricating, and optical devices, chemical sensors, and biosensors; tools to develop autonomous devices that articulate, sense, communicate, and function as a network, extending human presence beyond the normal senses; and robotics using nanoelectronics, biological sensors, and artificial neural systems.

National Institutes of Health (NIH)

1. *Current major interests in nanotechnology:* Biomaterials (e.g., materials-tissue interfaces, biocompatibility); devices (e.g., biosensors, research tools); therapeutics (e.g., drug and genetic material delivery); and infrastructure and training.
2. *Themes and modes of proposed R&D support for fiscal year 2001:* Fund academic research, small business research, and in-house studies on nanobiotechnology, including the following topics: advances in biomaterials; clinical diagnostic sensors; genomic sensors; and nanoparticles and nanospheres for drug and gene delivery.

National Science Foundation (NSF)

1. *Current major interests in nanotechnology:* Fundamental academic research on novel phenomena, synthesis, processing, and assembly at nanoscale; generation of new materials by design; biostructures and bio-inspired systems; system architecture at nanoscale; instrumentation and modeling tools; high-rate synthesis of nanostructures and scale-up approaches; infrastructure and education; university-industry collaborations.
2. *The research themes and modes of proposed R&D support for fiscal year 2001:* The main research themes are: (a) nano-biotechnology, including biosystems, biomimetics and composites; (b) synthesis and processing of nanostructures "by design," and investigation of new phenomena and processes at nanoscale; (c) integration of nanostructures and nanodevices into systems and architectures, including multiscale and multiphenomenal modeling and simulation; and (d) investigation of environmental processes at nanoscale and at long time scales, including studies of the interactions between biological, organic and inorganic structures. Increase funding is envisioned for individual academic research and for centers/networks awards (ERC, MRSEC, Science and Technology Centers, and the National Nanofabrication Users Network).

12.3 GOALS FOR THE NEXT 5-10 YEARS: BARRIERS AND SOLUTIONS

Principal Goals and Challenges

The cardinal goal defined by members of the IWGN is that U.S. Government funding agencies must foster an enduring nanoscale science and technology culture that can in turn nurture industrial enterprises on the 10-20 year timeframe.

The major barrier to this goal is to convince decision makers that nanotechnology is important enough to warrant the special attention required to provide and maintain a sufficient funding base over the long term for this emerging and rapidly growing set of disciplines. Informing and educating decision makers is primarily the responsibility of the scientific, technical, and business communities, since the funding agencies themselves are prohibited from activities that may appear to be lobbying. The January 1999 IWGN "Vision for Nanotechnology" workshop and this report, as well as many previous workshops and their reports, are parts of the educational process.

In addition, a nanotechnology agenda will have to be supported by a broad coalition of scientists, engineers, and others in order for the cardinal goal to be achieved. The message of the IWGN has to be clear: Exploring the promise and exploiting the potential of nanotechnology is a long-term investment that will bring enormous societal and economic benefits, primarily to those most able to innovate and capitalize on the opportunities as they arise. To be either the leader or a fast follower in nanotechnology, the United States will have to be strongly engaged in the effort. Thus, the immediate goal is to establish a national nanotechnology initiative.

After achieving initial recognition of the importance of nanotechnology, the next major challenge will be to implement a sustainable long-term strategy. The Federal budget operates on an annual cycle, priorities change, and institutional memories are short. A significant danger to this endeavor is that the difficulty of the task will be underestimated during the early stages, and an inability to quickly produce the astounding advances so often hyped in the popular press may cause a backlash in the public and in Congress against long-term support for nanotechnology. Funding agencies must resist the temptation to rush into misguided development programs before the necessary science and technology base exists to identify realizable goals.

A further problem for nanotechnology development will be long-term competition for limited resources from the legitimate interests of other scientific and technology groups, which will argue persuasively for funding increases in their own areas. The proposed National Nanotechnology Initiative will provide a much needed short-term infusion of funding into the nanotechnology research community that will be effectively absorbed and utilized, ensuring that the best ideas are supported and drawing even more talent into the field. However, a long-term commitment with a steadily rising funding profile is necessary to establish a vigorous nanoscale science and technology community. This will require a funding strategy that will have to be reintroduced annually into the Federal budget process and continually supported by a broad range of the technical community.

Ancillary Goals and Challenges

The funding agencies will also need to encourage new modes of research and educational models to create a vigorous nanotechnology culture, as well as to provide the funding for an appropriate physical infrastructure and to maintain the research community for at least a decade. Eventually, the technology will evolve to the point where private industry becomes the dominant source of nanotechnology jobs, but there needs to be a supply of skilled workers ready for industry when industry is ready for commercialization.

Because of the shear breadth of nanotechnology, no single person or traditional discipline can encompass the range of skills and knowledge required for dramatic breakthroughs. Thus, small but agile teams of transdisciplinary researchers are likely to be best suited for innovation. However, this runs counter to the present structure for performing research, in which either an individual investigator or a large group of investigators (a center) from closely related fields are supported by disciplinary divisions within the various funding agencies. To encourage creativity, discovery, and invention in this mostly exploratory phase of nanoscience and engineering, a large proportion of the grants for nanotechnology research should be intended for small groups of one to four principal investigators, usually representing different disciplines (e.g., physics, biology and computer architecture) and/or institutions (including academe, national labs, and industry). This requires a commitment from the principal investigators to engage their colleagues and learn how to communicate across intellectual or organizational boundaries. Proposals from such groups should be reviewed by transdisciplinary panels that are instructed to take chances if the potential pay-off from a proposal is seen to be large. The primary metric for renewal of such proposals should be accomplishment.

There should also be a broader range of educational opportunities for students coming into nanotechnology areas. The students must gain in-depth knowledge in one subject, but they also need to develop breadth by being able to transcend geographical location, institution, and discipline. The problem with this goal is that most graduate students in technical areas are funded by the grants to their research advisors, and thus they are tied to a specific discipline and location because their mentors cannot afford to pay for students who are not in their labs. Thus, there should be a significant number of nanotechnology fellowships and training grants that will give the best students the ability to craft their own education by specializing in one area but having the opportunity to work with one or more other mentors. This will further encourage a practice that is already occurring, since much of the current transdisciplinary nanotechnology research efforts are actually initiated by students who realize the benefits of working with more than one advisor. Programs that encourage intermingling among science, engineering, and business disciplines should also be supported strongly, since grooming future technically competent entrepreneurs is at least as important as educating future professors and researchers. Nanotechnology workshops focused on graduate students with primary expertise in a large number of different disciplines should be held that would allow them to see and understand the bigger picture and encourage them to communicate across boundaries.

Funding agencies must also ensure that there is a sufficient physical infrastructure available for nanotechnology research to flourish. This requires a broad range of facilities, from the scanning probe microscopes in each investigator's lab to the expensive high-resolution electron and ion beam microscopes and lithography systems that require institutional support. One major impediment to this goal is the fact that funding agencies award grants for the purchase of major equipment items but do not always provide adequate resources for operation and maintenance. In general, funding agencies should consider a significant contribution toward running and repairing a major instrument to be part of the equipment grant to a university. Industry should also contribute to these costs, especially where it derives benefit from access to those instruments. The National Nanofabrication Users Network (NNUN) provides an example of a group of regional facilities based in host universities that provide access to equipment and expertise to outside users. However, the number of such facilities needs to increase significantly from the current number of five.

There must be enough funding now to support the best nanoscale science research in the current academic and national laboratory groups. However, there has to be a clear understanding that although industry will hire excellent technically trained people with almost any background, there will be very little work in industry on nanotechnology until it is near (probably within three years) to having a significant market impact. For many, if not most, areas within the nanoscale sciences, this will be at least ten years in the future. In the meantime, there must be a fertile ground where the best young researchers trained in nanoscale science can continue to contribute to and advance the field. This "major league" for nanotechnologists will be primarily in universities and national labs for the next decade. Thus, the funding profile for university grants and national labs in nanotechnology must increase at a rate that will encourage the best young researchers to stay in the field and allow them to build up their own research programs. This indicates that the funding profile for nanotechnology during the next decade must increase at a rate significantly higher than inflation, and that it may require at least ten years to reach a steady state. The first two products to come out of the early stages of Government funding will be trained people and scientific knowledge. There must be a critical mass of both before the development of a technology and intellectual property can occur. Once these become compelling, then actual products, manufacturing infrastructure, and high paying jobs will emerge that will repay the investments that have been made in this area.

12.4 SCIENTIFIC AND TECHNOLOGICAL INFRASTRUCTURE

By its very nature, nanotechnology is an extremely transdisciplinary area. The major portion of the research funding should be concentrated in small groups, essentially one to four principal investigators, dedicated to a particular project; however, it is also important to identify a few "grand challenges" that will require larger centers and consortia where ideas can bridge traditional intellectual, organizational, and geographical borders. There should not be a specific formula around which these centers and consortia are constructed, but some of them should involve collaborations among academic, national, and industrial laboratories. Industrial groups should be required to contribute some of the resources if they participate in these efforts, but the funding agencies should provide some support to research programs in industry (for instance by funding collaborative activities in partnering universities) to act as leverage to their commitments. In addition, flexible fellowships and training grants are necessary that will allow students and postdoctoral fellows a considerable amount of freedom to move between academic disciplines and geographic locations.

The issue of equipment infrastructure must be addressed. The most common instruments will probably be various types of scanning probe, electron, and ion microscopes. On the one hand, there has to be an understanding that a single research group can easily have a need for several different scanning probe microscopes, since there are now many different types, each optimized for a different task. On the other, the best electron and ion microscopes are very expensive and costly to maintain, and a means should be provided for universities to acquire, maintain, and operate such systems. There will also be a need for a wide range of facilities and more traditional instruments, ranging from synchrotron radiation and neutron sources, X-ray diffractometers, all types of spectrometers, and computational facilities to both handle the processing of massive amounts of data and carry out the crucial modeling and simulation work needed to advance the field rapidly. Since the emphasis for most of the groups performing nanotechnology research needs to be on the science and not the equipment, a larger number of shared laboratories and regional facilities should be funded and staffed. As proposed in Chapter 3 of this report, some of these facilities should be charged with the responsibility to develop new instrumentation, essentially to address the grand challenge of nondestructively determining the three-dimensional elemental and chemical state map of a system with sub-nanometer resolution and one atom per cubic nanometer sensitivity.

There should also be a few multi-technology engineering demonstration centers. These would be pilot fabrication facilities to try out new manufacturing ideas, such as methods to attain large-scale production of carbon nanotubes or semiconductor nanocrystals. An example of such a facility is the University of Barcelona-Xerox Laboratory for Magnetics Research, which has been initiated by the University of Barcelona, Xerox Corporation, and a number of smaller companies to minimize the time for transition from discovery to commercialization. Such a facility would be open to use by a variety of groups, from academic to large industry, on a fee basis according to the nature of the group involved.

The issue of information sharing is paramount: an agency and specific funding must be identified to foster communication of ideas and results among the various subfields within nanotechnology. One approach would be for an agency such as NIST to sponsor a nanotechnology-specific information clearinghouse and maintain an up-to-date database addressable via the Web, as well as sponsor workshops that involve younger researchers. Professional science and engineering societies should also take on the challenge of improving communication between the disciplines they traditionally represent and other contributors to nanotechnology, both nationally and internationally. The societies should provide transdisciplinary nanotechnology forums that enable creative exchange of ideas; commingle university, government and industrial researchers; provide tutorials that breakdown barriers between disciplines (e.g., the biological and physical sciences); and educate the public.

12.5 R&D INVESTMENT AND IMPLEMENTATION STRATEGIES

In any discussion of implementation strategies, there is a significant tension between what is the ideal path to follow and what is practical or realistic to attain. On the one hand, nanotechnology will require a long-term and coordinated commitment from the funding agencies, but on the other hand, the budgets for the funding agencies are set annually and balance competing interests. The responsibility for alerting budget planners to the opportunities and risks presented by the emergence of nanotechnology rests primarily with the scientific and technical community, but the funding agencies are best suited to provide the framework for increasing the priority for nanotechnology research. In order to have a strategy to implement, those working in the area of nanotechnology will first have to convince decision makers that this is truly a national priority.

To obtain the high-level attention necessary for a sustained investment, the fact that nanotechnology has reached a critical stage requiring immediate attention will be best articulated through the creation of the National Nanotechnology Initiative. A dramatic increase in funding for nanotechnology, in particular a doubling of the investment portfolio, from the current $255 million/year in 1999 to on the order of $500 million/year, is an important short-term goal. However, in order to satisfy the strategic vision for creating a viable nanotechnology culture from which new industries can emerge, that level of investment will have to double again over a period of five to seven years. The funding agencies will have to cooperate and coordinate their efforts, since the needs of the field will evolve with time.

The first priority is to ramp up funding for small groups in universities. The number of grants must increase, since only a small fraction of worthy proposals are currently being funded, but it is also important to increase the size of individual grants to make sure investigators are adequately supported. Next, programs in U.S. Government (national) and private laboratories should grow to provide the critical mass of researchers necessary to have a vibrant field and to create the broad technology base required for invention to emerge. Finally, new businesses and industries should be seeded through programs such as SBIR grants and access to regional centers and technology demonstration facilities.

Will a National Nanotechnology Initiative be a wise investment, and can it be effectively absorbed and utilized by the research community? Nanoscale science and engineering knowledge is exploding worldwide because of the availability of new investigative tools and interdisciplinary synergism, and is driven by emerging technologies and their applications. New experimental and modeling tools have opened additional windows of research opportunity. The publication rate in nanoscience is doubling every two to three years, and the number of revolutionary discoveries can be expected to accelerate over the next decade. As indicated in the body of this report, the discovery and development of new nanoscience principles will affect existing and emerging technologies in almost all industry sectors and application areas, including computing and communications, pharmaceuticals and chemicals, environmental technologies, energy conservation, manufacturing, and healthcare-related technologies. Because of the highly competitive nature of nanotechnology research and the potential for high economic and social return on investment, the need to establish a national initiative is compelling.

The reported Federal Government expenditure for nanotechnology in fiscal year 1997 was approximately $116 million (Siegel et al 1998; summarized in Siegel et al. 1999). Nanotechnology as defined there only included work to generate and use nanostructures and nanodevices; it did not include the simple observation and description of phenomena at the nanoscale that is part of nanoscience. Utilizing the broader definition, the Federal Government expenditure is estimated to be about $255 million for fiscal year 1999. However, a much greater investment would be utilized effectively, and in fact many promising opportunities are not being pursued now because of lack of resources. The funding success rate for the small-group interdisciplinary research program, NSF's fiscal year 1998 "Functional Nanostructures" initiative, was only about 13%, about 1/3 of the proposals of high quality that could have been funded (significantly lower if one considers the limitation of two proposals per university imposed in that initiative). The success rate for the DOD 1998 MURI initiative on nanostructures was 17% (and only 5% if one starts with the number of white papers submitted to guide proposal development). Since one-third of proposals submitted are usually considered to be "very good" to "excellent" and thus deserving of funding with priority, the number of high-quality ideas worth pursuing significantly exceeds the current investment level.

A rough estimate of the interest in nanotechnology can be made from the total number of scanning probes purchased, approximately 4,000 in the United States. One instrument can support two full-time research efforts (considering that experimental design, data analysis, and reporting take up at least half the time of a research effort) at a level of about $300,000/year for both personnel and equipment. (This probably somewhat overestimates the university laboratory cost and underestimates the government/industrial laboratory cost.) On this basis, without factoring in the contributions from theorists and researchers using other analytical equipment (such as high-resolution electron microscopes, near-field visualization instruments, and small angle neutron scattering), the capacity of the United States to perform nanotechnology R&D is greater than $1.2

billion/year. Doubling the current R&D expenditures in fiscal year 2001 will satisfy less than one-half of that research capacity, and thus ensures that many of the best research groups and best ideas are funded. Also, since obtaining a grant in nanotechnology will be more accessible, many more strong researchers will be drawn into and enrich the field.

12.6 PRIORITIES AND CONCLUSIONS

Nanotechnology is an emerging set of fields that will have enormous societal and economic consequences in the next century. These fields have reached a critical stage where their potential can be reasonably anticipated but has not yet been realized. In order to accelerate the development of nanotechnology to ensure that the United States is at or near the lead in as many of the fields a possible, a significant increase in the level of the effort and a reorganization of the current research culture are required. To achieve such major changes, a National Nanotechnology Initiative is proposed. A short-term doubling of the national investment in nanotechnology, followed by a longer-term redoubling will provide the resources required sustaining the high quality of the research currently being performed and implementing important new initiatives. The funding agencies will have the responsibility to encourage new collaborative research modes, provide broader educational opportunities, support a national infrastructure to provide open access to instrumentation, techniques, and information, and overall to sustain the nanotechnology R&D community during its developmental stage.

12.7 ATTACHMENTS: ILLUSTRATION OF FUNDING THEMES

12.7.1 General Themes and Initiatives on Nanotechnology at DOC, DOD, DOE, DOT, NASA, NIH, and NSF

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Presented below is a summary of the main research and education themes, focused programs and initiatives, and R&D opportunities identified at the Federal departments and agencies with the largest contributions to nanotechnology.

1. DOC: Department of Commerce, especially the Role of the National Institute of Standards and Technology (NIST) in Nanotechnology

Main Themes

Nanotechnology has profound implications for NIST's mission to support the U.S. measurements and standards infrastructure. NIST's research interest in nanotechnology is due to its mandate to develop low-cost, widely available primary standards and atomically accurate measurement systems. Nanotechnology-based standards have the potential to greatly improve the efficiency of the U.S. standards system by reducing the currently laborious traceability chains needed for reliable products.

U.S. industry is also interested in nanotechnology, including the latest fundamental discoveries, as evidenced by the marketing of new nano-based products from computer disk storage to cosmetics and the many proposals for funding of nanotechnology-related projects by NIST's ATP program. ATP awarded approximately $8 million to industry for joint projects with NIST related to nanotechnology in fiscal year 98.

Focused Programs and Initiatives

Nanotechnology-based commercialization is expected to increase dramatically over the next decade. This will require NIST to respond with new standards and measurement capabilities in support of U.S. trade. The nanotechnology initiative will allow NIST to exploit these nanotechnology approaches in many more modes of activity. The research will lead to the development of a suite of intrinsic standards based on the manipulation and measurement at or near single atoms, electrons, and molecules. This new set of measurement and standards tools will enable NIST to anticipate industry requirements and respond at the same rapid pace as the technological innovations.

Research Opportunities

The main categories of research opportunity for DOC and NIST are to develop the measurement and standards infrastructure to support U.S. industry development and commercialization of nanotechnology, and to perform economic and foreign assessment studies. Major themes in fiscal year 2001 include nanodevices and biotechnology for quantum level measurement and calibration; magnetic measurements and standards research; nanoscale characterization: measurement systems, approaches and algorithms; standard data and materials; and nanoscale manipulation for synthesis and fabrication of measurement systems and standards.

2. DOD: Key Areas of DOD Interest in Nanostructures and Nanodevices

Main Themes

The Department of Defense depends on advanced technology to maintain U.S. military superiority. Rapid, complete, and accurate information is a key advantage in warfare. To meet this need, DOD has been the primary Federal supporter of electronics and materials sciences. The NSF Federal Funds for R&D Report (Meeks 1997) states that the DOD accounted for 64% of Federal technology base investment in electrical engineering in 1997, 36% in metallurgy and materials, and 55% in all engineering. Nanotechnology provides an opportunity for continued rapid progress in these fields.

Modern electronics and electro-optics are revolutionizing information acquisition, processing, storage, and display. The benefits to DOD of ongoing nanoscience R&D will include network centric warfare (near instantaneous collection and dissemination of information worldwide), augmented use of uninhabited combat vehicles (only surveillance platforms were available in 1999) to limit human casualties and enhance performance, and training aides (e.g., virtual reality tools to simulate real war without placing troops and equipment in actual physical danger).

<u>Information acquisition/processing/storage/display</u>

- Faster processors (smaller size enables higher speed)
- Denser memories (terabit per cm^2 implies 10 nm pixels)
- Lower-power, more affordable electronics (more innovative, more functional devices on chip)

– Sensor suites on a chip (NEMS, MEMS/electronics processing)

– Optoelectronic capabilities (giga-terahertz, multispectral, photonics)

Modern warfare is practiced with sophisticated weapons and platforms whose performance requirements far exceed normal commercial practices; higher-performance, more affordable materials are continually required to maintain military advantage.

Materials performance and affordability

– Extended life & maintenance (failure mechanisms initiate at nanometer scales)

– New properties in nanostructured materials (quantum and interface effects)

– Biomimetics (biological materials are frequently nanostructured composites)

Information, weapons, and platforms are tools; human performance ultimately determines warfare results. Improvements in monitors/controls of human physiology for performance assessment, casualty care, and susceptibility to chemical/biological agents are all important.

Bioengineering

– Chemical-bio-warfare defense (secondary/tertiary supramolecular structure key to sensing/protection)

– Casualty care (miniaturized devices to sense/actuate, protein manipulation)

– Personnel condition monitor/stimulus

Focused Programs and Initiatives

DOD has identified nanoscience as one of its six science and technology strategic research areas. The DOD S&T program is deliberately decentralized to more effectively couple the research to Service needs. Each Service—Air Force, Army, Navy/Marine Corps—has its own basic research program, funded by a Service budget line. These Service programs are largely single-investigator projects at universities; some additional work is performed at the Service laboratories. In addition, DARPA has a program to accelerate the development of promising but high-risk technologies, and DOD has a program to support research benefiting all the services. The DARPA and DOD programs are more likely to be multi-person, targeted at specific technology goals, and have well-defined lifetimes (3-5 years). Present DARPA and DOD programs targeting nanotechnology include the following:

- DARPA: Ultra Electronics, '91-'99; Advanced Microelectronics, '97-'00; Molecular Level Printing, '98-'00; Virtual Integrated Prototyping, '97-'00; Molecular Electronics, '99-'00; Terahertz (QD), '99-'02; Advanced Lithography, indefinite.
- MURI (Multidisciplinary University Research Centers): Mesoscale Patterning for Smart Material Systems, ARMY, Princeton U., '94-'99; Materials and Processing at the Nanometer Scale, AF, USC, '95-'00; Nanoscale Devices and Novel Engineered Materials, AF, U. Florida, '95-'00; Cluster Engineered Materials, ARMY, Northwestern U., '97-'02; Photonic Bandgap Engineering, ARMY, UCLA, '96-'01;

Quantum Structures for Thermoelectric Applications, NAVY, UCLA, ‘97-‘02; S&T of Nanotube-based Materials and Devices, NAVY, UNC, ‘98-‘03; Self-Assembled Semiconductors: Size/Distribution Control, AF, USC, ‘98-‘03; Computational Tools to Design/Optimize Nanodevices, AF, U. Minnesota, ‘98-‘03; Engineering of Nanostructures and Devices, ARMY, Princeton U., ‘98-‘03; Low-power High Performance Nanoelectronic Circuits, NAVY, Arizona State U., ‘98-‘03; Science Base for Nanolithography, ARMY, U. New Mexico, ‘99-‘04; Hybrid Molecular and Spin Semiconductors, ARMY, Purdue U., ‘99-‘04.

Research Opportunities

Nanoelectronics and nanoelectromechanical systems (NEMS) will require a significant investment from DOD. A science base must be established to provide new approaches to affordable fabrication of quality nanostructures, understanding of the physical/chemical properties of those structures, the physics of new device concepts, and system architectures to exploit those new concepts in circuits. High-performance materials based on nanostructures require investment in new concepts for nanocluster formation, high surface area materials such as aerogels, measurement of interfacial properties, and physics/chemistry of materials failure mechanisms (materials failure initiates at the nanoscale). The considerable non-DOD investments in medicine and health will inevitably lead to enhanced casualty care and human performance; however DOD must pay attention to adapting these advances to its specific needs, especially for chemical/biological warfare defense.

3. DOE: Nanotechnology Research in the Department of Energy

Main Themes

The Department of Energy has two interests in nanometer-scale research: first, understanding the science and engineering of nanoscale systems, and second, development and use of nanotechnology-based systems in DOE technology programs such as defense programs and waste management. Nanotechnology covers the broad base of almost all scientific fields and fits between classical mechanics and quantum mechanics. Nanoparticles include viruses, genes, particles, structures, neurons, chemicals, solid state crystals, small magnets, and more. Our uncertainty regarding the science of these systems is large. There are large gaps in the knowledge of nanoscale physics, engineering, and physical properties, such as heat transfer, electron motion, collective phenomena, assembly of systems, controlling systems, impurity effects, and diagnostics. New scientific research on these systems will open many doors to new capabilities in DOE-related areas. In materials science, many new opportunities will be opened that will have profound ramifications for energy and the economy in such areas as electronics, solar energy, smart materials, ultracapacitors, magnets for motors and generators, batteries, and microfilters for chemical processing, water treatment, and waste entrainment.

Focused Programs and Initiatives

Already the Basic Energy Science (BES) materials science program has initiated basic research in several areas of nanoscale materials, including theory, computer simulations, structure and properties, materials processing, and new materials. Research is being carried out on a wide variety of materials, including nanotubes, fullerenes, semiconductors, nanocrystals, magnet precipitates, quantum dots and nanoclusters, magnet particles, and organically templated self-assembled structures.

In the BES engineering program, which is much smaller than the material science program, work has already begun on diagnostics to measure small nanoparticles in air, on surfaces, and in water. This will be very important in controlling environmental contamination in a society that will use nanoparticles in large amounts. The engineering program is also active in studying electron and heat transfer and physical properties of nanosystems and the fabrication of systems, including quantum dots and nanoelectronics. In engineering, nanotechnology will have major impact on diagnostics of systems, robotics, remote controls, environmental protection and knowledge, computer development, mass storage, smaller cheaper systems, systems failure, security, and other areas.

Among the new areas of opportunity in chemistry that are being explored in BES are catalysis, where small particles have long been the focus of researchers, separation science, molecular-level detection, and photochemical energy conversion. Among the opportunities that nanoscale chemistry offers is the possibility that this size scale will enable an understanding of the relationship between colligative (bulk) properties and molecular properties. In the technology programs at DOE, nanotechnology plays an increasing role.

4. DOT: Enhanced Awareness and Application of Nanotechnologies in Transportation

Main Themes

Transportation offers many opportunities for application of nanotechnology products and processes, such as nanostructured coatings, sensors for infrastructure, and smart materials. Within the Department of Transportation (DOT), the focus of research and development is on advancing applications of innovative enabling technologies, including nanotechnology. This focus is necessarily shaped by the department's mission, which is primarily operational, regulatory, and investment-driven.

The research conducted by DOT's operating administrations (the United States Coast Guard, Federal Aviation Administration, Federal Highway Administration, Federal Railroad Administration, Federal Transit Administration, Maritime Administration, National Highway Traffic Safety Administration, and Research and Special Programs Administration) is at the applied or developmental end of the spectrum and typically addresses relatively short-term, specific problems and opportunities. As specific nanotechnology research results are achieved relevant to DOT needs and responsibilities, the department will seek to encourage and incorporate them into its focused research and technology activities.

Focused Programs and Initiatives

DOT is actively involved in outreach efforts to ensure that the largely private and state-level transportation sector is aware of the potential value of current technological advances and is thereby motivated to exploit these opportunities. DOT chairs the NSTC

Technology Committee (under which the IWGN falls) and its Transportation R&D Subcommittee. These committees are responsible for facilitating coordination of relevant research activities across the Federal Government and for fostering mutual awareness between the technology and transportation communities. As nanoscience and technology and related processes evolve, DOT will encourage and promote their application throughout the nation's transportation sector.

Research Opportunities

Relevant application areas and research opportunities for nanotechnology in transportation include atomic-level coating of metallic surfaces to achieve super-hardening, low friction, and enhanced corrosion protection; "tailored" materials with reduced life-cycle cost, greater strength-to-weight, and longer service life; and nanotechnology-based energy storage and fuel systems. Other opportunities include smart materials that monitor and assess their own status and health and that of the system or subsystem of which they are a part; developments here will result in a wide range of sensors (nanoscale to microscale) suitable for incorporation into microprocessor-controlled subsystems and components.

5. NASA: Towards Advanced Miniaturization and Functionality

Main Themes

The international space station program and Mars exploration studies have defined technology and research needs that are critical to their respective individual goals. These include research on micro- and nanotechnologies, manufacturing processes, and advanced materials. The goals of all are focused on enabling humans to live and work in space or on a planet, enhancing performance, reducing cost, and maintaining the health and well-being of the crew. Working in pursuit of these goals, a team of 11 people from the NASA Ames Research Center recently was presented the Feynman Prize for Molecular Nanotechnology by the Foresight Institute. Also in pursuit of these goals, NASA and the National Science Foundation have held cooperative discussions on nanotechnology, as well as on biomedical technology and bioengineering. The NASA Human Exploration and Development of Space enterprise requirements include the following categories:

- Manufacturing technology: Improve rapid prototyping using the stereolithography and fusion deposition modeling techniques to produce functional prototypes and working models, including use of single-wall nanotubes. Improve composites manufacturing using fiber placement, filament winding, lamination, and resin transfer molding techniques. Improve the manufacture and precision of miniature mechanical components and electronic assemblies, and develop micro- and nanotechnologies to manufacture components.
- Nanotechnology: Potential applications and manufacturing techniques of single walled carbon nanotubes (SWNT), or "buckytubes." Applications include structural reinforcement; electronic, magnetic, lubricating, and optical devices; and chemical sensors and biosensors.

NASA's other near-term thrusts involve technological outreach activities to the microelectronics industry. NASA is using established tools to develop autonomous devices that articulate, sense, communicate, and function as a network, extending human presence beyond the normal senses. These tools will allow humans to function more fully while monitoring and maintaining bodily health. These technologies can be applied to health, ecology, warfare, and recreation.

With applications of existing technologies, progress can be accomplished in all these areas, but only to a limited degree. In all fields, present and near-term devices pale in comparison to examples in nature. The efficiency of energy conversion in mitochondria or in photosynthesis has not been equaled by human inventions. The complexity and efficiency of a simple reptilian nervous system far outstrips modern computer-driven robots. Biological sensors such as a dog's nose or a bat's ears far outstrip any man-made sensing device. And the brains that process the information have no equal in our laboratories.

Research Opportunities

In the coming decades we will investigate the design of nature's finest inventions. Building devices that are closer to these biological models will require using techniques and materials that would be unfamiliar to any modern fabricator. These techniques are likely to grow out of combined efforts of molecular biologists, material scientists, electrochemists and polymer chemists. This synergy will surely result in new specializations that have not yet been conceived. Compared to the single crystalline-based technologies we now rely upon, future nanodevices will greatly outperform our current technologies due to their small size, varied composition, and molecular precision. Successful application of these technologies will augment our natural abilities, and, while conforming to human limitations, expand the human experience throughout our solar system and into the reaches of interstellar space.

6. NIH: Challenges in Nanobiotechnology

Main Themes

Currently, the National Institutes of Health support individual research efforts in the area of nanotechnology. NIH-supported nanotechnology-related projects span a range of research areas. Examples include the following:

- Design of DNA lattices that readily assemble themselves into predictable, two-dimensional patterns. These arrays are composed of rigid DNA tiles, about 60 nm^2, formed by antiparallel strands of DNA linked together by a double-crossover motif analogous to the crossovers that occur in meiosis. The precise pattern and periodicity of the tiles can be modified by altering DNA sequence, allowing the formation of specific lattices with programmable structures and features at a nanometer scale. This research has the potential to lead to the use of designed DNA crystals as scaffolds for the crystallization of macromolecules, as materials for use as catalysts, as molecular sieves, or as scaffolds for the assembly of molecular electronic components or biochips in DNA-based computers.

- Development of methodologies to improve the resolution and reduce the time and cost of nucleic acid sequencing.
- Work on understanding the principles of self-assembly, at different dimensional levels, and component material interfaces that define the formation of tooth enamel and bone.
- Development of nanotubules, nanoparticles, and nanospheres as drug delivery system scaffolds and for colorimetric detection of polynucleotides.
- Development of biosensors for the detection of single and multilayered molecular assemblies.
- Studies on motor proteins that convert chemical energy to mechanical energy and vice versa.
- Use of nanoscale structures for the development of nanostructured matrices and nanocomposite materials.
- Development of technologies such as atomic force microscopy to better visualize and understand cellular nanostructures, such as protein-DNA assemblies and cell organelles.

Future Planned Activities Relevant to Nanotechnology at NIH

Nanotechnology projects are currently supported under numerous programs; however, NIH has not yet planned specific initiatives focused exclusively in this area.

7. NSF Perspective: Fundamental Research and Education for Nanotechnology

Main Themes

- Scientific and engineering frontiers at nanoscale: Develop fundamental knowledge of basic nanoscale phenomena and processes by promoting discovery in key areas at the interfaces between physics, chemistry, biology, and engineering. Examples include research on novel phenomena, synthesis, processing, and assembly at nanoscale; modeling and simulation at nanoscale; creation of materials by design; functional engineering at nanoscale; exploratory research on biosystems at the nanoscale.
- Create a balanced infrastructure for nanoscale science, engineering, technology, and human resources in this field, including university-industry partnerships.
- Education: Nanotechnology provides new opportunities to promote education at the interfaces between physics, mathematics, chemistry, biology, and engineering.

Programs and Initiatives

NSF has had activities in the following areas:

- Nanoscale science and engineering research is supported within disciplinary programs in the NSF directorates for Mathematical and Physical Sciences, Engineering, Biology, Computer and Information Systems and Engineering, and other areas.

- The Advanced Materials and Processing Program included aspects of nanostructures, molecular self-assembly, and nanochemistry (1988-94).
- Ultrafine Particle Engineering: synthesis and processing of nanoparticles at high rates (1991-1998).
- The "National Nanofabrication Users Network" has had a focus on electronics, extending a MEMS top-down approach in the first four years; currently it is expanding in the entire nanotechnology field (1994-; four-year renewal in 1998).
- The network "Distributed Center for Advanced Electronics Simulations" (DesCArtES), with the main center in the University of Illinois, has a main focus on nanoelectronics modeling and simulation.
- NSF funds several other centers: Science and Technology Centers at the University of California Santa Barbara (QUEST, 1989-) and Cornell University (Nanobiotechnology, 1999-); MRSECs include University of Wisconsin–Madison, Johns Hopkins University, University of Kentucky; ERCs include the University of Illinois; and Industry-University Cooperative Research Centers include the Particle Center at Penn State.
- Nano-instrumentation, NANO-95, was focused on increasing the success rate in the acquisition and development of nano-instrumentation (1995).
- Education opportunities are funded in centers, in collaborations with industry, and in groups of young U.S. researchers working in Japan and Europe. Research Experience for Undergraduate sites include Stanford University, University of South Carolina, Cornell University, UCSB, and Penn State University. Course development initiatives are also supported.
- The initiative "Partnership in Nanotechnology: Functional Nanostructures" (NSF 98-20) funded small groups working on functional nanostructures; the initiative involved participation of other agencies, national laboratories, and industry.
- An STTR (small business technology transfer) Solicitation on Nanotechnology was issued in July 1998; awards were made in fiscal year 1999.
- University-industry partnerships are encouraged (using the models provided by the program, Grand Opportunities for Academic Liaison with Industry, or GOALI).
- Nanoscale Science and Technology was an area highlighted in the NSF budget for 1998/99. NSF expenditure was $75 million in fiscal year 1998, and $90 million in fiscal year 1999 (or ~ 3% of the NSF research budget).
- The initiative "Exploratory Research on Biosystems at the Nanoscale" (NSF 99-109) focuses on high-risk, high-payoff research on nanoscale processes in biological and bio-inspired systems.

Research Opportunities

Several topics with increased potential are investigation of new phenomena, properties and processes; interface with bio-synthesis approaches, bio-nanostructures, and biomedicine; theory and simulation techniques for predicting synthesis and behavior of clusters; multifunctional/adaptive nanostructures; time-effective, economical, high-rate production methods; and broad enabling tools with impact on other disciplines and technologies.

Initiatives are being considered in the following areas:

- Nano-biotechnology: biosystems, bio-mimetics and composites
- Interfaces in environment at nanoscale: small length-scale/long time-scale processes; functional interfaces between bio/inorganic, inorganic, and biostructures
- New paradigms of operation, synthesis, and fabrication: nanostructures "by design;" quantum realm; and exploratory computational principles—quantum, DNA, etc.
- Integration of systems and architectures at the nanoscale: integration at nanoscale and with other scales; multiscale and multiphenomenal modeling and simulations

12.7.2 Current Funding for Nanotechnology Research

Contact person: M.C. Roco, IWGN

The estimations of Federal Government support for nanotechnology research in fiscal years 1997 and 1999 are as shown in Table 12.1 (not including programs at DOT, USDA, EPA, the Treasury Department, or BMDO):

Table 12.1. Estimations of Federal Government Support for Nanotechnology

	Fiscal Year 1997 (Siegel et al. 1998)	**Fiscal Year 1999** (IWGN survey in September 1999)
NSF	$65M	$85M
DOD (including DARPA, ARO, AFOSR, ONR)	$32M	$70M
DOE	$7M	$58M
DOC (including NIST with ATP)	$4M	$16M
NASA	$3M	$5M
NIH	$5M	$21M
TOTAL	$116M	$255M

12.7.3 Priorities for Funding Agencies: A Point of View

Contact: G. Whitesides, Harvard University

Role of Federal Agencies

NSF. NSF has established its role as an important source of support for small, peer-reviewed single-investigator university programs. It also supports the materials research science and engineering centers (MRSECs); these organizations, or structurally related new ones, would provide a cost-effective way of supporting shared facilities and encouraging small collaborative programs in nanoscience.

DARPA. DARPA has historically been a major source of support for nanoscience. This agency has been particularly good at building focused scientific/technical communities (especially those that mix university, industry, and national labs), and at focusing enough support on specific areas to give those areas strong boosts. It would be the natural lead agency in an effort in nanoscience and nanotechnology, and it has established programs in the area.

Other DOD agencies. ONR has historically been a vital source of support for chemistry, physics, and materials science. It also has effective programs for building communities, although the programs are typically more university-centered than those in DARPA. ONR's budget would have to be supplemented to build a program in nanoscience that is large enough to have a significant impact on the field.

NIH. NIH is the obvious source of support for the development of nanostructures relevant to biomedical devices (for example, genomic and proteomic chips). It has historically been receptive only to so-called hypothesis driven research and has not been very active in supporting device fabrication, engineering, or fundamental science leading toward devices; however, this prejudice against engineering now seems to be disappearing. NIH would also be the plausible partner in shared support intended to integrate biologists/physiologists with device fabricators.

DOE. DOE has been an important source of support for specific classes of nanomaterials with implications for energy production (e.g., supported catalysts and zeolites) and for other areas of materials research (e.g., buckytubes). These activities would map well onto support for one of the important areas of nanoscience. There will be some requirement in nanoscience and technology for use of large facilities (for example, X-ray light sources for X-ray lithography and X-ray crystallography); supporting and managing these facilities within the Federal budget is usually the task of DOE.

DOC. DOC, through NIST, would be a plausible source of technical support for start-up and venture-backed companies in nanotechnology.

Startup/Venture Enterprises

One reason that biology and biotechnology research and development programs have been so effective in the United States has been that the difficult step of transferring technology from the universities has been accomplished, in part, by a specialized group of small, venture-backed, startup companies. In principle, the same structure could work to facilitate transfer of university science into commercial technology. It is not clear what the Federal Government can do to accelerate the formation of a venture capital community active in nanotechnology. Probably key issues are to develop intellectual property policies that make it attractive to transfer technologies into startups, and perhaps to provide (through DOD) protected markets for products just as they enter the marketplace.

Global Research

Nanotechnology—as an extension of microtechnology—is being explored by national-scale efforts in several countries. Among the leaders in such efforts are Japan and Israel; countries such as Finland are also emerging as powerful centers of microtechnology R&D, and these countries could be either leaders or fast followers into new technology areas. The United States had the luxury of developing microtechnology without serious competition until the early 1980s. We will not enjoy the same uncluttered environment in the development of nanotechnology; rather, the area will be fiercely competitive.

Priorities

- Build a broad program of R&D in nanoscience that includes research universities, relevant industry, and some of the national laboratories. Building a "community" focused on nanoscience/technology, and providing stable support for this community at a level high enough to allow the participating groups to reach a critical mass, are important objectives of public policy.
- Develop mechanisms for bridging communities interested in nanoscience that span the gaps between the physical and biological sciences.
- Develop policies explicitly designed to attract large companies as participants in programs of Federally funded groups. Without large company participation, technology development programs in nanoelectronics will probably fail at the stage of research planning and product definition.
- Develop a strategy for informal coordination of R&D among participating Federal agencies, centered at NSF.
- Maintain an active series of reports to Congress and the Office of Management and Budget, both to aid in educating policymakers about the progress, opportunities, and failures of the field, and to provide a general education about nanoscience at senior levels in the Government.
- Provide funds to push science that seems to offer the potential of developing into profitable technology rapidly to the point of manufacturable prototypes using focused, DARPA-style programs.
- Address the problems of public perception of threat from nanoscience by Federal Government regulatory programs and active programs in public education.

12.7.4 Functional Nanostructures: An Initiative and its Outcomes

Contact person: M.C. Roco, NSF

The NSF-wide initiative "Partnership in Nanotechnology on Functional Nanostructures" (NSF 98-20) was funded in fiscal year 1998. The initiative was addressed to interdisciplinary small-group projects, and only two proposals were accepted from each university. The NSF competition received 178 proposals and made 24 awards for a total of $13 million, of which 25% were GOALI projects, 37% had a formal international component, and 37% had direct contributions from other funding agencies. Programs in fourteen NSF divisions jointly funded the awards. The response has encouraged collaborative activities among NSF programs and other agencies.

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