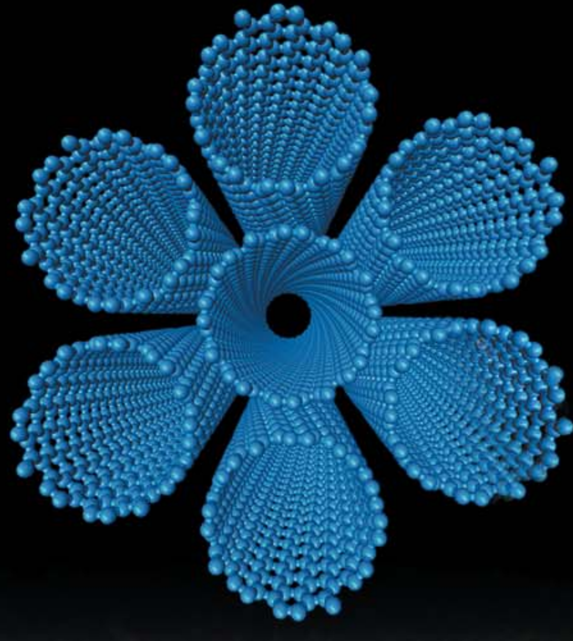
NATIONAL NANOTECHNOLOGY INITIATIVE

RESEARCH AND DEVELOPMENT SUPPORTING THE NEXT INDUSTRIAL REVOLUTION

SUPPLEMENT TO THE PRESIDENT'S FY 2004 BUDGET



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The National Science and Technology Council (NSTC) was established by Executive Order on November 23 1993. This cabinet-level council is the principal means by which the President coordinates science, space, and technology policies across the Federal Government. NSTC acts as a virtual agency for science and technology to coordinate the diverse parts of the Federal research and development enterprise.

An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in areas ranging from information technologies and health research to improving transportation systems and strengthening fundamental research. The Council prepares research and development strategies that are coordinated across Federal agencies to form a comprehensive investment package that is aimed at accomplishing multiple national goals.

Please call the NSTC Executive Secretariat at 202-456-6101 to obtain additional information regarding the NSTC, or see http://www.ostp.gov/NSTC/html/NSTC_Home.html.

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The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on all questions in which S&T are important elements; articulating the President's S&T policies and programs; and fostering strong partnerships among Federal, state and local governments, and the scientific communities in industry and academe. The Director of OSTP also serves as Assistant to the President for Science and Technology and manages the NSTC for the President.

Please call 202-456-7116 to obtain additional information regarding the OSTP, or visit the OSTP web site at: http://www.ostp.gov/.

About this document

This document is a supplement to the President's FY 2004 Budget Request submitted to Congress on February 4, 2003. It provides a summary of the organization and management of the National Nanotechnology Initiative, highlights recent accomplishments, and outlines the challenges and vision for the coming fiscal year and beyond.

About the cover

Front cover: Image of multiple single wall nanotubes provided courtesy of Columbia University Center for Electron Transport in Molecular Nanostructures.

Back cover: Illustration of well-ordered structure of ZnS nanoparticle when exposed to water molecules (shown in blue at surface of particle), courtesy of Zhang, Gilbert, Huang, & Banfield (University of California, Berkeley).

National Nanotechnology Initiative

Research and Development Supporting the Next Industrial Revolution

Supplement to the President's FY 2004 Budget

National Science and Technology Council
Committee on Technology
Subcommittee on Nanoscale Science, Engineering, and Technology

Report prepared by

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SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, and TECHNOLOGY (NSET)

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August 29, 2003

MEMBERS OF CONGRESS:

I am pleased to forward with this letter a report on the multi-agency National Nanotechnology Initiative (NNI). Federal investments under the NNI in nanoscale science and engineering research and development (R&D) are extending the frontiers of scientific knowledge and leading to technological advances that have the potential to impact virtually every facet of industry and society. For example, nanoscale science and engineering may one day enable real-time medical diagnoses, enhanced imaging, and targeted drug delivery; efficient manufacturing processes that reduce waste and pollution; new methods for energy conversion and storage; and generations of electronic devices that are smaller, faster and cheaper. Applications that draw on advances in multiple disciplines, such as chemistry, physics, biology and materials, are blurring the distinctions of traditional scientific domains and creating a new culture of interdisciplinary science and engineering.

A recent report of the National Research Council (NRC), *Small Wonders, Endless Frontiers*, underscored the importance of nanoscale science and engineering research and praised the NNI for its role in coordinating interagency nanotechnology funding. To further strengthen this initiative, the NRC panel made several recommendations, including establishing a means for directing advice from the private sector to those in the Federal Government who are managing and coordinating the R&D program, developing strategic goals—and metrics with which to measure progress towards them, increasing interdisciplinary and cross-agency research, stimulating partnerships with industry, and leveraging regional, state, and local initiatives.

The Administration is committed to addressing these and other recommendations by the NRC panel. As a first step, an external advisory board will review and provide advice aimed at strengthening the NNI. The President's Council of Advisors for Science and Technology (PCAST), with expertise relevant to nanotechnology or the management of large-scale, multidisciplinary research and development programs, is conducting this external review.

Investments in nanoscale science and technology R&D are essential to achieving the President's top three priorities: winning the war on terrorism, securing the homeland, and strengthening the economy. Programs such as the NNI will help ensure our global leadership in nanotechnology and the many areas that it impacts.

Sincerely,

John Marburger

John H. Marburger, III
Director

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Nanotechnology: From Imagination to Reality

Imagine a single area of scientific discovery with the potential to enable a wealth of innovative new technologies across a vast array of fields including healthcare, information technology, energy production and utilization, homeland security and national defense, biotechnology, food and agriculture, aerospace, manufacturing, and environmental improvement. Nanoscience, the study of the unique properties of matter that occur at extremely small scales, has this potential.

Advances in nanoscience and nanoengineering are already ushering in new applications—or nanotechnologies—that are leading to improved products across a broad realm of sectors, from textiles to electronics. Some of these improved products are already available, including improved catalysts, stain resistant fabrics, better sunscreens, superior dental bonding materials, high resolution printer inks, digital camera displays, and high capacity computer hard disks, to name a few.

In addition to making existing products and processes better, nanotechnology promises breakthroughs that will revolutionize the way we detect and treat disease, monitor and protect the environment, produce and store energy, and build complex structures as small as an electronic circuit or as large as an airplane. For example, microscopic devices small enough to be carried in the human bloodstream may someday monitor the body for early signs of disease and deliver treatments that are targeted to the appropriate cells of the body. Exquisitely sensitive and selective sensors could be deployed in uses ranging from environmental stewardship to food safety to homeland security. And materials with superior characteristics—many times stronger than steel but a fraction of its weight, for example—could be used to build better cars, planes, spacecraft, buildings, and creations we have yet to imagine. Clearly, nanotechnology has the potential to profoundly change our economy, to improve our standard of living, and to bring about the next industrial revolution.

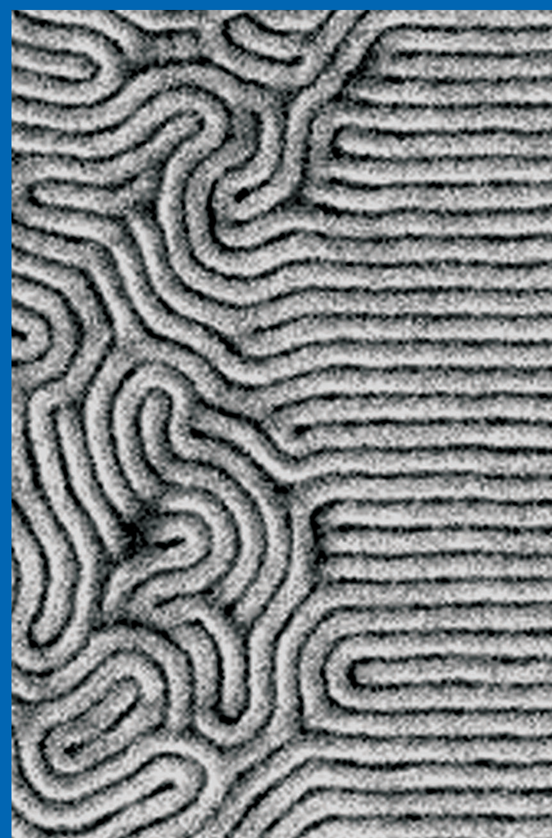


Figure 1. Scanning electron-microscope image of top edges of thin sheets of polystyrene and polymethyl-meth-acrylayte. The ordered arrangement of the stripes , each about 24 nm wide, on the right was generated by a striped nano-pattern on the substrate surface. The left part of the substrate was unpatterned (courtesy P.F. Nealey and S.O. Kim, University of Wisconsin).

The scientific discoveries that will enable these breakthroughs entail more than simply the miniaturization of existing technologies. Nanoscale science, engineering, and technology, collectively referred to as nanotechnology, define research and development (R&D) aimed at understanding and working with—seeing, measuring, and manipulating—matter at the atomic, molecular, and

Recent achievements in nanotechnology funded in whole or in part by the National Nanotechnology Initiative

- Use of the bright fluorescence of semiconductor nanocrystals (quantum dots) for dynamic angiography in capillaries hundreds of micrometers below the skin of living mice—about twice the depth of conventional angiographic materials and obtained with one-fifth the irradiation power.
- Nano-electro-mechanical sensors that can detect and identify a single molecule of a chemical warfare agent—an essential step toward realizing practical field sensors.
- Nanotube-based fibers requiring three times the energy-to-break of the strongest silk fibers and 15 times that of Kevlar fiber.
- Nanocomposite energetic materials for propellants and explosives that have over twice the energy output of typical high explosives.
- Prototype data storage devices based on molecular electronics with data densities over 100 times that of today's highest density commercial devices.
- Field demonstration that iron nanoparticles can remove up to 96% of a major contaminant (trichloroethylene) from groundwater at an industrial site.

supramolecular levels. This correlates to length scales of roughly 1 to 100 nanometers. At this scale, the physical, chemical, and biological properties of materials differ fundamentally and often unexpectedly from those of the corresponding bulk material. Nanotechnology R&D is directed toward understanding and creating improved materials, devices, and systems that exploit these fundamentally new properties, phenomena, and functions. An example of the type of nanoscale structures that can be grown by highly controlled fabrication processes is shown in Figure 1.

With any new and disruptive technology, and particularly one that has significant potential for extremely broad impact, there will be societal and ethical implications. Understanding these implications and ensuring that their consideration is integrated with the development of the technology is vital to achieving the maximum societal benefit. The Federal R&D program includes societal and ethical implications as one of its principal elements.

In order to coordinate the multiagency Federal R&D program in nanotechnology, the National Nanotechnology Initiative (NNI) was established in FY 2001. The goals of the NNI are to: (1) conduct R&D to realize the full potential of this revolutionary technology; (2) develop the skilled workforce and supporting infrastructure needed to advance R&D; (3) better understand the social, ethical, health, and environmental implications of the technology; and, (4) facilitate transfer of the new technologies into commercial products.

The National Nanotechnology Initiative: Fueling Innovation...

... By Improving Fundamental Understanding

The state of nanotechnology today represents something of a paradox. On the one hand, new products using nanotechnology have been developed and are in the marketplace. On the other hand, understanding of the underlying properties of nanoscale materials and structures is still at a rudimentary level. Many existing models for explaining material, device, and system behavior do not extrapolate to the nanoscale regime. In order to maximize the development of future innovations, a significant portion of the NNI investment is directed toward basic research to achieve a fundamental understanding of nanoscale properties and processes.

Basic research, even when aimed at a specific problem, can lead to surprising new results. Such surprises frequently are the bases for the most innovative technological advances. Therefore, a broad-based, balanced, knowledge-oriented research investment is crucial not only to advancing the frontiers of science, but also to realizing the full economic potential of nanotechnology. The surprising discoveries and new research tools that result from investment in nanotechnology research will undoubtedly have far-reaching impacts in other fields of science and engineering as well. Many agencies such as NSF and DOE have a focus on support for fundamental research.

As it has in the past in areas such as information technology and biotechnology, investing in basic research in nanotechnology is expected to lead to significant, new economically valuable technologies. However, the time to take a concept developed through basic nanotechnology research to a commercial product is beyond five or even ten years—or, for truly fundamental research, may be altogether unknown. Therefore, private investors are not generally in a position to provide the necessary financial support. Because nanotechnology is of such critical import to U.S. competitiveness, both economically and technologically, even at this early stage of development, it is a top priority within the Administration's R&D agenda.

... By Focusing on Applications

A broad, balanced basic research program both complements and supports more focused work aimed at incorporating scientific discoveries into innovative technologies. Many agencies such as DOD, DOE, EPA, NASA, NIH, NIST, and USDA support applied research aimed at developing technology related to the agency's mission. Federal investment in a combination of fundamental and applied research will move novel concepts closer to applications that are useful for both government and commercial purposes.

... Through Multidisciplinary Collaborations

Another aspect of nanotechnology R&D worth noting is the key role played by multidisciplinary and interdisciplinary efforts. That is, advances will be built upon progress in more than one area of research or on truly collaborative interactions among researchers from various disciplines. A key component of the NNI is coordination of the Federal investment and strengthening of intra- and interagency efforts fostering multidisciplinary research.

... By Facilitating Technology Transfer

At this early stage, an important mechanism by which nanotechnology can find its way into commercial applications is through interaction among industry, academic, and government researchers. Such networking and partnering is facilitated and encouraged under the NNI by the establishment or support of centers, networks, and facilities that are available to researchers from all sectors. Examples include the existing National Nanofabrication Users Network (NNUN) and a suite of Nanoscale Science Research Centers (NSRCs), each with a specific focus, to be colocated at Federal laboratories across the country. Interaction among researchers from various sectors is also facilitated under the NNI through the organization of topical workshops.

Additionally, small businesses, which are frequently at the forefront of the development of new, high technology products, can receive support through the agency-run Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs directed specifically at nanotechnology-based solutions. A goal of all of these efforts is to expedite knowledge transfer and, ultimately, to facilitate commercialization of nanotechnology. By addressing measurements, standards, and manufacturing directly in the grand challenges, the NNI is ensuring that the appropriate infrastructure is developed to facilitate the rapid commercialization of laboratory successes.

... For Enhanced U.S. Competitiveness

The United States is not the only nation to recognize the tremendous economic potential of nanotechnology. While difficult to accurately measure, some have estimated that worldwide government funding has increased to about five times what it was in 1997, exceeding $2 billion in 2002.[1] In the United States, the Federal investment in nanotechnology R&D has increased from $116 million in FY 1997[2] to a request of $849 million in FY 2004. In order to realize nanotechnology's full potential and to maintain a competitive position in the worldwide nanotechnology marketplace, the Federal Government's investment will continue to play a critical role in accelerating scientific discovery and nurturing new technologies and fledgling industries.

... Responsibly

Since the inception of the NNI, assessing the implications of the technology has been an integral part of the planning and programs of the Initiative. Research on implications for human health, society, and the environment is increasingly being emphasized as tangible new nanostructures and nanomaterials are discovered and new nanotechnology products are developed. The results of such research are being taken into consideration by those Federal agencies whose work is directed at regulatory issues.

[1]M.C. Roco. 2002. "International Strategy for Nanotechnology Research and Development," *Journal of Nanoparticle Research,* Kluwer Academic Publishers, Vol. 3, No. 5-6, 2001, pp. 353-360, as updated April 5, 2002: http://nano.gov/intpersp_roco.html.
[2]R.W. Siegel et al. 1999. *Nanostructure Science and Technology,* Kluwer Academic Publishers, Chapter 8, p. 133: http://www.wtec.org/loyola/nano/08_01.htm.

NNI Program Overview: Interagency Coordination in Support of National Priorities

This report describes the multiagency National Nanotechnology Initiative (NNI), which was established in FY 2001. The 15 agencies participating in this program have diverse missions, but each expects to derive benefits that support its mission and to advance national priorities through an increased basic understanding of nanoscale phenomena and the development of novel technologies.

Organization and Management

The NNI is an interagency effort aimed at maximizing the return on the Federal Government's investment in nanoscale R&D through coordination of funding, research, and infrastructure development activities at individual agencies. Ten of the Federal agencies participating in the Initiative have funding dedicated to nanotechnology R&D. Other Federal organizations perform related studies and research, apply technologies based on the results from those agencies performing nanoscale R&D, and participate in various NNI activities (See box below for lists of both sets of agencies).

In addition to sponsoring research, Federal support through the NNI provides crucial funds for the creation of university and government facilities with the specialized equipment and facilities required for nanoscale R&D. Federal support also helps educate the nanotechnology researchers of the future, as well as the workforce necessary for the growing use of nanotechnology in industry, primarily by providing funds for undergraduate, graduate, and postgraduate training in nanotechnology-related disciplines. The NNI plays a key role in fostering cross-disciplinary networks and partnerships, and in disseminating information to participating agencies and to the public, through workshops and meetings, as well as via the Internet (www.nano.gov). Finally, it encourages businesses, especially small businesses, to exploit the opportunities offered by nanotechnology.

Federal agencies with R&D budgets dedicated to nanotechnology research and development

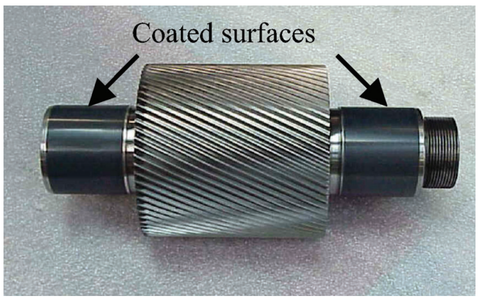
Department of Agriculture
Department of Commerce (in particular, the National Institute of Standards and Technology)
Department of Defense
Department of Energy
Department of Health and Human Services (in particular, the National Institutes of Health)
Department of Homeland Security (in particular, the Transportation Security Administration)
Department of Justice
Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation

Other agencies participating in the NNI

Department of State
Department of Transportation
Department of Treasury
Food and Drug Administration
Intelligence Agencies

Nanotechnology on a Fast Track

The transition of nanotechnology research into manufactured products, while limited and preliminary, has already had significant impact. For example, a new form of carbon—the nanotube—was discovered in 1991. In 1995 it was recognized that carbon nanotubes were excellent sources of field-emitted electrons. By 2000, the "jumbotron lamp," a nanotube-based light source that uses these field-emitted electrons to bombard a phosphor, was already available as a commercial product. By contrast, the period of time between the modeling of the semiconducting property of germanium in 1931 and the first commercial product (the transistor radio) was 23 years.



Another example of rapid insertion of nanotechnology into useful applications is in the field of wear-resistant coatings. In the mid-1990s nanoceramic coatings exhibiting much higher toughness than conventional coatings were first developed. Beginning in 1996, the DOD supported partnerships among the Navy, academia, and industry to develop processes suitable for use in manufacturing and to evaluate the coatings for use in the marine environment. In 2000, the first nanostructured coating was qualified for use on gears of air-conditioning units for U.S. Navy ships; an example of such a gear is shown at left. In 2001, the technology was selected to receive an R&D100 Award. DOD estimates that use of the coatings on air valves will result in a $20 million reduction in maintenance costs over 10 years. The development of wear-resistant coatings by the DOD is clearly allied with its mission, yet will lead to commercial applications that can extend the lifetime of moving parts in everything from personal cars to heavy industrial machinery.

The NNI is managed within the framework of the National Science and Technology Council (NSTC). The NSTC is the principal means by which the President coordinates science and technology programs across the Federal Government, providing policy leadership and budget guidance. The NSTC's Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) coordinates the plans, budgets, programs, and reviews for the NNI. The Subcommittee is composed of representatives from each participating agency, the Office of Science and Technology Policy, and the Office of Management and Budget.

The National Nanotechnology Coordinating Office (NNCO) serves as the secretariat to the NSET Subcommittee, and supports the Subcommittee in the preparation of multi-agency planning, budget, and assessment activities. To adequately support the growing NNI activities, the position of NNCO Director was changed from part-time to full-time in April 2003. The NNCO also serves as the point of contact on Federal nanotechnology activities for government organizations, academia, industry, professional societies, foreign organizations, and others. Finally, the NNCO develops and makes available printed and other communications materials concerning the NNI, and maintains the Initiative's website.

The Administration is focusing significant attention on the NNI. In order to further strengthen the Initiative, the President's Council of Advisors on Science and Technology (PCAST) has begun an external review of the NNI. The PCAST review will include a comprehensive assessment of the current NNI programs, and will lead to recommendations on how to improve the management of the program. PCAST's review of the Federal nanotechnology research program is an ongoing, long-term activity.

Funding Strategy

The NNI funding strategy is based on five modes of investment, each of which builds on previous and current nanotechnology programs.

The first investment mode supports a balanced investment in fundamental research across the entire breadth of science and engineering. Such fundamental research advances knowledge and understanding of novel physical, chemical, and biological properties of nanoscale materials and systems. This broad investment is critical because the outcome of basic research cannot always be anticipated, and discoveries in one discipline can have unexpected implications in another.

The second investment mode, collectively known as the "grand challenges," focuses on nine specific R&D areas that are more directly related to applications of nanotechnology and that have been identified as having the potential to realize significant economic, governmental, and societal impact.

The nine grand challenge areas are:

1. Nanostructured Materials by Design
2. Manufacturing at the Nanoscale
3. Chemical-Biological-Radiological-Explosive Detection and Protection
4. Nanoscale Instrumentation and Metrology
5. Nano-Electronics, -Photonics, and -Magnetics
6. Healthcare, Therapeutics, and Diagnostics
7. Efficient Energy Conversion and Storage
8. Microcraft and Robotics
9. Nanoscale Processes for Environmental Improvement

Research directed toward the grand challenge areas aims to efficiently and effectively accelerate the transition of scientific discovery into innovative technologies that show a return on investment as quickly as possible.

The third mode of investment supports centers of excellence that conduct research within the host institution(s). These centers pursue projects with broad multidisciplinary research goals that are not supported by more traditionally structured programs. These centers also promote education of future researchers and innovators, as well as training of a skilled technical workforce for the growing nanotechnology industry.

The fourth investment mode funds the development of infrastructure (e.g., the DOE user facility shown in Figure 2), instrumentation, standards, computational capabilities, and other research tools necessary for nanoscale R&D. The centers and infrastructure developed under the third and fourth modes facilitate the basic and applied research supported under the first two modes.

The fifth and final investment mode recognizes and funds research on the societal implications of nanotechnology, and addresses educational needs associated with the successful development of nanoscience and nanotechnology.

The FY 2004 Funding Request

As part of the FY 2004 Budget, President Bush requested $849 million for nanotechnology R&D across all of the agencies that participate in the NNI. This represents an increase of approximately 10% over the amount appropriated by Congress for FY 2003. Roughly two-thirds of the funding proposed under the NNI will support university-based research. Table 1 presents the nanotechnology R&D budget for FY 2002 through FY 2004 by agency.

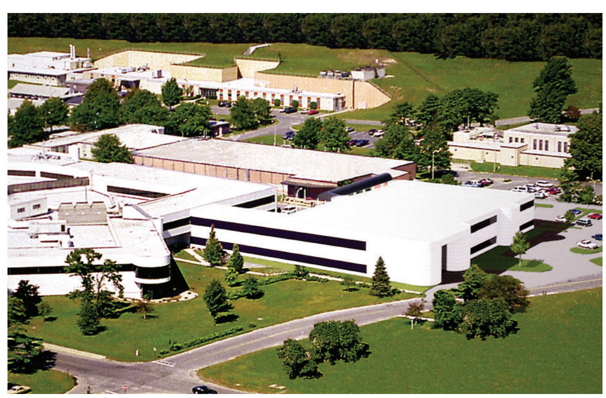


Figure 2. Conceptualization of the Center for Functional Nanomaterials, to be co-located with the National Synchrotron Light Source at the Department of Energy's Brookhaven National Laboratory.

Table 1. FY 2004 NNI Budget Overview by Agency
(Budget Authority, dollars in millions)

Agency	2002 Actual	2003 Request	2003 Appropriated*	2004 Request**	Change, 2003 to 2004†	% Change, 2003 to 2004†
NSF	204	221	221	249	28	13%
DOD	224	243	243	222	-21	-8%
DOE	89	133	133	197	64	48%
HHS (NIH)	59	65	65	70	5	8%
DOC (NIST)	77	69	66	62	-4	-6%
NASA	35	33	33	31	-2	-6%
USDA	0	1	1	10	9	900%
EPA	6	6	5	5	0	0%
DHS (TSA)#	2	2	2	2	0	0%
DOJ	1	1	1	1	0	0%
TOTAL	**697**	**774**	**770**	**849**	**79**	**10%**

*"2003 Appropriated" refers to planned outlays with appropriated dollars; actual FY 2003 outlays may vary.

**The total NNI request for FY 2004, as originally published in the President's FY 2004 Budget, was $792 million (see http://www.whitehouse.gov/omb/budget/fy2004/pdf/spec.pdf, p. 185). By the February Budget release, some agencies had identified additional items within their FY 2004 R&D budget requests as falling under the purview of the NNI. These updated figures are reflected in this table (see also http://www.ostp.gov/html/budget/2004/2004.html).

† Change between 2003 Appropriated and 2004 Request.

The NNI programs that are currently under DHS were under DOT prior to the formation of DHS in 2002.

Agency Abbreviations Used throughout this Report

DHS Department of Homeland Security
DOC Department of Commerce
DOD Department of Defense
DOE Department of Energy
DOJ Department of Justice
DOT Department of Transportation
EPA Environmental Protection Agency
HHS Health and Human Services
IA Intelligence Agencies
NASA National Aeronautics and Space Administration
NIH National Institutes of Health
NIST National Institute of Standards and Technology
NSF National Science Foundation
TSA Transportation Security Administration
USDA Department of Agriculture

Investment Mode 1:
Fundamental Nanoscale Science and Engineering Research—Knowledge Generation

Interdisciplinary fundamental research offers a productive fusion of traditional ideas that frequently leads to unanticipated results and significant breakthroughs. By exploiting the opportunities afforded by the nanoscale instrumentation for analysis and manipulation of matter, interdisciplinary fundamental research will foster the development of unifying principles, phenomena, and tools.

Specific areas of focus that draw on multiple disciplines include:

- Novel phenomena, material structures, processes, and properties
- Nano-biosystems
- Nanoscale devices and system architecture
- Theory, modeling, and simulation

Agency Participation
(lead in bold)

DOD	National security
DOE	Energy, national security, and the environment
IA	National security
NASA	Aeronautics and space exploration
NIH	Biological phenomena
NIST	Basic nanoscale measurement science
NSF	Traditional discipline-based research as well as multidisciplinary research in biological sciences; computer and information science and engineering; education and human resources; engineering; mathematical and physical sciences; and, social, behavioral, and economic sciences
USDA	Biological and agricultural production systems

Novel Phenomena, Material Structures, Processes, and Properties

Opportunity

The discovery of the novel phenomena and material structures that appear at the nanoscale will affect the entire range of applications that the grand challenges identify, and more.

Priorities

Research in this area supports the discovery of the fundamental physics, chemistry, materials science, and mechanics of nanostructures; the development of new experimental tools to characterize and measure nanostructures and phenomena;

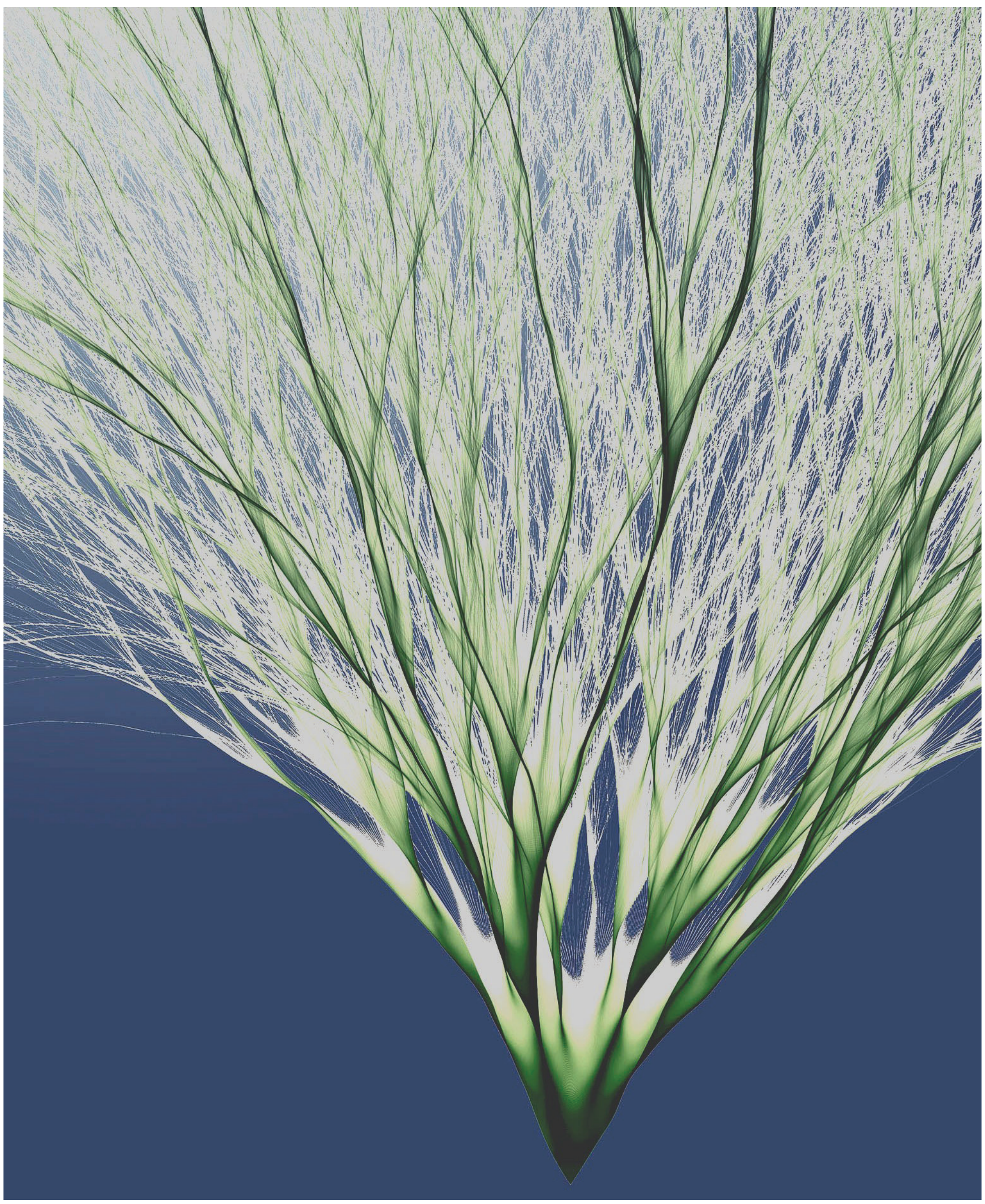


Figure 3a. Theoretical simulations of electron flow in nanostructures: Two-dimensional flow of electrons injected at the bottom of the image. (courtesy E.J. Heller, Harvard University).

novel synthesis or fabrication techniques; and the development of new mathematical and simulation tools to aid our understanding of nanoscale phenomena.

Research Example: Imaging Coherent Electron Flow in Nanostructures (supported by NSF)

As electronic devices get smaller, electron-transport properties will play an increasingly important role in device operation and performance. At the nanometer scale, real surfaces have imperfections that affect electron flow patterns. A Harvard group is conducting systematic investigations on the flow of electrons in nanostructures (Figures 3a and 3b). This research will provide a foundation for the design of electronic circuits in future nanodevices.

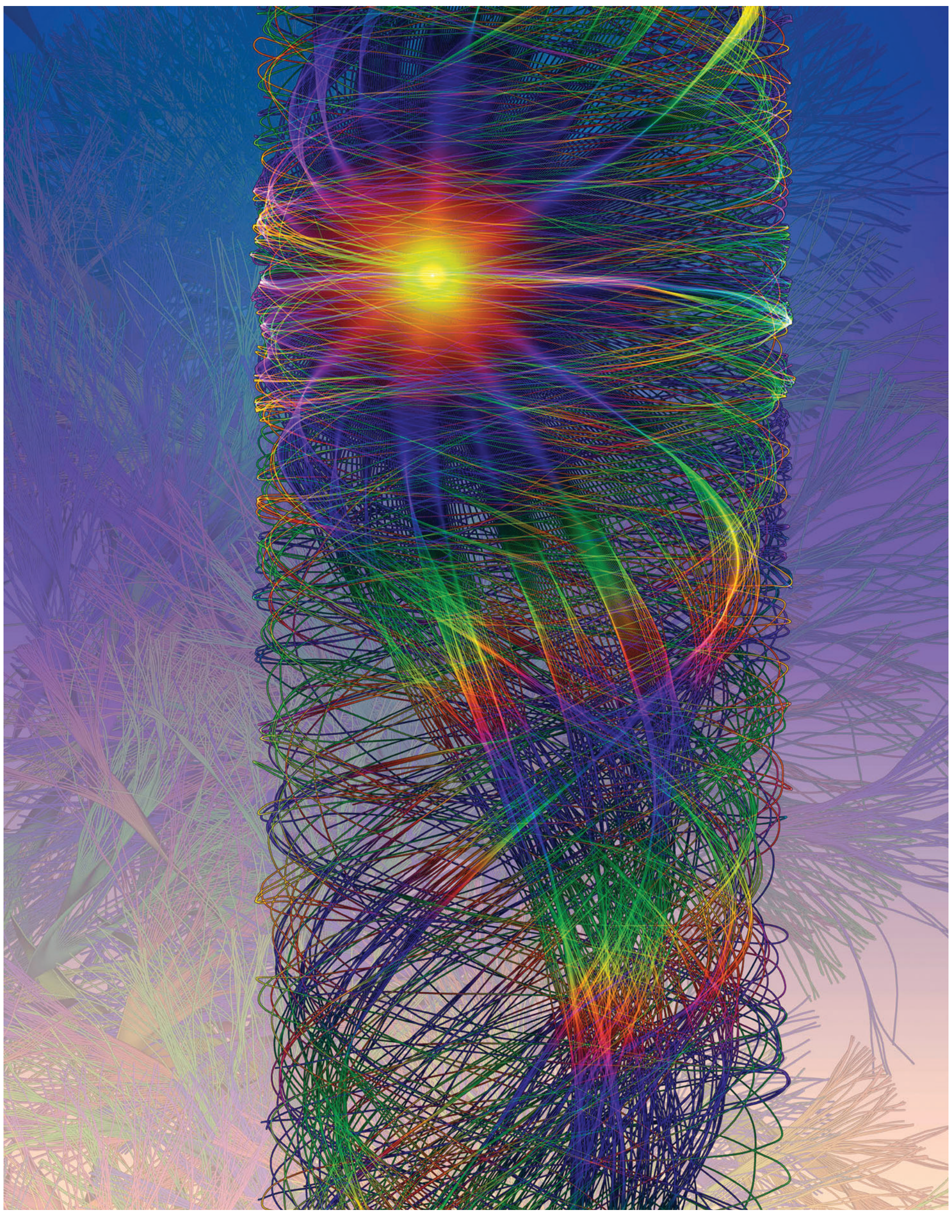


Figure 3b. Theoretical simulations of electron flow in nanostructures: Flow of electrons injected at the "bright spot" into a 500 nm diameter "nanowire." Electrons are scattered due to interactions at the wire surface. Variation in the quantum phase of the scattered electron waves is indicated by changes in color. The dynamics of such electron scattering affects the electronic properties of the wire, its resistance, the speed of response to external stimuli, and coherence of information flow along its length (courtesy E.J. Heller, Harvard University).

Nano-Biosystems

Opportunity

A cell is a micrometer-sized factory with molecular machinery operating on the nanometer scale. Thus, a fundamental understanding of nano-biostructures and processes will open broad opportunities in nano-biotechnology, nano-medicine, and biomaterials.

Priorities

Priority areas include developing an understanding of the relationships among composition, structure, single molecule behavior, and biological function. Additional research areas include the study of organelles and subcellular complexes such as ribosomes and molecular motors; construction of nanometer-scale probes and devices for research in genomics, proteomics, cell biology, and nanostructured tissues; and synthesis of nanoscale materials based on the principles of biological self-assembly.

Research Example: Nature's Tools to Assemble Materials with Atomic Precision (supported by NSF)

Among the basic assembly processes nature uses are nanoscale self-assembly, molecular recognition, self-correction, and nano-structural regularity. Researchers at the University of Texas at Austin have developed new assembly techniques, based on biomolecular recognition. Using this technique, amino acids, such as those in simple peptides or on the surfaces of viruses, are designed to recognize and bind to specific nonbiological electronic and magnetic materials. Complex structures can be assembled by tailoring the biomolecules appropriately, as shown in Figure 4. One advantage is that such processes take place at near-ambient conditions. In the future, biologically inspired assembly may provide cost-effective alternative manufacturing processes.

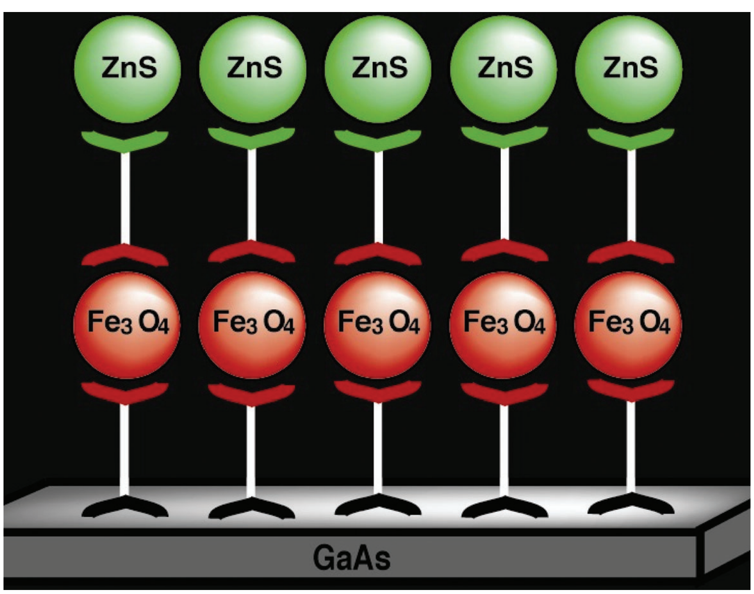


Figure 4. Illustration of how biomolecular recognition processes may be used to assemble a magneto-electronic structure composed of zinc sulfide (ZnS) and iron oxide (Fe_3O_4) nanoparticles. Two tailored bifunctional peptides, one that binds the gallium arsenide substrate to iron oxide, and the other that binds the iron oxide particle to zinc sulfide, control the formation of the layered structure. Such directed self-assembly processes have the potential to replace far more complex processes used in conventional micro- and nano-electronic manufacturing (courtesy A.E. Belcher, now at Massachusetts Institute of Technology).

Nanoscale Devices and System Architecture

Opportunity

New concepts and design methods are needed to create new nanoscale devices, assemble them into functional systems, and create architectures compatible with various operational environments.

Priorities

Research in this area includes the development of (a) new tools and techniques for sensing, manipulating, and assembling; (b) architectures that integrate across multiple length scales; (c) software for automated design of specialized nanosystems; and (d) design automation tools for assembling large numbers of heterogeneous nanocomponents into a system.

Research Example of a Nanoscale Device: Molecular Transistor (supported by NSF)

Researchers at Cornell University have demonstrated a transistor-like device with the principal functional element being just one molecule (Figure 5). The device is fabricated from two gold electrodes separated by a very narrow gap that is bridged by a single molecule containing a cobalt atom. The flow of electrons from one electrode to the other, which occurs by an electron hopping on and off the cobalt atom, is controlled by the voltage on a third electrode near the bridging molecule. The electrical characteristics of the transistor can be varied by making chemical changes to this molecule, such as lengthening the molecule's connecting "arms." This research demonstrates that electron devices ~10,000 times smaller than present devices are possible.

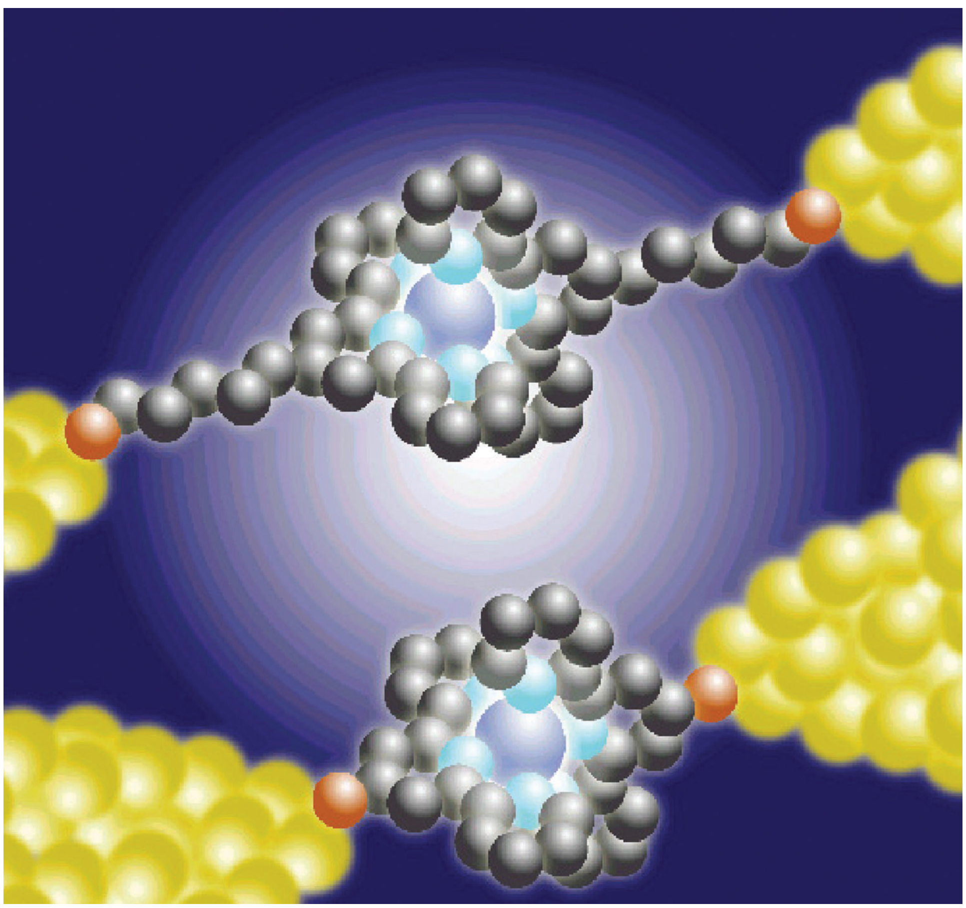


Figure 5. Artist's rendition of a molecular transistor ~10,000 times smaller than present devices. The flow of electrons (current flow) through the molecule bridging between the two gold electrodes is controlled by the voltage on a third electrode, not shown. The electric field from the third electrode determines the rate electrons can hop on and off a cobalt atom (dark blue) in the bridging molecule. The well-defined and deliberately designed molecular configuration is attached to the gold electrodes by sulfur atoms (red) (courtesy P. McEuen, Cornell University).

Theory, Modeling, and Simulation

Opportunity

The emergence of new behaviors and processes in nanomaterials, nanostructures, nanodevices, and nanosystems creates an urgent need for theory, modeling, large-scale computer simulation, and new design tools in order to understand, control, and accelerate development.

Priorities

Research on mathematical methods to model and simulate physical, chemical, and biological systems at the nanoscale will include techniques such as quantum mechanics and quantum chemistry, multi-particle simulation, molecular simulation, continuum-based models, stochastic methods, and nanomechanics. Approaches that integrate more than one such technique will play an important role in this effort.

Modeling and simulation of the time variation of processes in nanostructures is also an urgent need. Current research is limited to modeling only a relatively small number of time increments of process variation and dynamics of complex structures, such as shown in Figure 6. Improved computational methods and tools will enable more realistic time scales of process variation to be modeled.

Research Example: Modeling and Simulation of Biological Ion Channels to Cure Illnesses (supported by NSF and DOD)

Researchers from the Network for Computational Nanotechnology at the University of Illinois at Urbana-Champaign and Stanford University, in collaboration with Rush Medical Center, have simulated transport through nanoscale biological ion channels (Figure 6). Ion channels regulate the transport of ions in and out of cells, which is essential to proper cell function. In turn, understanding cellular processes is critical to understanding and treating diseases at the cellular level.

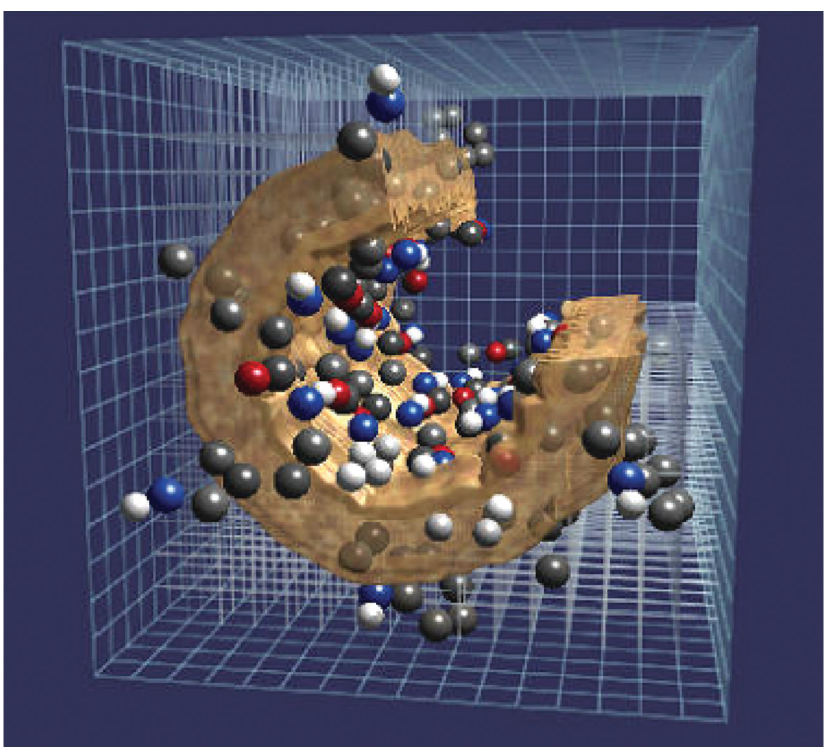


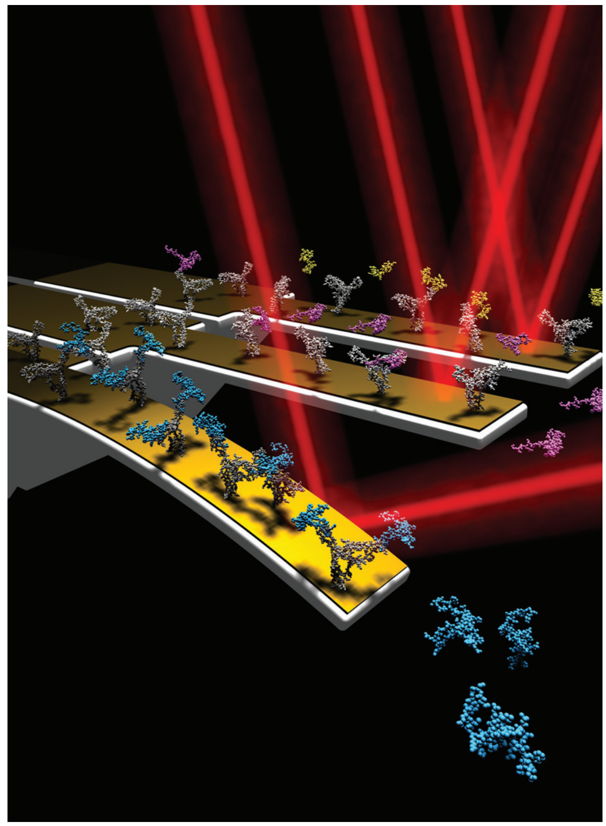
Figure 6. Computer simulation of biological ion-channel pore formed by the antibiotic gramicidin. Formation of ion channels through bacteria cell membranes is one mechanism by which antibiotics kill bacteria. The simulated pore is approximately 3 nanometers long and 0.5 nanometers in diameter. The different colored spheres represent specific atoms in the proteins constituting the wall of the ion channel (courtesy K. Hess and U. Ravaioli, University of Illinois).

Investment Mode 2:
NNI Grand Challenge Areas

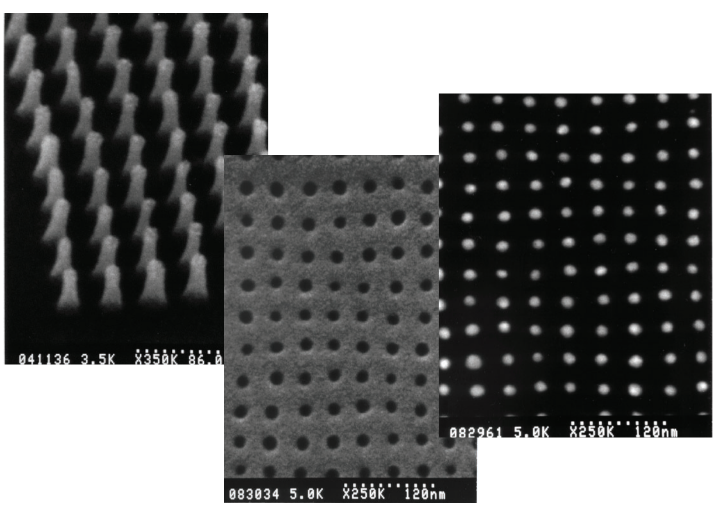
This section provides an overview of the nine grand challenge areas. Each overview covers the specific challenge area, a vision of how nanotechnology can drive progress in that area, the participating agencies, and an example demonstrating the progress that has been made to date.

The grand challenge areas are presented in the following order:

- Nanostructured Materials by Design
- Manufacturing at the Nanoscale
- Chemical-Biological-Radiological-Explosive Detection and Protection
- Nanoscale Instrumentation and Metrology
- Nano-Electronics, -Photonics, and -Magnetics
- Healthcare, Therapeutics, and Diagnostics
- Energy Conversion and Storage
- Microcraft and Robotics
- Nanoscale Processes for Environmental Improvement



(Above) Silicon cantilevers with chemically or biologically selective coatings for a biochemo-opto-mechanical chip. Adsorption of the target molecules on the coatings produces an expansion of the coating, resulting in deflection of the cantilever. Cantilever deflection can be sensed via light deflection as shown in the figure or by diffraction of light from interdigital fingers formed on the cantilever. This device provides the potential for rapid, sensitive, cost-effective detection of biomolecules and chemical species (courtesy A. Majumdar, University of California at Berkeley).



(Far left) Imprint mold with 10 nm diameter pillars. *(Left center)* 10 nm diameter holes imprinted in a polymer substrate. *(Near left)* 10 nm metal dots fabricated using a template such as in the center picture (courtesy S. Chou, Princeton University).

Grand Challenge Area Nanostructured Materials by Design

Challenge

Nanoscience involves structures with a limited number of atoms or molecules, larger numbers than traditionally handled by chemistry and smaller numbers than traditionally handled by materials science or solid-state physics. This departure from traditional material sizes can fundamentally change the way nanostructured materials behave, such that their properties frequently cannot be predicted from current models of materials behavior.

One reason for the difference in the properties of nanoscale materials compared to the analogous macroscale, or bulk, material is the large surface area per unit volume. Atoms at surfaces often behave differently from those located in the interior of a grain or particle. In addition, tiny variations in the structure and composition of nanostructured materials can have a dramatic effect on their properties. As a result, many important physical and chemical interactions, like catalysis, take place at surfaces or interfaces and, because of the high surface area and unique properties, are enhanced in nanostructured materials.

Other properties, such as magnetism and electrical and heat conductivity can change substantially as size is reduced to the nanoscale. The differences in these properties stem from surprising collective effects and so-called quantum-size effects that arise from the confinement of electrons in nanometer-sized structures.

Vision

When manufactured into usable products, nanostructured materials manifest the unique properties of their component parts. By gaining understanding and control at the nanoscale, materials scientists will be able to develop novel, high-performance, affordable, and environmentally benign materials. These novel materials could be custom designed for special purposes, having structural, optical, electronic, magnetic, and/or other special properties suited to their intended uses.

Modeling and simulation, aided by the expected continued advances in computational power, will play a major role in the realization of this vision. With the relatively small number of atoms contained in nanostructures, their properties can be predicted with increasingly accurate and fundamental models of atomic interactions. Therefore, theory and experimentation are expected to be highly interactive.

Agency Participation

(lead in bold)

DOD	Improved armor, high strength-to-weight materials, lower life-cycle costs
DOE	Modeling/simulation, energy storage/ transmission, friction, wear, corrosion
DOT	Improved materials and systems for transportation infrastructure
FDA	New or improved pharmaceuticals, cosmetics, biologicals, and medical device implant materials
IA	Materials-by-design for intelligence applications
NASA	High-performance, low-weight materials for space
NIST	Standard reference materials, materials property data, materials characterization methods
NSF	Novel structures, synthesis, and processing methods
USDA	Nanostructured materials from agricultural origins, nanocomposite polymers to enhance packaging functionality

Research Example: Molecular Perfection – The Fullerene Ideal (supported by DOD, NASA, and NSF)

Imagine a soccer ball shrunk to one billionth of its normal size. In 1985 researchers at Rice University created a geodesic-sphere-shaped molecule made of 60 carbon atoms (C60), dubbed the "buckyball." It was the first of a new class of molecularly perfect nanostructures now called fullerenes, named after the American architect Richard Buckminster Fuller.

The C60 molecule was soon followed by other fullerenes containing many more atoms of carbon and taking different shapes. One of the most interesting of these is the "buckytube," or carbon nanotube (CNT), an elongated nanoscale tube made entirely out of carbon. A computer model of a CNT is shown in Figure 7.

CNTs have unique properties, which, like those of diamond, arise from its perfect structure. Depending on the precise pattern of the carbon network, a CNT can act as either a highly conductive metal wire only one nanometer in diameter, or as a semiconductor. It has been used to build the first room-temperature transistor ever made from a single molecule, and is widely expected to be the key ingredient in nanoelectronics that will vastly extend the power and shrink the size of computers and other "smart" devices. Carbon nanotubes are also efficient electron emitters, which may lead to their application in affordable flat panel displays.

In addition to their remarkable electrical properties, carbon nanotubes are incredibly strong. Pulled end-to-end, a CNT has a tensile strength about 30 times greater than that of steel, while having only 1/6th its weight, making it the strongest fiber ever made. Researchers at the University of Texas at Dallas, with funding from the Defense Advanced Research Projects Agency in DOD, have woven fabric from fibers spun from a composite of polymers and CNTs. The new CNT-based fiber has a very high breaking strength and can be used to replace materials like Kevlar in bulletproof vests and other applications.

Finally, the thermal conductivity down the length of a single carbon nanotube has been measured to be 50% higher than diamond – previously the material with the highest known thermal conductivity – making it a superb material for piping heat from one place to another. Heat removal is a key issue, for example, in computers and other high-density electronic devices.

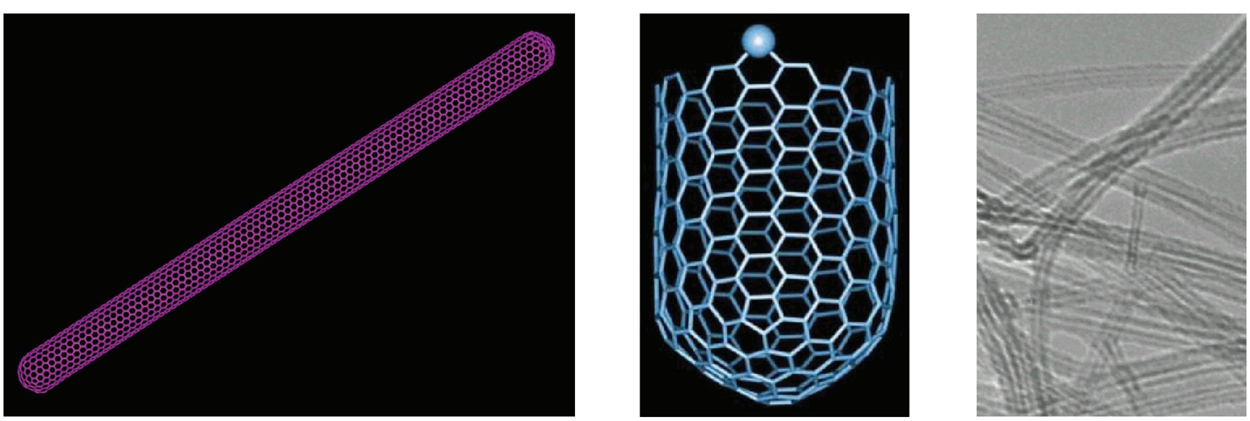


Figure 7. Single-walled carbon nanotubes. (Left) Computer drawing (courtesy Richard Smalley, Rice University). (Center) Enlarged view of computer drawing; (Right) High-resolution electron micrograph of nanotubes (courtesy NASA).

Grand Challenge Area

Manufacturing at the Nanoscale: New Methods for Traditional and Emerging Technologies

Challenge

Because nanostructures have little mass and are dominated by surface-area effects and size effects, the processes and equipment for nanotechnology-based manufacturing are expected to differ significantly from those currently used. Nanofabrication thus requires the invention of new instruments, measurement tools, models, methods, and standards to characterize nanoscale materials and processes. Only through such developments can the manufacture of commercial volumes of products—with a high degree of repeatability—become economically viable. Manufacturing at the nanoscale is a central challenge for the NNI because it is a prerequisite for realizing the benefits of nanotechnology. A concomitant challenge is the creation of high quality, diverse nanoscale building blocks that enable their assembly into large systems.

Vision

Manufacturing at any scale is a complex endeavor involving the use of many types of equipment and processes to transform raw materials into tangible products with desired properties or performance characteristics, generally in large quantities. Atoms and molecules are the raw materials for nanotechnology-based manufacturing. And only those raw materials that will become part of the final product will be selected for the nanofabrication process.

This bottom-up approach differs greatly from that of current manufacturing processes that involve assembling large quantities of materials, from which product parts are cast, machined or otherwise derived and waste products are left for disposal.

Nanostructured materials, devices, and systems will be manufactured with precise control over the location of individual atoms and molecules. The resulting nanoscale components will be hierarchically integrated and incorporated into macroscale devices and systems. Innovative ideas will be required to allow for nanoscale positioning; addition and removal of material; directed self-assembly; and biomimetic (i.e., life-imitating) fabrication paradigms.

Since an entirely new approach to manufacturing is required, there is a need to concurrently develop new tools and facilities to support this effort.

Agency Participation

(leads in bold)

DOE	Novel synthesis and processing approaches
EPA	"Green manufacturing" with minimal waste streams
IA	Prototype functional nanodevices
NIST	Measurement technology and standards for process characterization and quality control
NSF	Research for manufacturing processes, new theoretical models, and simulations
USDA	Biological manufacturing

In addition to the above agencies, which have specific efforts in manufacturing at the nanoscale, each NNI agency is committed to this grand challenge area and will incorporate it into their plans as appropriate to their respective mission-specific programs.

Research Example: Dip-pen Nanolithography—A new approach to nanoscale fabrication (supported by NSF and DOD)

The ability to make nanoscale patterns on surfaces is a critical process in, for example, the manufacture of electronic circuits, the performance of high-throughput biomedical research, and the design of advanced sensors. However, the cost of extending currently used methods to smaller and smaller scales is substantial. Researchers at Northwestern University have developed a new approach called "Dip-Pen Nanolithography" (DPN) that utilizes an atomic force microscope tip as an "ink pen" (Figure 8). DPN is a direct, single-step process that does not require the use of patterned masks or light-sensitive films, or other steps to form patterns on a substrate. Additionally, it may be performed under ambient conditions. DPN provides a reliable approach to writing nanoscale lines of a variety of molecules onto various solid surfaces. Repetitive patterns of nanoscale lines may be created in parallel using an array of writing tips. The inventors of the DPN technology have formed a start-up company that plans to develop products and services for the fabrication of patterned nanostructures.

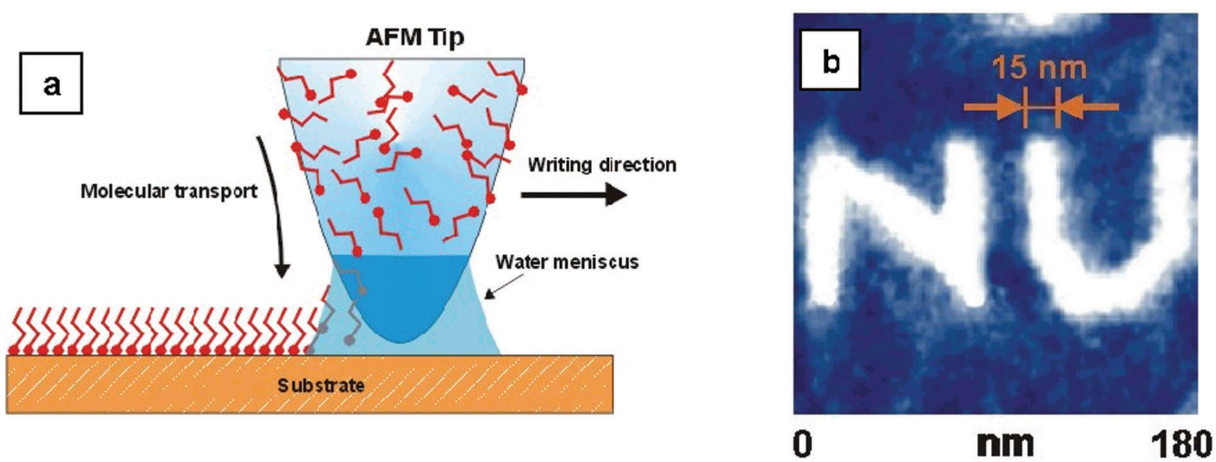


Figure 8. (a) Cartoon showing how dip-pen nanolithography "writes" molecules onto a substrate. A major advantage of this process is that it creates a nanostructure pattern on a surface in one step. Conventional processes to create such a patterned nanostructure require up to five complex steps and very sophisticated fabrication tools. (b) Linear force microscope image of an acid "ink" patterned on a gold substrate. The patterned feature size is 15 nm and spatial resolution is ~5 nm (courtesy C. Mirkin, Northwestern University).

Grand Challenge Area

Chemical-Biological-Radiological-Explosive (CBRE) Detection and Protection: The Application of Nanotechnology to Homeland Defense

Challenge

Conventional explosives have been the weapon of choice for terrorists, and their use remains a serious threat to the Nation's security. At the same time, the recognition that small amounts of chemical, biological, or radiological agents can exact a much greater human toll than an equivalent amount of explosives has prompted the need for additional precautions and mitigation methods. New technologies that reliably and rapidly detect trace amounts of chemical, biological, radiological, or explosive materials are critical to the national defense, as are new technologies to protect people from the devastating effects of these substances.

Vision

Nanotechnology offers the potential for unprecedented improvements in the sensitivity, selectivity, response time, and affordability of detection technologies. Nanoscience and nanostructures also offer the opportunity for revolutionary advances in adsorbent materials (personal and collective protection), separation technologies (protective clothing and filters), decontamination and neutralization of agents, and prophylactic measures.

One key objective for this grand challenge area is the development of miniaturized intelligent sensors. Such devices would have the potential to sense the presence of specific molecules with accuracy and sensitivity well beyond what is commercially available today. Building such devices will require a much better understanding of nanoscale forces and interactions.

Another key objective is to develop novel protection, neutralization, and prevention technologies. Protective masks and clothing depend on high surface area materials. Nanostructures inherently have large surface-to-volume ratios and also tend to have highly reactive surfaces that may neutralize the toxic material rather than simply hold it. Nanostructures also can be tailored to selectively disrupt the biological activity of pathogens.

Agency Participation

(lead in bold)

DOD	Detection of and protection against CBRE agents
DOE	System integration, lab-on-a-chip, CBRE detection
DHS	Detection of and protection against CBRE agents
DOT	Advanced transportation security systems
EPA	Reduction and remediation of hazardous material
FDA	Processes to ensure safety and security of the food chain
IA	Detection of CBRE agents
NASA	System integration, miniaturization, robotic systems
NIH	Detection of and treatment for chemical, biological, and radiological exposure
NIST	Chemical microsensors, single-molecule measurement
NSF	Sensors and basic principles for detection of and protection against CBRE agents
USDA	Processes and detection techniques to secure agricultural production and food resources

Note: The NNI works closely in this area with the interagency Technical Support Working Group (TSWG), which coordinates efforts in CBRE detection as part of its mission to facilitate development of technologies to combat terrorism.

Research Example: Cantilever Array for Chemical and Biological Threat Analysis (supported by DOE)

Experience with the micro-cantilevered probes used in atomic force microscopes has stimulated the development by various researchers of nanoscale cantilever-based physical, chemical, and biological sensors. Extending the fabrication techniques for microelectromechanical systems (MEMS) to produce devices with nanoscale components not only allows for even smaller and lighter detectors, but also enhances sensitivity. Demonstrated applications include detection of chemical warfare agents, alpha particles, biomolecules, TNT, and plastic explosives. It is possible to arrange arrays of micro- and nano-cantilevers on a single chip to allow detection of multiple targets or to extend the dynamic range (i.e., range of concentrations that can be detected).

One cantilever-based approach detects adsorbed molecules by measuring the change in resonance frequency of individual cantilevers. In general, the smaller the cantilever, the higher its resonance frequency will be and the greater its sensitivity. To date, frequencies from one megahertz to over one gigahertz have been achieved by pushing the cantilever dimensions into the nanometer scale. Whereas cantilever geometry determines sensitivity, selectivity is controlled by coating the cantilever surface with compounds that bind only to the molecule of interest. Researchers at Oak Ridge National Laboratory have developed a cantilever sensor (Figure 9) that uses this approach to detect the presence of nanoscale quantities of material. By having a range of cantilever shapes, and hence frequencies, the sensor array is able to detect a wide range of molecular concentrations. In addition, individual cantilevers may be treated with different coatings to allow detection of multiple target compounds. The Oak Ridge team has demonstrated the ability to detect certain agents down to the single molecule level.

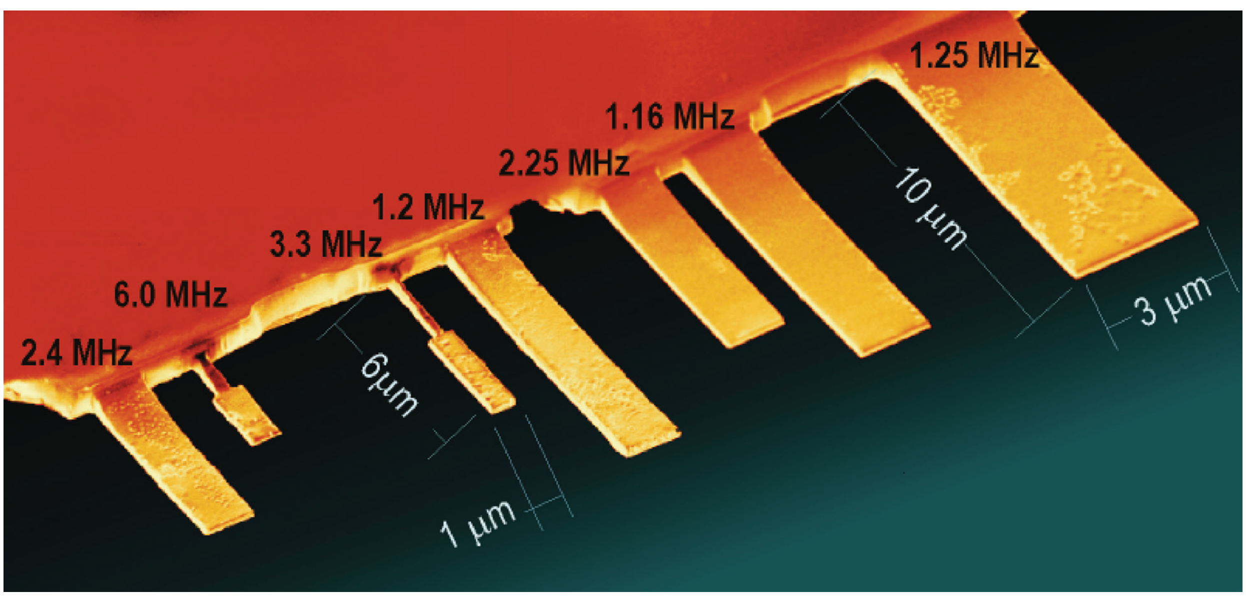


Figure 9. Scanning electron micrograph of an array of silicon cantilevers, milled to various dimensions with a range of resonance frequencies. Detection of adsorbed molecules is achieved by measuring frequency shifts. The cantilevers shown here are coated with gold, which allows detection of as little as a few femtograms (10^{-15} g) of an acidic test compound (courtesy P. Datskos, Oak Ridge National Laboratory).

Grand Challenge Area

Nanoscale Instrumentation and Metrology: A New Age of Measurement Standards and Tools

Challenge

Nanotechnology-based industry requires the development of highly capable, low-cost, reliable instrumentation and internationally accepted standards for the measurement of nanoscale phenomena and for the characterization and manipulation of nanostructures. Improvement in measurement and manipulation capabilities is critical to the progress of nanotechnology.

Vision

Improved measurement methods to better characterize nanoscale processes and structures are needed. Additionally, present nanoscale measurements have little metrological underpinning and few standards to ensure their reliability and repeatability. Standard reference materials need to be developed and calibrated to establish the accuracy and reproducibility of a given nanoscale measurement tool. Standardized instruments with nanoscale resolution will accelerate scientific discovery and provide quality control in the fabrication and assembly of manufactured nanostructures. These research tools also will be adapted into miniaturized sensor and actuator technologies.

The complexity and breadth of nanotechnology provides a wealth of opportunities for innovation in instrumentation and metrology. Analytical instrumentation with increased resolution and sensitivity is needed to characterize the chemical composition and structure of materials at the nanoscale. Quantitative models for interpretation of scanned probe images are lacking. New analytical approaches are needed to characterize soft materials—materials otherwise deformed by the proximity of tips used in scanning probe microscopes. Progress in understanding biological systems is severely hampered by inadequate capability for probing cellular and subcellular nanoscale phenomena. Instrumentation for precise nanometer-position control across samples of centimeter dimensions will be required to realize commercial nanoscale device fabrication.

The creation of atomically controlled and measured structures may lead to the establishment of new fundamental standards. For example, quantized electron devices may provide improved electrical current standards.

Agency Participation

(leads in bold)

DOE	Centers to exploit unique national laboratory measurement capabilities
NIH	*In situ* diagnostics and therapeutics, medical imaging
NIST	Nanoscale measurement science, instrument calibration, standard reference materials, and nanoscale physical and chemical properties standard reference data
NSF	Broad based science as a source of new instrumentation concepts

In addition, DOD, DOE, EPA, IA, FDA, NASA, and DHS are developing measurement instrumentation with improved signal-to-noise for more sensitive detectors for each agency's mission-related needs.

Research Example: State-of-the-Art Nanoscale Measurement and Manipulation (supported by NIST)

Propelled by the constant need for increased speed and density and reduced cost, electronic and magnetic devices continue to get smaller. Integrated circuits in present day electronic devices have dimensions of less than 100 nanometers. Measurement of such nanostructures demands novel fabrication and characterization systems, such as illustrated in Figure 10. The facility shown here enables the atom-by-atom assembly of complex nanostructures under completely autonomous computer control. The facility is designed with the goal of atomic-resolution imaging and the ability to probe electronic properties of nanostructures with high-electron energy resolution. Cryogenic temperatures are required to achieve electron energy measurements sufficient to resolve the variation of quantum energy states in nanostructures. *In situ* fabrication and transfer of samples is essential to the study of well-designed and characterized nanostructures.

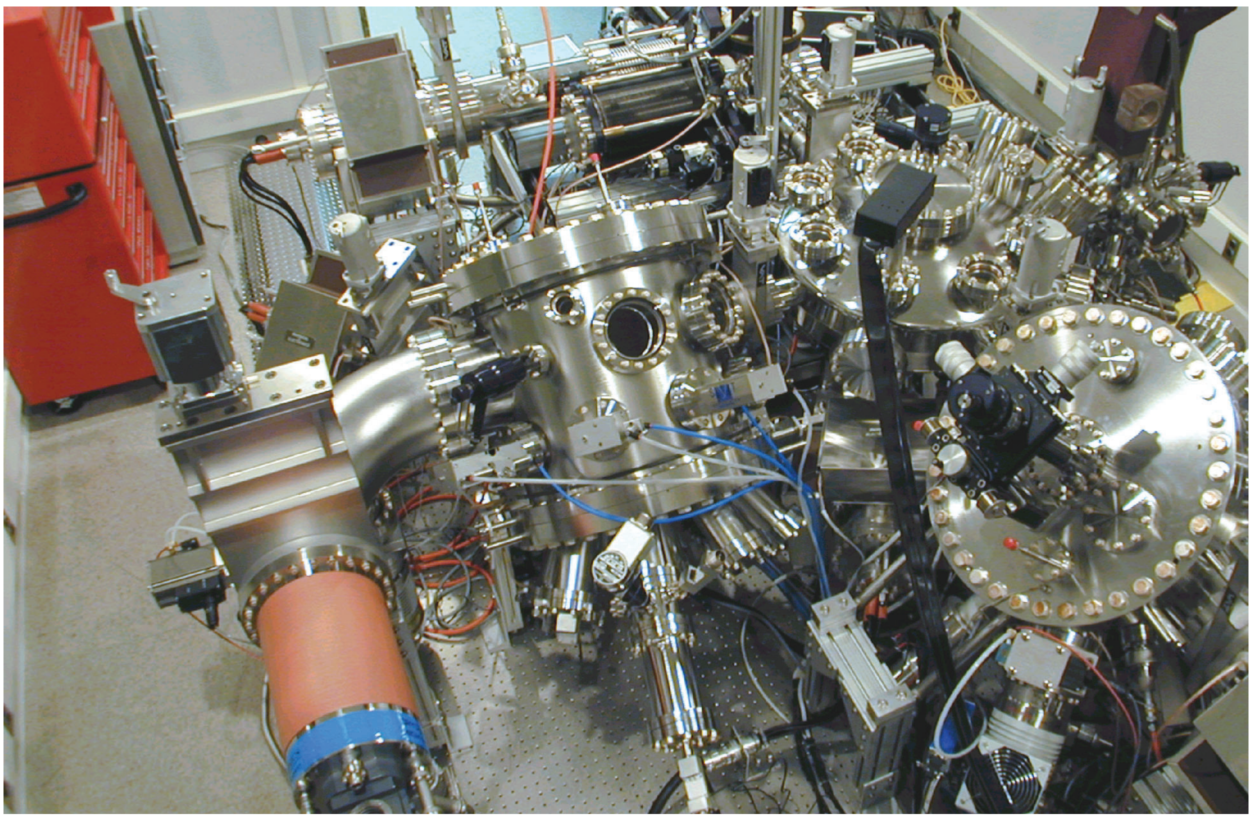


Figure 10. The NIST Nanoscale Physics Facility is a unique state-of-the-art instrument for the fabrication, characterization, and manipulation of novel nanostructures, with the following specific capabilities:

- Scanning tunneling microscope operating at ultra-high vacuum and controlled temperatures from about -270˚C to -150˚C
- Superconducting magnet system with 1.5 Tesla vector magnetic fields at the microscope position and 10 Tesla vertical magnetic fields at the microscope position
- Molecular beam epitaxy system to deposit semiconductors and metals with *in-situ* transfer of samples to the scanning tunneling microscope system
- Tip preparation system to image the atomic structure of tips with *in-situ* transfer of tips to the scanning tunneling microscope system
- Acoustically and electrically shielded measurement environment with extraordinarily high attenuation of external environmental disturbances

Courtesy J.A. Stroscio and R.J. Celotta, NIST Physics Laboratory

Grand Challenge Area

Nano-Electronics, -Photonics, and -Magnetics: The Next Generation of Information Technology Devices

Challenge

Further miniaturization of microelectronics – with more functionality and at lower cost – will require new approaches to fabrication and processing, and new methods for acquiring, storing, processing, transmitting, and displaying data.

Vision

Nano-electronic systems offer the potential to sustain the revolution in information technology devices provided by silicon-based micro electronics over the last 30 years. Nano-based systems will improve computer speed, expand mass storage, and reduce power consumption. Communication paradigms will change by increasing bandwidth for data transmission, and by developing flexible, flat displays that are many times brighter than conventional displays.

The physics of today's transistor devices does not scale to the length of a few nanometers. The properties of nanostructures need to be measured and incorporated into new device concepts, and the devices placed into new system architectures.

Without breakthroughs, the continued miniaturization of information technology devices may stall, due in part to economically unacceptable increases in manufacturing costs. The cost of a single fabrication plant for 65 nanometer electronic devices is now estimated at approximately $4 billion. Therefore, it is necessary to identify novel synthesis, processing, and manufacturing technologies such as (a) printing and stamping approaches to pattern transfer; (b) processing of devices in parallel via arrays of microelectromechanical systems (MEMS) technologies; (c) innovations in surface processing, controlled nucleation, directional growth, and directional etching innovations; and (d) batch formation of precursor nanostructures followed by directed self-assembly.

Agency Participation

(leads in bold)

DOD	Devices for communication, command, control, surveillance, and reconnaissance
DOE	MEMS, laboratory-on-a-chip
IA	Molecular electronics and advanced communication systems
NASA	Highly effective, miniaturized, low-power devices for spacecraft
NIST	Standards for measurement, manufacturing quality control
NSF	Novel phenomena, devices, and architectures

Research Example: Molecular Electronics—Nanowire interconnects (supported by DOD and NSF)

Researchers have been working on molecular-scale electronics devices for years. Advances in this field may extend the famous "Moore's Law" for an additional 10 to 20 years, or well beyond the fundamental limits of purely silicon-based technology. Moore's law describes the exponential growth of computational power over time, and has become a standard guide by which computational manufacturers judge their technological advancements.

One concept for molecular electronics comes from the work of researchers at Hewlett-Packard (HP), the California Institute of Technology and the University of California at Los Angeles (UCLA). They have placed a particular molecule, a rotaxane, into one of two electrically distinct states that correlate to a "0" or a "1." This approach preserves the digital nature of electronics and permits the current approach for memory and logic to be carried forward. The most complex elements of logic and memory can be extracted from such a molecular electronic "bit," which is formed by a few rotaxane molecules that are "sandwiched" between two crossed wires. Thus, the rotaxane or a similar molecule can be arranged to represent digital logic and memory. An array of such bits (similar to an expanded tic-tac-toe board) allows for error-free computation even in the presence of defective components, a critical characteristic for many nanotechnologies.

An early application of this technology is as highly efficient, random access memory. Today, random access memories are patterned at a density of about 3×10^8 bits/cm^2. Using rotaxane switches, the HP, Caltech, and UCLA research team has demonstrated working memory and logic prototypes that are up to 100 times more dense than conventional devices (see Figure 11). Although certain challenges, such as interconnection, must yet be met in order to demonstrate working circuitry at these densities, this molecular electronics technology is already exceeding traditional approaches by orders of magnitude in laboratory demonstrations.

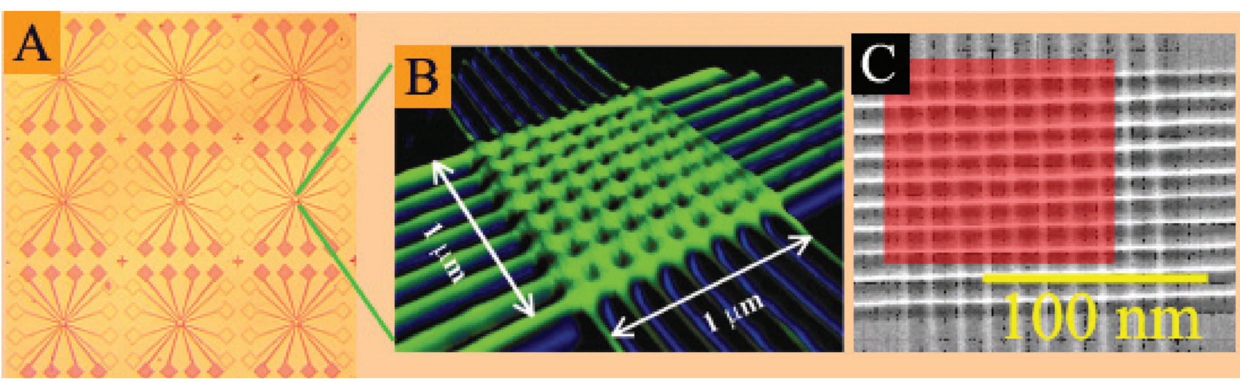


Figure 11. (A) Optical micrograph of an array of 64-bit molecular electronic circuits. (B) Atomic force micrograph revealing the detailed structure of one of the 64-bit circuits, patterned at a density of 7×10^9 bits/cm^2. This circuit has been utilized for simultaneous logic and memory operations. (C) The smallest circuit currently known (5×10^{11} bits/cm^2). As in (B), a bit is formed at each intersection of the lines. The highlighted 64 bits of this ultra-dense circuit fits inside a single bit of the circuit shown in (B) (courtesy J. Heath, Caltech).

Grand Challenge Area

Healthcare, Therapeutics, and Diagnostics: Using Nanotechnology for Better Disease Detection and Treatment

Challenge

Three critical areas within healthcare, therapeutics, and diagnostics lend themselves to nanoscale science and technology solutions. The first is improved implants developed by using biocompatible materials, tissue engineering, and regenerative medicine. The second is delivery of drugs, gene therapies, and other therapeutics. The third is earlier detection of disease, which could greatly enhance the success rate of existing treatment strategies and significantly advance our ability to employ prevention strategies.

Vision

Biological phenomena are largely governed by nanoscale structures. For example, the mechanisms of protein synthesis, replication, signal transduction, and infection occur at the nanoscale. Therefore, advances in a wide range of nanoscale science and technology will be relevant to biological research, and vice versa. Special opportunities exist for collaboration among life scientists and physical scientists. Collaborative programs leverage the knowledge base from each discipline, affording the best opportunities to shift life science paradigms from "hypothesis-driven" to mechanistic understanding.

As we achieve a better understanding of the design of biomolecular systems and learn how to build and control materials at this size scale, technologies for intervening in biological processes will emerge. These technologies offer promising routes to earlier detection of disease, more effective diagnostics and therapeutics, novel biocompatible materials, targeted gene and drug delivery systems, novel vision and hearing aids, and "smart" medical devices for treatment modes that minimize collateral damage.

Agency Participation

(lead in bold)

DOD	Casualty care, monitoring war fighter physiology, improving human capability to respond to threats
DOE	Radiation effects, sensors, hard/soft matter interfaces
FDA	Safety, efficacy, and quality assurance of drugs, medical devices, and biological products
NASA	Remote and autonomous medical care in space environment
NIH	Therapeutics, diagnostics, and regenerative medicine
NIST	Standards for bioscience and bioengineering
NSF	Nano-bioscience, nano-bioengineering
USDA	Food safety, animal health, plant disease prevention and treatment

Research Example: Peptide Nanotubes as Antibacterial Drugs (supported by NIH)

Bacterial resistance to antibiotics is a growing problem worldwide that is compromising the medical community's ability to treat many infectious diseases. Most antibiotics used today target invading bacteria by latching onto specific molecules in the bacteria's outer membrane. If the bacteria can modify those molecules even slightly, they become resistant to the antibiotic and can go on to infect their host.

Researchers at the Scripps Research Institute in San Diego have developed peptide nanotubes, shown schematically in Figure 12, that kill bacteria by punching holes in the bacteria's membrane. Each tube is formed from strings of amino acid subunits called peptides that, because of their structure, assemble into tiny rings. These rings stack on top of each other to form tubes on the order of barely one nanometer in diameter. By controlling the type of peptides used to build the rings, scientists are able to design nanotubes that selectively perforate bacterial membranes without harming the cells of the host.

In theory, these nano-bio agents should be far less prone than existing antibiotics to the development of bacterial resistance. The invading bacterium would have to substantially alter its membrane, not just alter a particular molecule, to become resistant to the nanotubes. Even if bacteria succeeded in altering their membranes, scientists could counter by modifying the structure of the nanotubes. Moreover, peptide nanotubes are resistant to proteases (protein-digesting enzymes found in the body) and therefore bypass a common problem in designing antibiotic agents.

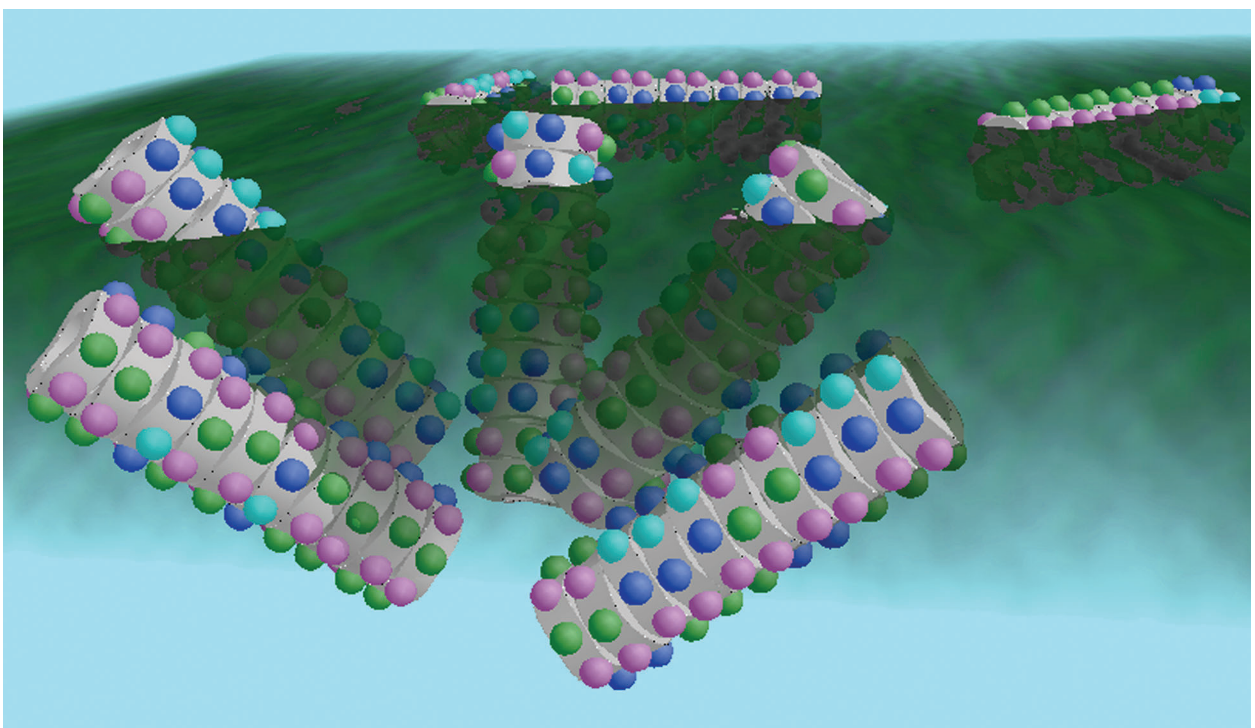


Figure 12. Schematic of designed peptide nanotubes that have penetrated a bacterial cell wall, effectively killing the bacterium. The nanotubes are formed from stacks of rings, which in turn are made up of various peptides (indicated by colored dots) (courtesy A. Olson and M.R. Ghadiri, Scripps Research Institute).

Grand Challenge Area

Energy Conversion and Storage: New Materials and Processes for Energy Needs

Challenge

Inexpensive energy underlies economic prosperity. A nation's ability to develop new energy sources within its own borders can reduce dependency on international energy supplies and finite oil reserves. Novel abilities and improved efficiencies in converting, storing, transmitting, and conserving energy are also critical to the challenge of providing clean, abundant, and secure energy for domestic needs.

Vision

Nanotechnology promises significant improvements in solar energy conversion and storage, thermoelectric converters, high-performance batteries and fuel cells, and efficient electrical power transmission lines. For example, nanoscale control of materials structure and composition has shown promise for novel approaches to photovoltaic systems. A deeper understanding of the physics of phonon and electron transport in nanostructured materials may facilitate production of practical all-solid-state and environmentally clean thermoelectric energy conversion devices. Currently, hard and soft magnets are widely used in electric power production and utilization. Improved nanostructured magnets may yield substantial energy savings by reducing losses incurred in the generation and use of electricity.

Nanostructures may also enhance the controlled release of chemical energy toward specific goals such as more efficient combustion, greater thrust in rocket propulsion, thermobaric destruction of chemical or biological agents, and tailored electromagnetic emission from propulsion systems (lower intensity signatures or better decoys to foil missile seekers). Nanoscale control of the shapes, chemistry, and phases of catalyst particles and supports clearly will impact energy conversion, chemical processing, and related fields.

Opportunities also exist for increasing thermal transport rates in fluids by utilizing nanocrystalline particulate suspensions. These "doped" nanofluids have recently been shown to exhibit substantially increased thermal conductivities and heat transfer rates compared to their "undoped" counterparts.

Agency Participation

(lead in bold)

DOD	Energetic materials for propulsion, decoys, explosives
DOE	All aspects of energy research, including catalysis, fuel cells, hydrogen
IA	Nano-enabled advanced power systems
NASA	Energy conversion and storage for space systems
NSF	Materials science and engineering
NIST	Manufacturing processes and equipment
USDA	Biomass conversion to energy and chemicals, hydrogen production, distributed power production

Research Example: Polymeric Nanostructures for Conversion of Solar Energy (supported by DOE)

Nanotechnology may provide a path to a new generation of solar cells. Presently, low-cost solar cells with power efficiencies of around 12% are readily available, while high-end solar cells with efficiencies of 34% can be made for satellites, but are prohibitively expensive for large-scale terrestrial applications. Researchers at the University of California at Berkeley and Lawrence Berkeley National Laboratory have reported a new type of "paint-on" solar cell that has promise for relatively low fabrication cost and the potential to achieve efficiencies comparable to those of high-end cells.

At the heart of all solar cells are two separate material layers, one with a reservoir of electrons that functions as the "negative pole," and one having vacancies for electrons called electron holes that functions as the "positive pole" of the cell. Absorption of light from the sun or other light source by the cell provides energy to drive the electrons from the negative to the positive pole, creating a voltage difference between the two and thus enabling the cell to serve as a source of electrical energy.

The new devices are based on a combination of a semiconductor polymer (an organic material) and cadmium selenide nanorods (an inorganic material) (Figure 13). In this cell, each microscopic step in the performance of the solar cell is independently optimized. Absorption of light can occur in either the nanorods or the polymer, and charge separation takes place at the interface between them, followed by charge transport to the harvesting electrodes—indium tin oxide (ITO) and aluminum (Al).

Solar cells made with these devices have the potential to provide low-cost, ultra-lightweight, and flexible cells with a wide range of applications. Due to the nanoscale dimensions of the nanorods, quantum-size effects influence their optical properties. By tailoring the size of the rods, they can be made to absorb light within a specific narrow band of colors. By stacking several cells with different sized rods, a broad range of wavelengths across the solar spectrum can be collected and converted to energy. Moreover, the nanoscale volume of the rods leads to a significant reduction in the amount of semiconductor material needed compared to a conventional cell.

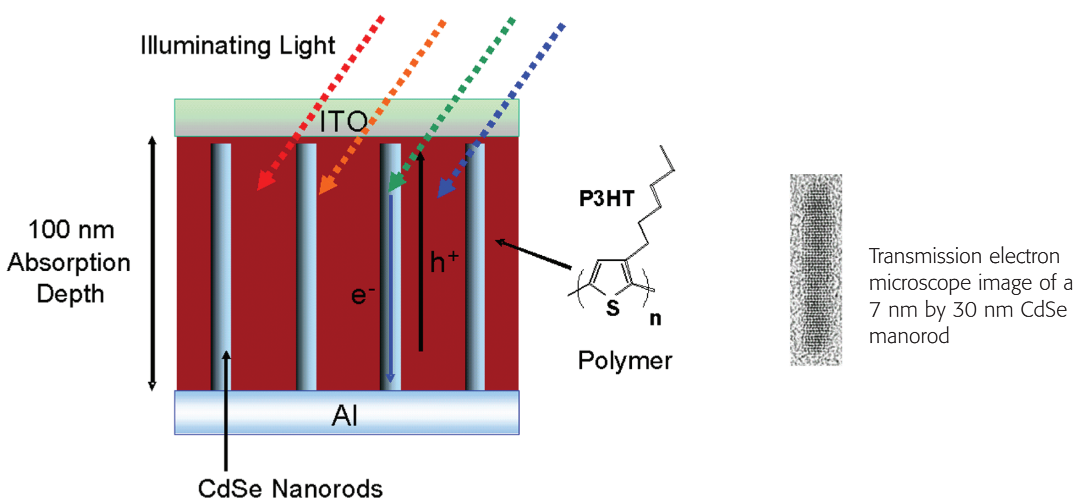


Figure 13. Schematic design of the nanorod-polymer solar cell illustrating how light energy activates the polymer (P3HT) and cadmium selenide (CdSe) components of the cell to drive electrons (e-) and holes (h+) to opposing aluminum (Al) and indium-tin oxide (ITO) electrodes (courtesy P. Alivisatos, University of California, Berkeley).

Grand Challenge Area
Microcraft and Robotics

Challenge

Integrating the miniaturization of machinery and computers can provide platforms to operate in hazardous or confined environments without human presence and can augment productivity by automating more routine operations. For instance, reduced payload weight and energy usage are critical factors that impact our ability to reach ever more remote and hostile environments on Earth and in space. Miniaturized, intelligent machinery also will enable the development of other highly desirable systems such as unmanned military combat platforms that reduce risks to personnel and *in vivo* systems that improve the detection and treatment of disease.

Vision

Nanotechnology will provide the ability to design very small-scale microcraft, vehicles and robots. Microelectromechanical systems (MEMS) are already providing some system miniaturization down to the microscale. Building on the fabrication processes and devices of MEMS technologies, nanoelectromechanical systems (NEMS) will open qualitatively new functional approaches and applications.

Nanosystems based on biological principles and building blocks are a key area for future research. For instance, long duration missions or missions in hazardous environments may benefit greatly from adopting strategies and architectures from the biological world. Utilization of *in situ* resources to create complex structures and craft that can adapt and react to changing environmental or mission needs are examples of the kinds of advances enabled through the application of nanotechnology and the principles of molecular biology. If the application is *in vivo,* then the use of molecular motors fueled by the body's metabolites might even provide a "self-powered" system.

Sensing, processing, and managing information is critical to the control of any microcraft or robot. A compelling need exists for miniaturized electronics with increased capability that can be embedded in system controls. The development of ultra-lightweight and ultra-strong materials that can survive extreme environments will be key to expanding our reach into applications such as space exploration.

Agency Participation

(lead in bold)

DOD	Surveillance, unmanned combat platforms, improving human capability to respond to threats
FDA	Safety, efficacy, and quality assurance of medical products
IA	Novel robotic systems
NASA	Intelligent spacecraft, smart materials/devices, autonomous healthcare systems
NIH	Telemedicine diagnostics/surgery; *in vivo* systems for diagnosis/therapeutics
NSF	Fundamental research on new principles and architectures for devices and systems
NIST	Intelligent systems research

Research Example: Molecular Motors—A New Nanoscale Biomimetic Paradigm for Energy Conversion (supported by NSF)

A biological cell has micrometer dimensions with the molecular machinery inside that cell having nanometer dimensions. Many cell functions require the action of "biological motors" that convert chemical energy to mechanical energy. For example, biological motors allow muscle fibers, flagella, and cilia to perform their functions.

One of the goals of researchers in this field is to develop an understanding of the mechanisms and processes of biological molecular motors and to incorporate similar approaches in nanoscale manmade devices. Researchers at Boston College have made steps toward this goal by designing and demonstrating a simple molecular motor that exhibits unidirectional rotary motion. The molecular motor consists of 78 atoms and consists of a rotating paddle-like structure attached to a base. Normally, thermally stimulated motion would cause this wheel-like molecule to rotate randomly in either direction. However, by tailoring the paddle wheel's molecular structure so that it is no longer entirely symmetrical, it can be induced to preferentially rotate in one direction. The impetus for rotation comes from chemical interaction between the paddle wheel part of the molecule and a common chloride compound, carbonyl dichloride. This particular molecular motor is not yet capable of continuous rotation—it rotates just 120 degrees—however, it represents a step toward being able to design nanoscale motors with controlled motion.

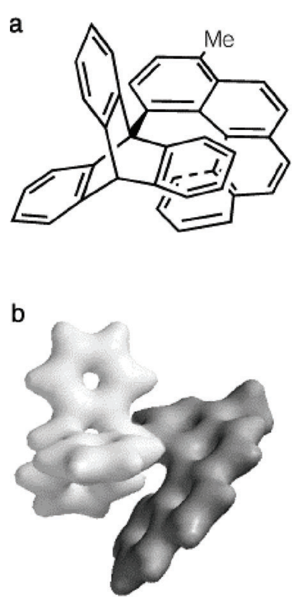


Figure 14. Diagram of a molecule designed to perform unidirectional rotary motion. The chemical structure is shown in (a). The molecule consists of two parts—a structure with three ringshaped paddles and a flat base—connected by a single bond about which rotation can occur. Figure 14(b) shows a calculated electron density surface map of the molecule as seen from a side view of the paddle wheel, which is shown in lighter gray. Upon interaction with carbonyl dichloride, the paddle wheel rotates 120 degrees in a clockwise direction (courtesy T.R. Kelly, Boston College).

Grand Challenge Area

Nanoscale Processes for Environmental Improvement

Challenge

Pollution has long been recognized as a serious threat to both the local and global environments and to our quality of life. The development of new technologies that enable industrial economies without harming human health and the environment is of critical importance in the 21st century. Development of innovative technologies for manufacturing, transportation, and other activities that reduce or eliminate the production of harmful by-products, or for treatment and remediation of existing toxic substances in the environment, presents major challenges for our society.

Vision

Nanoscale science and engineering can significantly improve our understanding of molecular processes that take place in the environment and help reduce pollution by leading to the development of new "green" technologies that minimize the use, production, and transportation of waste products, particularly toxic substances. Environmental remediation will be improved by the removal of contaminants from air and water supplies to levels currently unattainable, and by the continuous and real-time measurement of pollutants. In addition, increasing knowledge of the environmental, social, and human health implications of nanotechnology is crucial.

In order to understand the consequences of contaminants moving through the environment, interdisciplinary research is needed on molecular and nanoscale processes that take place at one or more of the interfaces or within nanoscale structures in natural systems. Such research includes studies of inorganic/inorganic, inorganic/organic, and organic/organic interfaces, with a focus on the specific processes dominated by small length scales. Separation science—exploiting the evolving capability to tailor nanostructured membranes—offers new opportunities to selectively extract contaminants from air, water, and soil.

Novel interdisciplinary research that adapts newly developed experimental, theoretical, and computational methods for characterizing nanostructures is needed. The community of scientists and engineers studying the fundamental properties of nanostructures must be connected with the community attempting to understand complex processes in the environment in order to hasten the integrated understanding of the environmental implications of nanoscale phenomena.

Agency Participation

(leads in bold)

DOE	Extraction of radionucleotides from otherwise benign materials
EPA	Detection, remediation, and prevention of environmental pollution
FDA	Ensuring safety and security of the food chain
NSF	Nanoscale processes in nature, "green" manufacturing
USDA	Agriculture technologies for minimizing environmental footprints, pollution remediation, precision agriculture, carbon sequestration

Research Example: Treatment of Contaminated Groundwater with Iron Nanoparticles (supported by EPA and NSF)

Researchers at Lehigh University recently found that nanoscale particles of metallic iron could potentially play a large role in the remediation of contaminated groundwater (Figure 15). Interaction between iron and the pollutant trichloroethylene (TCE) results in the degradation of TCE to more environmentally benign products. Palladium or platinum is added to the nanoparticles to enhance the rate at which this reaction takes place. The researchers carried out a field demonstration at an industrial site in which nanoparticles injected into a groundwater plume containing TCE reduced contaminant levels by up to 96%. A wide variety of contaminants (including chlorinated hydrocarbons, pesticides, explosives, polychlorinated biphenyls, and perchlorate) have been successfully broken down in both laboratory and field tests. The potential for remediation stems from the high reactivity of the nanoparticles and the fact that the technology is portable and highly scalable. The high reactivity of these particles can be attributed to their extraordinarily large surface area (~33.5 m^2/g). With an average particle diameter of less than 100 nanometers, the particles are injectable and can be delivered to contaminant hot spots or source areas as needed. This work is currently being funded by EPA to explore its potential in treating hazardous waste. The technology is being tested at several Federal and industrial sites for soil and groundwater remediation.

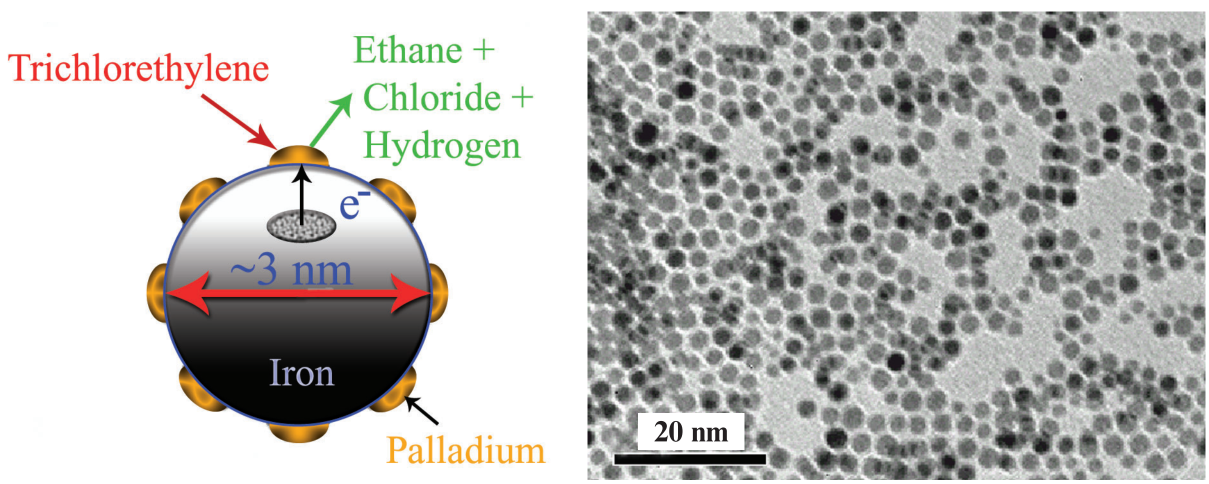


Figure 15. Schematic depiction of the remediation process in which iron nanoparticles transform a contaminant (trichloroethylene) in water into more environmentally benign products. In the process shown on the left, elemental iron acts as an electron (e-) donor while trichloroethylene serves as the electron acceptor for the chemical reaction. The presence of palladium metal on the surface of the iron nanoparticles enhances the transformation. The right portion of the figure shows a electron microscope image of the iron nanoparticles (courtesy W. Zhang, Lehigh University).

Investment Mode 3: Centers of Excellence

Centers provide opportunities and support for multidisciplinary research among investigators from a variety of disciplines and from different research sectors, including academia, industry, and government laboratories. Such multidisciplinary research not only leads to advances in knowledge, but also fosters relationships that enhance the transition of the results of basic research to devices and other applications. Fourteen multidisciplinary centers to encourage research networking have been initiated throughout the country. Seven have been funded by NSF, three by DOD, and four by NASA. A list of these centers is shown in Table 2. More are planned by NSF to broaden the range of topics and the geographical distribution.

Table 2. NNI Centers of Excellence

Center Name	Principal Investigator	Institution
NSF		
Nanoscale Systems in Information Technologies Nanoscale Science and Engineering Center (NSEC)	Buhrman	Cornell University
Nanoscience in Biological and Environmental Engineering NSEC	Smalley	Rice University
Integrated Nanopatterning and Detection NSEC	Mirkin	Northwestern University
Electronic Transport in Molecular Nanostructures NSEC	Yardley	Columbia University
Nanoscale Systems and their Device Applications NSEC	Westervelt	Harvard University
Directed Assembly of Nanostructures NSEC	Siegel	Rensselaer Polytechnic Institute
Nanobiotechnology Science and Technology Center	Baird	Cornell University
DOD		
Institute for Soldier Nanotechnologies	Thomas	Massachusetts Institute of Technology
Center for Nanoscience Innovation for Defense	Awschalom	University of California, Santa Barbara
Nanoscience Institute	Prinz	Naval Research Laboratory
NASA		
Institute for Cell Mimetic Space Exploration	Ho	University of California, Los Angeles
Institute for Intelligent Bio-Nanomaterials & Structures for Aerospace Vehicles	Junkins	Texas A&M
Bio-Inspection, Design, and Processing of Multifunctional Nanocomposites	Aksay	Princeton University
Institute for Nanoelectronics and Computing	Datta	Purdue University

Investment Mode 4: Research Infrastructure

A strong but flexible infrastructure is required to enable and stimulate new discoveries and innovations and to support the transition of those with commercial value from the laboratory to the marketplace. However, the cost of nanotechnology instrumentation, equipment, and facilities can be high, putting it out of the reach of researchers from small businesses and academic institutions. Government funding of infrastructure development that is accessible to virtually all researchers can substantially facilitate the creation of innovative technology and its transition to useful applications. An important focus of the NNI, therefore, is to develop measurements and standards, research instrumentation, modeling and simulation capabilities, and R&D user facilities. This type of funding has been used to support the National Nanofabrication Users Network and the modeling and simulation Network for Computational Nanotechnology, both of which are sponsored by NSF. Table 3 lists NNI user facilities, principle investigators, and host institutions.

Research infrastructure funding is also being used by DOE to create a group of five Nanoscale Science Research Centers (NSRCs) that are colocated with existing major facilities at DOE laboratories across the country. The NSRCs will be operated as user facilities that are available to all researchers on a merit-reviewed basis. Other infrastructure dedicated to nanotechnology R&D that is under development at Federal laboratories includes a nanoscience facility at the Naval Research Laboratory and portions of the Advanced Measurement Laboratory at NIST.

Table 3. Infrastructure: Nanotechnology R&D User Facilities

User Facility Name	Principal Investigator	Institution
NSF		
National Nanofabrication Users Network (NNUN)*	Tiwari	Cornell University
	Harris	Howard University
	Plummer	Stanford University
	Fonash	Pennsylvania State University
	Hu	University of California, Santa Barbara
Network for Computational Nanotechnology	Lungstrom	Purdue University
	Hess	University of Illinois
	Dutton	Stanford University
	Fortes	University of Florida
	Lush	University of Texas, El Paso
	Ratner	Northwestern University
	Scott	Morgan State University
DOE		
Center for Functional Nanomaterials	Hwang	Brookhaven National Laboratory
Center for Integrated Nanotechnologies	Michalske	Sandia and Los Alamos National Laboratories
Center for Nanophase Materials Sciences	Lowndes	Oak Ridge National Laboratory
Center for Nanoscale Materials	Bader	Argonne National Laboratory
Molecular Foundry	Alivisatos	Lawrence Berkeley National Laboratory
NIST		
NIST Center for Neutron Research (NCNR)	Rowe	NIST

* Note: The NNUN predates the NNI, but is funded under the NNI through 2003. In 2004, the NNUN will be expanded to create the National Nanotechnology Infrastructure Network.

Investment Mode 5:
Societal Implications and Workforce Preparation

Societal Aspects

When new technologies with high impact are developed, societal issues often arise. These issues require specific measures to take best advantage of opportunities while reducing the potential risks associated with technology development and subsequent commercialization. The NNI provides funding for research that addresses the ethical, social, legal, economic, and workforce implications of nanoscience and nanotechnology. For example, following the establishment of the NNI in FY2001, NSF has introduced a theme on, "Societal and Educational Implications of Scientific and Technological Advances on the Nanoscale" in its Nanoscale Science and Engineering program solicitation. Studies under this program include economic implications of innovation; knowledge barriers to adoption of nanotechnology in commerce; implications for health and the environment; educational and workforce needs; ethical issues; and implications of new fields arising at the intersection of traditional areas of science and engineering. Some specific examples include the following:

- The University of Virginia received a five-year NSF award for 2001-2006 to investigate "Ethics and Belief Inside the Development of Nanotechnology."
- The University of South Carolina received an award in 2002 to study "Philosophical and Societal Dimensions of Nanoscale Research." This award helped to create a center on societal implications of nanotechnology at that university.
- Another award supports the creation and maintenance of a nanotechnology commercialization database.

Education and Training

Science, engineering, and technology education play three critical societal roles in (1) producing the next generation of researchers and innovators, (2) providing the workforce of the future with the technological skills they will need to succeed, and (3) educating a citizenry capable of making well-informed decisions in an increasingly technologically driven society. The NNI plays a special role in each.

With respect to training future scientists and engineers, a major impact of NNI-supported research is the hands-on training of undergraduates, graduate students, and postdoctoral researchers via funding of nanoscience and nanotechnology research at universities. NNI programs also provide direct funding for student fellowships and traineeships. Because nanotechnology research often cuts across traditionally distinct disciplines, including physics, chemistry, biology, materials, mathematics, and engineering, new teaching paradigms that emphasize a multidisciplinary approach to research will be particularly relevant.

Industry must have an adequate supply of skilled technical workers in order to meet the increasing workforce demands that are expected to accompany progress in nanotechnology. A key objective of the NNI is to develop new approaches to education and training that will lead to a new generation of skilled workers with the multidisciplinary perspective and knowledge necessary for rapid progress in nanotechnology. Such programs are aimed at community colleges and other institutions and programs that emphasize job-related skills, as well as at four-year colleges and universities.

Clearly, education and training takes place well before the college level in the primary and secondary schools. Therefore, improvement in K-12 science and mathematics education is critical not just to nanotechnology but to all scientific and engineering disciplines. Towards this end, the NSF Nanoscale Science and Engineering Centers have funds specifically aimed at addressing K-12 education. In addition, the National Nanotechnology Coordination Office (NNCO) has prepared a paper entitled, "Extending Outreach Success for the National Nanoscale Science and Engineering Centers—A Handbook for Universities," which provides information on how universities can engage K-12 educators and students.

National Nanotechnology Coordination Office Activities

Outreach is an important component of the NNI. One mechanism by which outreach is accomplished is through the National Nanotechnology Coordination Office, which serves as the point of contact on Federal nanotechnology activities for government organizations, academia, industry, professional societies, foreign organizations, and others. Examples of the mechanisms by which the NNCO communicates with interested parties are the publication of reports on workshops organized by the NSET and ongoing development and maintenance of the NNI website (www.nano.gov).

The NNCO also facilitates outreach to a broad cross-section of industry, another NNI objective. For example, the NNCO is working with members of NSET and DOC's Technology Administration to organize a series of regional workshops to increase industry awareness of pending nanotechnology developments and address scientific and technical deficiencies that are limiting industrial commercialization of nanotechnology. The first workshop (western region) was held on Sept 10, 2001, at UCLA. The second (southern region) was held in Houston, Texas, on May 23, 2002. Additional meetings are to be held in the midwestern and eastern regions.

Outreach to regional, state, and local organizations that are coordinating nanotechnology-based efforts is also an integral part of NNCO's mission. The list of states that have organized nanotechnology programs is a lengthy one and continues to grow. Other state programs that are not specifically directed at nanotechnology are also providing support to ventures in this area. For instance, Nanoscale Materials, Inc., was the first tenant in Kansas State University's K-State Research Park. In addition, the NSF's Experimental Program to Stimulate Competitive Research (EPSCoR), which supports development of research infrastructure in less research-intensive states, has provided funding to Oklahoma for NanoNet. This program coordinates a statewide network of scientists and engineers, including students at state colleges and universities, involved in developing three critical nanoscale components: epitaxial nanostructures, colloidal particles, and integrated circuit connectors.

Several private initiatives also are accelerating the introduction of nanotechnology into the market. For instance, the NanoBusiness Alliance is actively fostering nanoscience and nanotechnology by compiling three nanotechnology directories for the venture capital, industry, and nanotechnology service and support communities. The NNCO contributes to these efforts as an information resource.

Through the NNCO, as well as the participating agencies, the NNI maintains close ties with professional societies as a valuable means of disseminating information on current activities, promoting education for nanoscale science and technology, and as a source for insight on opportunities for future research. In addition, as the worldwide investment in nanotechnology grows, it is vital that the NNI reach out to programs, institutions, and researchers overseas to foster collaboration and to allow U.S. nanotechnologists to learn from activities taking place abroad.

NSTC Committee on Technology

Co-chair: **Richard M. Russell**
Co-chair: **Phillip J. Bond**
Executive Secretary: **Benjamin H. Wu**

Subcommittee on Nanoscale Science, Engineering and Technology (NSET) Contact List for NSET Members and Relevant Executive Office of the President and NNCO Staff Actively Involved as of August 2003

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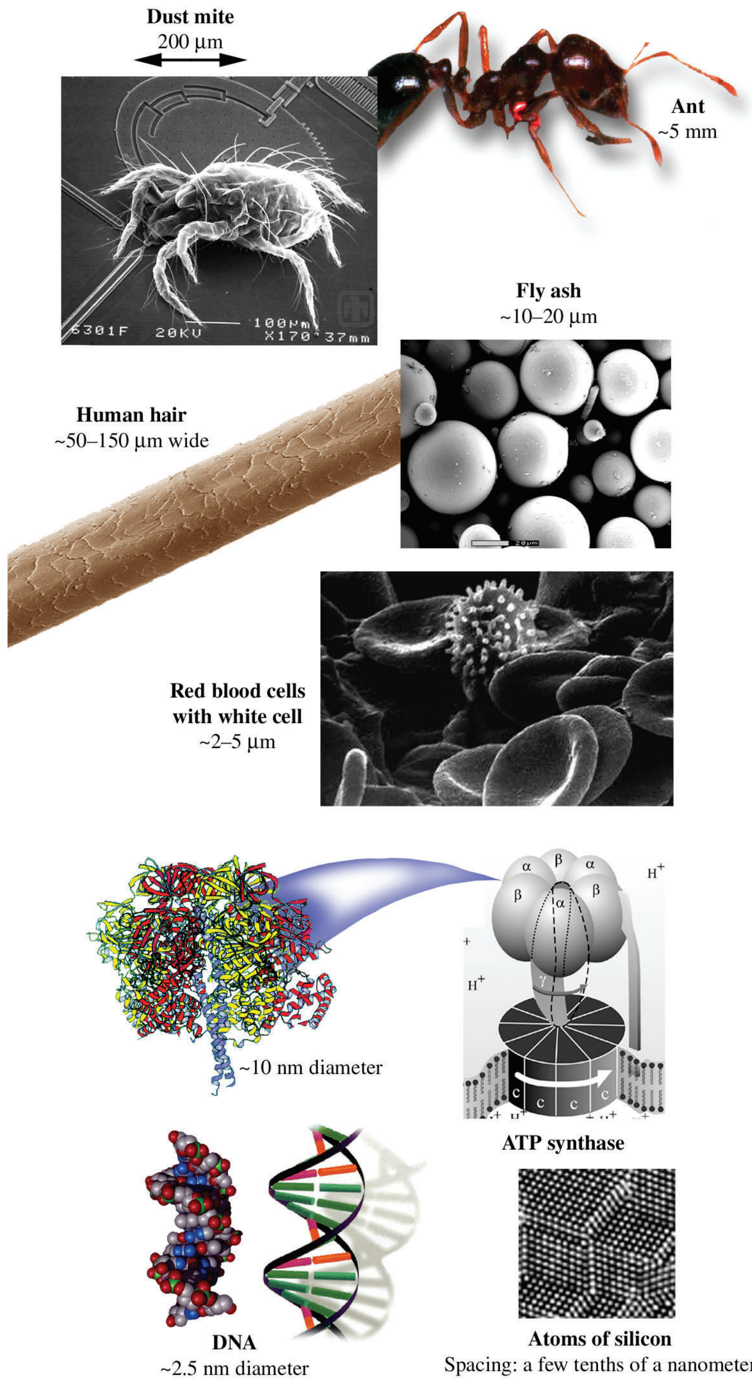
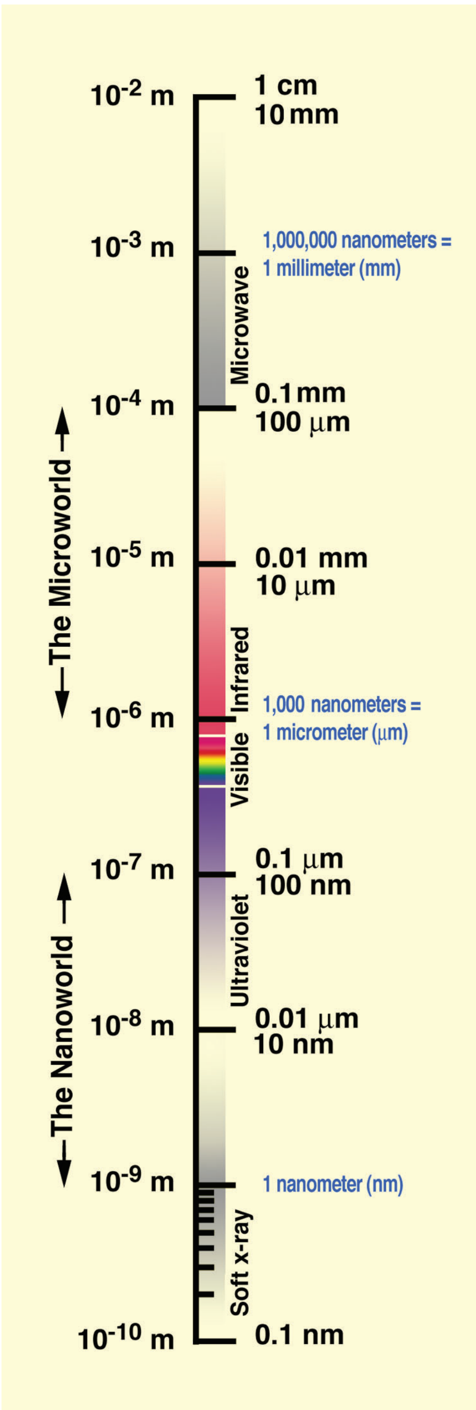
the Scale of Things....

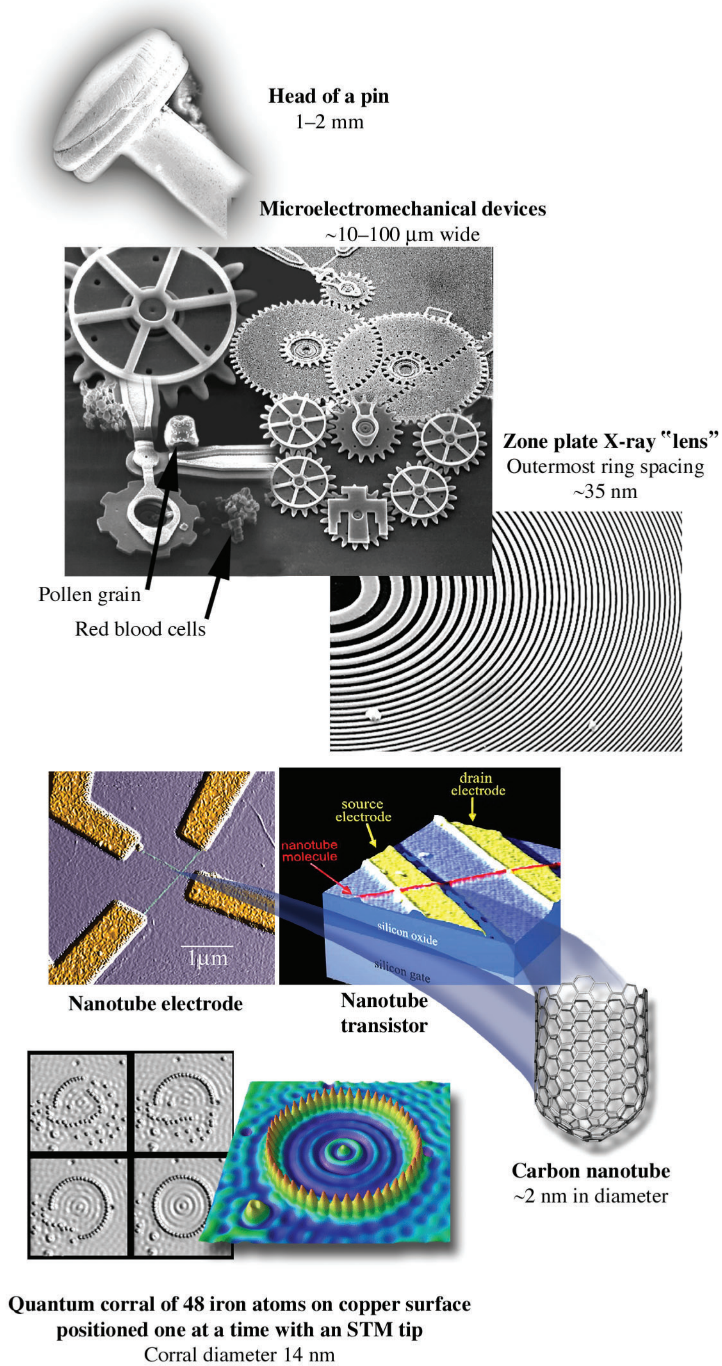
Nanometers & More

things Natural



things Manmade





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