Nanotechnology Research Directions: IWGN Workshop Report

Vision for Nanotechnology R&D in the Next Decade

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EXECUTIVE SUMMARY

Nanotechnology is the creation and utilization of materials, devices, and systems through the control of matter on the nanometer-length scale, that is, at the level of atoms, molecules, and supramolecular structures. The essence of nanotechnology is the ability to work at these levels to generate larger structures with fundamentally new molecular organization. These "nanostructures," made with building blocks understood from first principles, are the smallest human-made objects, and they exhibit novel physical, chemical, and biological properties and phenomena. The aim of nanotechnology is to learn to exploit these properties and efficiently manufacture and employ the structures.

Control of matter on the nanoscale already plays an important role in scientific disciplines as diverse as physics, chemistry, materials science, biology, medicine, engineering, and computer simulation. For example, it has been shown that carbon nanotubes are ten times as strong as steel with one sixth of the weight, and that nanoparticles can target and kill cancer cells. Nanoscale systems have the potential to make supersonic transport cost-effective and to increase computer efficiency by millions of times. As understanding develops of the way natural and living systems are governed by molecular behavior at nanometer scale, and as this understanding begins to be felt in science and medicine, researchers seek systematic approaches for nanoscale-based manufacturing of human-made products.

All natural materials and systems establish their foundation at the nanoscale; control of matter at molecular levels means tailoring the fundamental properties, phenomena, and processes exactly at the scale where the basic properties are determined. Therefore, by determining the novel properties of materials and systems at this scale, nanotechnology could impact the production of virtually every human-made object—everything from automobiles, tires, and computer circuits to advanced medicines and tissue replacements—and lead to the invention of objects yet to be imagined. Nanotechnology will be a strategic branch of science and engineering for the next century, one that will fundamentally restructure the technologies currently used for manufacturing, medicine, defense, energy production, environmental management, transportation, communication, computation, and education.

As the twenty-first century unfolds, nanotechnology's impact on the health, wealth, and security of the world's people is expected to be at least as significant as the combined influences in this century of antibiotics, the integrated circuit, and human-made polymers. Dr. Neal Lane, Advisor to the President for Science and Technology and former National Science Foundation (NSF) director, stated at a Congressional hearing in April 1998, "If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering." Recognizing this potential, the White House Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) have issued a joint memorandum to Federal agency heads that identifies nanotechnology as a research priority area for Federal investment in fiscal year 2001.

This report charts "Nanotechnology Research Directions," as developed by the Interagency Working Group on Nano Science, Engineering, and Technology (IWGN) of the National Science and Technology Council (NSTC). The report incorporates the views of leading experts from government, academia, and the private sector. It reflects the consensus reached at an IWGN-sponsored workshop held on January 27–29, 1999, and detailed in contributions submitted thereafter by members of the U.S. science and engineering community. (See Appendix A for a list of contributors.) This report describes challenges that are posed and opportunities that are offered by nanotechnology and outlines the steps we must take as a nation if we are to benefit from the advances that are envisioned. Moreover, it proposes a national nanotechnology initiative consistent with the OSTP/OMB memorandum. This emphasizes three crucial areas: developing a balanced research and development infrastructure, advancing critical research areas, and nurturing the scientific and technical workforce of the next century. The initiative proposes doubling the Federal investment in nanotechnology and founding a cooperative grand alliance of government, academia, and the private sector to promote U.S. world leadership in nanotechnology.

SYNOPSIS OF RECOMMENDATIONS

Workshop participants agreed that the benefits of nanotechnology could best be realized through a cooperative national program involving universities, industry, government agencies at all levels, and the government/national laboratories. To address the scientific and technological challenges and reap nanotechnology's social and economic benefits, workshop participants recommended a national initiative with the following objectives:

- Support long-term nanoscience and engineering research leading to fundamental discoveries of novel phenomena, processes, and tools
- Improve institutional structures so they foster and nourish developments
- Encourage the type of transdisciplinary and multi-institutional cooperation required in this new area
- Provide new types of educational opportunities to train the nanotechnologists and entrepreneurs of the future
- Create the physical infrastructure to enable first-class basic research, exploration of applications, development of new industries, and rapid commercialization of innovations

Within their vision of a "grand coalition" contributing to a national nanotechnology initiative, workshop participants proposed specific objectives for academe, private industry, Government laboratories, Government funding agencies, and professional science and engineering societies, as follows:

1. Academe

- Promote interdisciplinary work involving multiple departments
- Foster on-campus nanotechnology centers for greater interaction
- Introduce nanoscience and engineering in existing and new courses
- Create or connect "regional coalitions" that involve industry/technology generation
- Ease intellectual property restrictions to improve information flow with industry
- Establish graduate and postdoctoral fellowships for interdisciplinary work

2. Private Sector

- Build up investment by maintaining in-house research activities in nanotechnology
- Join, contribute to, or lead regional coalitions for precompetitive nanotechnology research and information dissemination
- Sponsor nanotechnology startups/spin-offs

3. Government R&D Laboratories

- Pursue applications of nanotechnology in support of respective agency missions
- Join regional coalitions with universities and industry, and cultivate information flow
- Provide unique measurement and manufacturing capabilities at nanoscale facilities (synchrotrons, microscopy centers, etc.)
- Provide measurement standards for the nanotechnology field

4. Government Funding Agencies

- Establish a national nanotechnology initiative in fiscal year 2001 that will approximately double the current Government annual investment of about $255 million (in fiscal year 1999) in R&D supporting nanoscience, engineering and technology
- Emphasize small, transdisciplinary research groups in academe within and among universities, and promote policies that foster collaboration between academe, private sector, and government laboratories
- Support nanoscience and engineering fellowships that are not tied to one discipline
- Develop and maintain an information system and databases specifically for nanoscience and engineering available to the community at large to serve rapid development of research and education in the field
- Sponsor regional university and Government lab centers in partnership with industry to cultivate exploratory research, shared research in critical areas, education and information flow
- Establish "vertical centers" where fundamental research, applied research, technology development, and prototype construction or clinical evaluations can be pursued concurrently
- Promote international collaborations for cost-sharing and joint centers/networks of excellence, where appropriate, for fundamental studies

5. Professional Science and Engineering Societies

- Establish interdisciplinary forums that accelerate progress in research and development in nanoscience, engineering and technology, and facilitate its transition into other technologies
- Convene groups of scientists and engineers who have not collaborated traditionally
- Reach out to the international research communities to ensure U.S. awareness of the latest advances
- Develop symposia to explore educational opportunities at K-12, undergraduate, and graduate levels
- Invite industrial players to participate in interdisciplinary job fairs and interview prospective scientists and engineers for nano-related openings

On behalf of the
Interagency Working Group on Nanoscience, Engineering and Technology (IWGN),

Dr. M.C. Roco, National Science Foundation, Chair of the IWGN

Dr. R.S. Williams, Hewlett-Packard Co. (representing the private sector)

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TECHNICAL SUMMARY

The National Science and Technology Council's Interagency Working Group on Nano Science, Engineering, and Technology (IWGN) held a workshop on January 27–29, 1999, to survey research and development as well as education opportunities in nanoscience, engineering and technology, examine what opportunities exist, develop a baseline understanding of the Federal role, and ascertain what is required to ensure that the United States benefits from this new field. Participants at the workshop and other contributors after the meeting represented academic, industrial, and Government organizations and a range of disciplines, including biology, chemistry, materials science, physics, and engineering.

From workshop presentations it was clear that the on-going discovery of novel phenomena and processes at the nanometer scale is providing science with a wide range of tools, materials, devices, and systems with unique characteristics. By using structure at the nanoscale as a physical variable, it is possible to greatly expand the range of performance of existing chemicals and materials. Scientists can already foresee using patterned monolayers for a new generation of chemical and biological sensors; nanoscale switching devices to improve computer storage capacity by a factor of a million; tiny medical probes that will not damage tissues; entirely new drug and gene delivery systems; nanostructured ceramics, polymers, metals, and other materials with greatly improved mechanical properties; nanoparticle-reinforced polymers in lighter cars; and nanostructured silicates and polymers as better contaminant scavengers for a cleaner environment. Current research is moving rapidly from observation and discovery to design and fabrication of complex nanoscale assemblies. Soon, a systems approach grounded in multidisciplinary research will be required for continued and rapid progress.

Workshop participants—all respected experts in the nanotechnology field—emphasized the breadth and variety of applications and the common obstacles facing extremely disparate research areas. They frequently noted nanotechnology's potential to displace major existing technologies, create new industries, and transform archetypal scientific models in the areas of energy, environment, communications, computing, medicine, space exploration, national security, and any area based on materials. However, while recognizing nanotechnology's potential to spawn an industrial revolution in coming decades, the consensus was that the challenges ahead in basic discovery, invention, and eventual manufacturing are formidable. New methods of investigation at the nanoscale, novel scientific theories, and different fabrication paradigms are critical.

The main objectives of the IWGN workshop and this report were to identify science and technology paradigm changes underway as a result of nanoscale research and development; current and potential applications of nanotechnology; and means to strengthen the U.S. research and development infrastructure to capture the potential of nanotechnology in the next decade.

After an introduction for non-specialists, Chapters 1-3 of this report outline the fundamental scientific challenges in nanotechnology and the investigative tools that have made possible the development of this field. Chapter 4 surveys current developments and visionary perspectives for synthesis and assembly of nanostructures; Chapters 5-10 survey the main areas of nanotechnology application; Chapter 11 describes future infrastructure needs for research and development and education as compared to the present; and Chapter 12 analyzes roles, priorities, and strategies for U.S. funding agencies. Recommendations for academe, the private sector, Government R&D laboratories, Government funding agencies, and professional societies begin on page xix.

Definition of Nanotechnology

Nanotechnology is the popular term for the construction and utilization of functional structures with at least one characteristic dimension measured in nanometers. Such materials and systems can be rationally designed to exhibit novel and significantly improved physical, chemical, and biological properties, phenomena, and processes because of their size. When characteristic structural features are intermediate in extent between isolated atoms and bulk materials, in the range of about 10^{-9} to 10^{-7} m (1 to 100 nm), the objects often display physical attributes substantially different from those displayed by either atoms or bulk materials.

Properties of matter at the nanoscale are not necessarily predictable from those observed at larger scales. Important changes in behavior are caused not only by continuous modification of characteristics with diminishing size, but also by the emergence of totally new phenomena such as quantum size confinement, wave-like transport, and predominance of interfacial phenomena. Once it is possible to control feature size and shape, it is also possible to enhance material properties and device functions beyond what are already established. Currently known nanostructures include such remarkable entities as carbon nanotubes, proteins, DNA, and single-electron transistors that operate at room temperature. Rational fabrication and integration of nanoscale materials and devices herald a revolutionary age for science and technology, provided we can discover and fully utilize their underlying principles.

A Revolution at the Limits of the Physically Possible

In 1959 Nobel laureate physicist Richard Feynman delivered his now famous lecture, “There is Plenty of Room at the Bottom.”[1] He stimulated his audience with the vision of exciting new discoveries if one could fabricate materials and devices at the atomic/molecular scale. He pointed out that, for this to happen, a new class of miniaturized instrumentation would be needed to manipulate and measure the properties of these small—“nano”—structures.

It was not until the 1980s that instruments were invented with the capabilities Feynman envisioned. These instruments, including scanning tunneling microscopes, atomic force microscopes, and near-field microscopes, provide the “eyes” and “fingers” required for nanostructure measurement and manipulation. In a parallel development, expansion of computational capability now enables sophisticated simulations of material behavior at the nanoscale. These new tools and techniques have sparked excitement throughout the scientific community. Scientists from many disciplines are now avidly fabricating and analyzing nanostructures to discover novel phenomena based on structures with at least

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[1] Published later: Feynman, R.P. 1961. There is plenty of room at the bottom. In *Miniaturization*. New York: Reinhold.

one dimension under the "critical scale length" of 100 nm. Nanostructures offer a new paradigm for materials manufacture by submicron-scale assembly (ideally, utilizing self-organization and self-assembly) to create entities from the "bottom up" rather than the "top down" ultraminiaturization method of chiseling smaller structures from larger ones. However, we are just beginning to understand some of the principles to use to create "by design" nanostructures and how to economically fabricate nanodevices and systems. Second, even when fabricated, the physical/chemical properties of those nanostructured devices are just beginning to be uncovered; the present micro- and larger devices are based on models working only at scale lengths over the 100+ nm range. Each significant advance in understanding the physical/chemical properties and fabrication principles, as well as in development of predictive methods to control them, is likely to lead to major advances in our ability to design, fabricate and assemble the nanostructures and nanodevices into a working system.

What the Visionaries Say

John Armstrong, formerly Chief Scientist of IBM, wrote in 1991, "I believe nanoscience and nanotechnology will be central to the next epoch of the information age, and will be as revolutionary as science and technology at the micron scale have been since the early '70s." More recently, industry leaders, including those at the IWGN workshop, have extended this vision by concluding that nanoscience and technology have the potential to change the nature of almost every human-made object in the next century. They expect significant improvements in materials performance and changes in manufacturing to lead to a series of revolutionary changes in industry.

At the workshop, Horst Stormer, Nobel Laureate, articulated the vision many share: "Nanotechnology has given us the tools. . . to play with the ultimate toy box of nature — atoms and molecules. Every thing is made from it. The combination of our top-down tools and methods with self-assembly on the atomic scale provides an impressive array of novel opportunities to mix-and-match hunks of chemistry and biology with artificially defined, person-made structures. The possibilities to create new things appear limitless."

George Whitesides, Professor of Chemistry at Harvard, in 1998 gave information storage as an example of the radical changes nanotechnology could make possible: "You could [with nanodevices] get, in something the size of a wristwatch, the equivalent of 1,000 CDs. That starts approaching a fraction of the reference library that you need for your life…It's one of those ideas that shifts a little bit the notion of how a life should be led."[2]

Although considerable uncertainty is prevalent in predicting future benefits of investments, this report attempts to anticipate benefits that will most likely occur within a few decades. A significant lesson from the 20th century is that predictions of the state of a particular technology several decades in the future often fall far short of what is actually accomplished because one foresees only evolutionary changes, while scientific and technological revolutions are almost impossible to predict (see "Introduction to Nanotechnology for Nonspecialists," page xxv).

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[2] Whitesides, G.M. 1998. Nanotechnology: Art of the possible. *Technology Review* November/ December.

Fundamental Science Issues to be Explored

The investigative tools and level of understanding of basic nanoscale phenomena are now only rudimentary. For the promise of nanotechnology to be realized, much more fundamental scientific knowledge is needed, including understanding of molecular self-organization, how to construct quantum devices, and how complex nanostructure systems operate. It is difficult at this moment to make sharp distinctions between fundamental and applied science in nanotechnology. This is not a new phenomenon: recall that the discovery of the laser revolutionized several fields, including both communications and surgery, while the basic scientific principles were still being investigated. There are several areas in physics, chemistry, materials science, electrical engineering, and other disciplines where the basic sciences must be thoroughly developed before a concrete nanotechnology will have the chance to emerge. Several broad, transdisciplinary questions being asked in current fundamental nanoscience R&D illustrate the challenge:

1. What new and novel quantum properties will be enabled by nanostructures, especially at room temperatures?
2. How different from bulk behavior will be the properties of interfacial regions between contiguous nanostructures? How can new technologies exploit these properties?
3. What are the surface reconstructions and rearrangements of atoms in nanocrystals and nanorods? Is it possible to prepare epitaxial core-shell systems in nanocrystals?
4. Can carbon nanotubes of a single length and helicity be synthesized and purified as isolated molecular species? Is it possible to reproducibly prepare heterojunctions in one-dimensional nanostructures?
5. What new insights in our understanding of complex polymer, supramolecular, and biological systems will come from the capability to examine single-molecule properties?
6. How extensively can one use parallel self-assembly techniques to control the relative arrangements of nanoscale components according to a complex, designed sequence before error rates become unacceptable?
7. Are there processes that would lead to economic preparation of nanostructures with the control of size, shape, composition, and surface states necessary for advanced device applications?

The Societal and Economic Impacts of Nanotechnology

Potential applications of nanotechnology are pervasive, in the fields described below:

Materials and Manufacturing

Nanotechnology is fundamentally changing the way materials and devices will be produced in the future. The ability to synthesize nanoscale building blocks with precisely controlled size and composition and then to assemble them into larger structures with unique properties and functions will revolutionize segments of the materials manufacturing industry. Nanostructuring is expected to bring about lighter, stronger, and programmable materials; reductions in life-cycle costs through lower failure rates;

innovative devices based on new principles and architectures; and use of molecular/cluster manufacturing.

Molecular/cluster manufacturing takes advantage of assembly at the nanoscale level for a given purpose. Structures not previously observed in nature can be developed. Challenges include synthesis of materials by design, development of bio- and bio-inspired materials, development of cost-effective and scalable production techniques, and determination of the nanoscale initiators of materials failure. Applications of nanotechnology to materials and manufacturing include the following:

- Forming nanostructured metals and ceramics at exact shapes without machining
- Improved color printing brought about by nanometer-scale particles that have the best properties of both dyes and pigments
- Nanoscale cemented and plated carbide materials and nanocoatings for cutting tools, and other electronic, chemical, and structural applications
- New standards for measurements at nanoscale
- Nanofabrication on a chip with high levels of complexity and functionality

Nanoelectronics and Computer Technology

The Semiconductor Industry Association (SIA) has developed a roadmap for continued enhancements in miniaturization, speed, and power reduction in information processing devices, e.g. sensors for signal acquisition, processors, memories and displays. The SIA's 1997 edition of The National Technology Roadmap for Semiconductors[3] projects the advances required in all the industries that support semiconductor manufacturing to maintain the historical rate of improvement (Moore's Law) of integrated circuits. The projections extend to the year 2012, at which time the smallest component of a device would have a linear dimension of 50 nm. However, for years beyond 2006 and device features 100 nm or smaller, the roadmap is filled with the notation "No Known Solution." Indeed, in the Sept. 24 edition of *Science*, Paul Packan of Intel described the technical difficulties currently experienced in semiconductor manufacturing. He stated that Moore's Law "now seems to be in serious danger" and that maintaining the rate of improvement in the next decade "will be the most difficult challenge the semiconductor industry has ever faced."[4]

The SIA roadmap ends just short of true nanostructure devices because the principles, fabrication methods, and way of integrating devices into systems are unknown. The roadmap explicitly states that "sustained government support of semiconductor research is mandatory if this industry is to continue to provide for strong economic growth in the U.S." and recognizes that new architectures, materials, and processes will be required to meet the goal of achieving 100 nm feature sizes.

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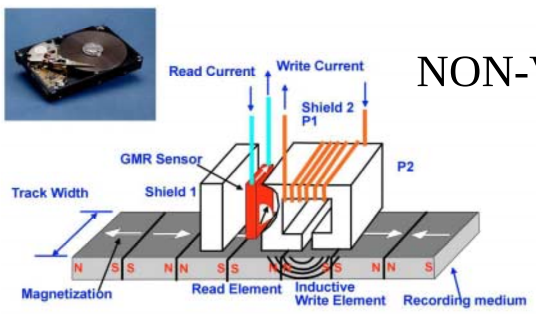
[3] Semiconductor Industry Association. 1997. *The national technology roadmap for semiconductors: Technology needs*. San Jose, CA (http://www.semichips.org).

[4] Packan, P.L. 1999. Pushing the limits. *Science* 285: 2079-2081.

The lead time for science maturing into technology is approximately 10 to 15 years; now is the critical time for Government investment in the science and technology of nanostructures for timely impact in information technology. Further, the investment will have spin-offs that enable the attainment (or acceleration) of other SIA roadmap goals. The area of magnetic information storage is illustrative. Within ten years of the fundamental discovery of the new phenomenon of giant magnetoresistance, this nanotechnology is rapidly replacing older technologies for disk computer heads in a hard disk market worth $34 billion in 1998 (see Figure TS.1).



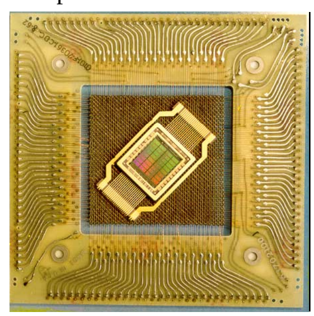
Magnetic recording process.

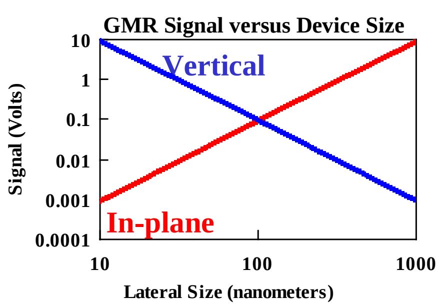
INFORMATION TECHNOLOGY

NON-VOLATILE HIGH DENSITY MEMORY

Within ten years from the fundamental discovery, the giant magnetoresistance (GMR) effect in nanostructured (one dimension) magnetic multilayers has demonstrated its utility in magnetic sensors for magnetic disk read heads, the key component in a $34 billion/year hard disk market in 1998. The new read head has extended the density of magnetic disk information storage from 1 to ~20 Gbits/in^2. Because of this technology, most hard disk production is done by U.S.-based companies.

A future application of GMR is nonvolatile magnetic random access memory (MRAM) that will compete in the $100 billion RAM market. In-plane GMR promises 1 Mbit memory chips in 1999; at the right, the size of this chip (center of image) is contrasted to an earlier 1 kbit ferrite core memory. Not only has the size per bit been dramatically reduced, but the memory access time has dropped from milliseconds to 10 nanoseconds. The in-plane approach will likely provide 10-100 Mbit chips by 2002. Since the GMR effect resists radiation damage, these memories will be important to space and defense applications.





The in-plane GMR device performance (signal to noise) suffers as the device lateral dimensions get smaller than 1 micron. Government and industry are funding work on a vertical GMR device that gives larger signals as the device dimensions shrink. At 10 nanometer lateral size, these devices could provide signals in excess of 1 volt and memory densities of 10 Gbit on a chip, comparable to that stored on magnetic disks. If successful, this chip would eliminate the need for magneto-mechanical disk storage with its slow access time (msec), large size, weight and power requirements.

Dr. G. Prinz, NRL, et al.

Figure TS.1. Use of a new phenomenon (giant magnetoresistance—GMR) in information technology for non-volatile high density memory.

Other potential nanoelectronics and computer technology breakthroughs include the following:

- Nanostructured microprocessor devices that continue the trend in declining energy use and cost per gate, thereby potentially improving the efficiency of computers by a factor of millions

- Higher transmission frequencies and more efficient utilization of the optical spectrum to provide at least ten times more bandwidth, with consequences in business, education, entertainment, and defense
- Small mass storage devices with capacities at multi-terabit levels, a thousand times better than today
- Integrated nanosensor systems capable of collecting, processing, and communicating massive amounts of data with minimal size, weight, and power consumption

Other potential applications of nanotechnology include affordable virtual reality stations to provide individualized teaching aids (and entertainment); computational capability sufficient to enable unmanned combat and civilian vehicles; and communication capability that obviates much commuting and other business travel in an era of increasingly expensive transport fuels.

Medicine and Health

Recent insights into the uses of nanofabricated devices and systems suggest that today's laborious process of genome sequencing can be made orders of magnitude more efficient through utilization of nanofabricated surfaces and devices. Expanding our ability to characterize an individual's genetic makeup will revolutionize the specificity of diagnostics and therapeutics. Beyond facilitating optimal drug usage, nanotechnology can provide new formulations and routes for drug delivery, enormously broadening the therapeutic potential of such drugs.

Increasing nanotechnological capabilities will also markedly benefit basic studies of cell biology and pathology. As a result of the development of new analytical tools capable of probing the world of the nanometer, it is becoming increasingly possible to characterize the chemical and mechanical properties of cells (including processes such as cell division and locomotion) and to measure properties of single molecules. These capabilities thus complement (and largely supplant) the ensemble average techniques presently used in the life sciences. Moreover, biocompatible, high-performance materials will result from controlling their nanostructure. The molecular building blocks of life—proteins, nucleic acids, lipids, carbohydrates, and their biological mimics—are examples of materials that possess unique properties determined by their size, folding, and patterns at the nanoscale. Based on these biological principles, bio-inspired nanosystems and materials are currently being formed by self-assembly or other patterning methods. Artificial inorganic and organic nanoscale materials can be introduced into cells to play roles in diagnostics (e.g., quantum dots in visualization), but also potentially as active components.

Nanotechnology-enabled increases in computational power will permit the characterization of macromolecular networks in realistic environments. Such simulations will be essential elements in the development of biocompatible implants and in the drug discovery process. There are numerous other potential applications of nanoscience to biology:

- Rapid, efficient genome sequencing, revolutionizing diagnostics and therapeutics
- Effective and less expensive healthcare using remote and in-vivo devices

- New formulations and routes for drug delivery that enormously broaden their therapeutic potential by effecting delivery of new types of medicine to previously inaccessible sites in the body
- More durable, rejection-resistant artificial tissues and organs
- Sensor systems that detect emerging disease in the body, which will shift the focus of patient care from disease treatment to early detection and prevention

Aeronautics and Space Exploration

The stringent fuel constraints for lifting payloads into earth orbit and beyond, and the desire to send spacecraft away from the sun (diminishing solar power) for extended missions, compel continued reduction in size, weight, and power consumption of payloads. Nanostructured materials and devices promise solutions to these challenges. Nanostructuring is also critical to the design and manufacture of lightweight, high-strength, thermally stable materials for aircraft, rockets, space stations, and planetary/solar exploratory platforms. Moreover, the low gravity, high vacuum space environment may aid development of nanostructures and nanoscale systems that cannot be created on Earth. Applications of nanotechnology in this area are broad, with potential relevance to other fields as well:

- Low-power, radiation-tolerant, high-performance computers
- Nanoinstrumentation for microspacecraft
- Avionics made possible by nanostructured sensors and nanoelectronics
- Thermal barrier and wear-resistant nanostructured coatings

Environment and Energy

Nanotechnology has the potential to significantly impact energy efficiency, storage, and production. It can be used to monitor and remediate environmental problems; curb emissions from a wide range of sources; and develop new, “green” processing technologies that minimize the generation of undesirable by-product effluents. The impact on industrial control, manufacturing, and processing will be impressive and result in energy savings. Several technologies that utilize the power of nanostructuring, but that were developed without benefit of the new nanoscale analytical capabilities, illustrate this potential:

- A long-term research program in the chemical industry on the use of crystalline materials as catalyst supports has yielded catalysts with well-defined pore sizes in the range of 1 nm; their use is now the basis of an industry that exceeds $30 billion/year.
- The discovery of the ordered mesoporous material MCM-41 produced by Mobil Oil Co., with pore size in the range 10 to 100 nm, is now widely applied in removal of ultrafine contaminants.
- Several chemical manufacturing companies are developing a nanoparticle-reinforced polymeric material that can replace structural metallic components in the auto industry. Widespread use of those nanocomposites could lead to a reduction of 1.5 billion liters of gasoline consumption over the life of one year’s fleet of vehicles

and reduce related carbon dioxide emissions by more than five billion kilograms annually.

- The replacement of carbon black in tires by nanometer-scale particles of inorganic clays and polymers is a new technology that is leading to the production of environmentally friendly, wear-resistant tires.

Potential future breakthroughs also include use of nanostructured materials for environmental and nuclear waste management.

National Security

The Department of Defense recognized the importance of nanostructures over a decade ago and has played a significant role in nurturing the field. Critical defense applications of nanotechnology include the following:

- Continued information dominance (see nanoelectronics and computer technology section, pp. x-xii), identified as an important capability for the military
- More sophisticated virtual reality systems based on nanostructured electronics, leading to more affordable, effective training
- Increased use of enhanced automation and robotics to offset reductions in military manpower, reduce risks to troops, and improve vehicle performance; for example, several thousand pounds could be stripped from a pilotless fighter aircraft, resulting in longer missions, and fighter agility could be dramatically improved without the necessity to limit g-forces on the pilot, thus increasing combat effectiveness
- Achievement of the higher performance (lighter weight, higher strength) needed in military platforms, while simultaneously providing diminished failure rates and lower life-cycle costs
- Badly needed improvements in chemical/biological/nuclear sensing and in casualty care
- Design improvement of systems used for nuclear non-proliferation monitoring and management

Other Government Applications

Potential benefits from nanoscience and technology affect other Government missions, including the following:

- Lighter and safer equipment in transportation systems (Department of Transportation)
- Measurement, control, and remediation of contaminants (Environmental Protection Agency)
- Enhanced forensic research (Department of Justice)
- Printing and/or engraving of high quality, forgery-proof documents and currency (Bureau of Engraving and Printing)

Science and Education

The science, engineering, and technology of nanostructures will require and enable advances in a fabric of disciplines: physics, chemistry, biology, materials, mathematics, and engineering. In their evolution as disciplines, they all find themselves simultaneously ready to address nanostructures; this provides a fortuitous opportunity to revitalize their interconnections. The dynamics of interdisciplinary nanoscience efforts will reinforce educational connections between disciplines and give birth to new fields that are unknown at this moment. Further development of the field requires changes in the laboratory and human resource infrastructure in universities and in the education of nanotechnology professionals, especially for industrial careers.

Global Trade and Competitiveness

Technology is the major driving factor for growth at every level of the U.S. economy. Nanotechnology is expected to be pervasive in its applications across nearly all technologies. Investment in nanotechnology research and development is necessary to maintain and improve our position in the world marketplace. The proposed nanotechnology initiative will allow the development of critical enabling technologies with broad commercial potential, such as nanoelectronics, nanostructured materials and nanoscale-based manufacturing processes. These are necessary for U.S. industry to take advantage of nanotechnology innovations and improve our capability to compete globally.

An Outstanding Opportunity and Urgent Responsibility

The potential indicated above for nanotechnology to transform so many aspects of human existence is almost without precedent. In the last few years, applying fundamental discoveries related to nanotechnologies has already developed multibillion-dollar businesses. These latter include giant magnetoresistance (for hard disks), nanolayers (for data storage and the photographic industry), nanoparticles (for drugs in the pharmaceutical field and colorants in printing), confinement effects (for optoelectronic devices and lasers), nanostructured materials (for nanocomposites and nanophase metals), and chemical and biological detection (for national security and the food industry). Fundamentally novel phenomena and processes have led to new, high-value-added technologies. Investment in enabling basic research and infrastructure for nanoscience and engineering promises extraordinarily high economic and societal returns; it is due primarily to this fact that the need to establish a nationally coordinated nanotechnology initiative is so compelling.

National Perspective

According to the 1998 WTEC report summarizing U.S. activities in nanotechnology (Siegel et al. 1998)[5], Federal Government expenditure for nanotechnology in fiscal year

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[5] Siegel, R.W., E. Hu, M.C. Roco, eds. 1998. *R&D status and trends in nanoparticles, nanostructured materials, and nanodevices in the United States.* Baltimore: International Technology Research Institute, World Technology (WTEC) Division, Loyola College. NTIS #PB98-117914. http://itri.loyola.edu/nano/US.Review/.

1997 was approximately $116 million. Nanotechnology as defined in that report only included work to generate and use nanostructures and nanodevices; it did not include the simple observation and description of phenomena at the nanoscale that is part of nanoscience. Utilizing the broader definition, the Federal Government expenditure is estimated to be about $255 million for fiscal year 1999. However, 1999 IWGN workshop contributors concluded that a much greater investment could be utilized effectively to increase the rate of discovery, and in fact, many opportunities are not being pursued because of lack of resources. Currently, only about one-third of high quality academic research proposals are being funded. Doubling current Federal expenditures in fiscal year 2001 would ensure that more of the best ideas are funded, increasing the current rate of scientific breakthroughs and drawing more strong researchers to enrich the field. Private industry cannot be expected to fund advancements in basic knowledge on a significant scale. Once nanotechnology has been firmly established, the Government investment will be dwarfed by industry R&D investment, which in the high-technology areas generally is about 10% of sales. Until that time, Government agencies should stimulate and support basic research and infrastructures that will enable subsequent development and commercialization.

Nanoscience research in the United States has developed in open competition with existing disciplines. This has been healthy for the early stages of development, but it is also the main reason that U.S. nanotechnology research efforts tend to be fragmented and overlap among areas of relevance and sources of funding. A coordinated effort should focus resources on enabling nanoscience and engineering, on developing infrastructure, stimulating cooperation, and avoiding unwanted duplication of efforts. It should take full advantage of the extraordinarily rich research opportunities and potential technological advances promised by early nanoscience work. A key feature of the IWGN proposal for a national nanotechnology initiative is promotion of synergistic efforts in research, development, and education among Federal agencies.

It is the consensus of the IWGN participants and contributors that the promises of nanotechnology can best be realized through long term and balanced investment in U.S. infrastructure and human resources in five R&D categories in particular:

- <u>Nanostructure properties</u>: Investigate biological, chemical, electronic, magnetic, optical, and structural properties in nanostructures.

- <u>Synthesis and processing</u>: Enable atomic and molecular control of material building blocks to provide the means to assemble and utilize these tailored building blocks for new processes and devices in a wide variety of applications. Extend the traditional approaches to patterning and microfabrication to include parallel processing with proximal probes, stamping, and embossing. Give particular attention to the interface with bionanostructures and bio-inspired structures, to multifunctional and adaptive nanostructures, to scaling approaches, and to affordability at commercial scales.

- <u>Characterization and manipulation</u>: Develop new experimental tools to broaden the capability to measure and control nanostructured matter, including developing new standards of measurement. Pay particular attention to tools capable of measuring and/or manipulating single macro- and supra-molecules of biological interest.

- Modeling and simulation: Accelerate the application of novel concepts and high-performance computation to the prediction of nanostructured properties, phenomena, and processes.

- Device and system concepts: Stimulate the innovative application of nanostructure properties to new technologies.

International Perspective

The United States does not dominate nanotechnology research. There is strong international interest, with nearly twice as much ongoing research overseas as here (see the worldwide study *Nanostructure Science and Technology*, Siegel et al. 1999, NSTC Report[6]). Other regions, particularly Japan and Europe, are supporting work equal to the quality and breadth of the science done in the United States, because there too, scientists and national leaders have determined that nanotechnology has the potential to be a major economic factor during the next several decades. This situation is unlike other post-World War II technological revolutions, where the United States enjoyed earlier leads. Since it will be impossible to lead in every aspect of this emerging super-field, the United States should look to partner with other countries through mutually beneficial information sharing, cooperative research, and study by young U.S. researchers at foreign centers of excellence. We should also build suitable infrastructures to both compete and collaborate with international nanotechnology efforts.

High-Level Recognition of Nanotechnology's Potential

The promise of nanoscience and engineering has not passed unnoticed. Dr. Neal Lane, currently the President's Advisor for Science and Technology and former NSF director, stated at a Congressional hearing in April 1998, "If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering." In March 1998, the President's Science Advisor Dr. John H. Gibbons identified nanotechnology as one of the six technologies that will determine economical development in the next century. NSF started the initiative, Synthesis and Processing of Nanoparticles, in 1991 and the National Nanofabrication User Network in 1994, and has highlighted nanoscale science and engineering in its fiscal year 1998 budget. The Department of Defense identified nanotechnology as a strategic research objective in 1997. The National Institutes of Health identified nanobiotechnology as a topic of interest in its 1999 Bioengineering Consortium (BECON) program.

More recently, on May 12, 1999, Richard Smalley, Nobel Laureate, concluded in his testimony to the Senate Subcommittee on Science, Technology, and Space that "We are about to be able to build things that work on the smallest possible length scales. It is in our Nation's best interest to move boldly into this new field." On June 22, 1999, the

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[6] Siegel, R.W., E. Hu, and M.C. Roco, eds. 1999. NSTC (National Science and Technology Council) Report. *Nanostructure science and technology*. Baltimore: International Technology Research Institute, World Technology (WTEC) Division. Web site: http://itri.loyola.edu/nano/IWGN.Worldwide.Study/. Also published by Kluwer Academic Publishers (1999).

House Subcommittee on Basic Research of the Committee on Science organized a hearing on “Nanotechnology: The State of Nano-Science and Its Prospects for the Next Decade.” The Subcommittee Chairman Nick Smith, Michigan, concluded the hearings stating that "Nanotechnology holds promise for breakthroughs in health, manufacturing, agriculture, energy use and national security. It is sufficient information to aggressively address funding of this field.”

Vision of the Future

Nanoscience and engineering knowledge is exploding worldwide, leading to fundamental scientific breakthroughs and technological paradigm changes in the ways materials, devices, and systems are understood and created. Potential breakthroughs include emergence of entirely new phenomena in physics and chemistry; nanofabrication of three-dimensional molecular architectures; achievement of orders-of-magnitude increases in computer efficiency; utilization of novel data processing architectures such as quantum computing and cellular automata; repair of human tissues with tissue replacements; and realization of a continuous presence in space. In education, nanoscience offers an opportunity to energize the interdisciplinary connections between biology, chemistry, engineering, materials, mathematics, and physics. Nanotechnology will give birth to new fields that at present are only visions of leading researchers.

The national nanotechnology initiative proposed in this report would leverage the existing strong foundation of nanoscience in the United States and address the formidable challenges that remain. It will seize nascent opportunities to advance this field, stimulating domestic job growth and strengthening U.S. competitiveness in international markets. Nanoscale science and engineering promises to become a strategic, dominant technology in the next 10-20 years, because control of matter at the nanoscale underpins innovation and progress in most industries, in the economy, in health and environmental management, in quality of life, and in national security. The consensus of IWGN workshop participants and contributors is that nanotechnology will lead to the next industrial revolution.

RECOMMENDATIONS: A NATIONAL INITIATIVE

There are three fundamental reasons why IWGN workshop participants and contributors believe the time is right for the nation to establish a significant R&D initiative to support nanotechnology: (1) nanotechnology R&D has reached a high level of competitiveness and dynamism, with unusually high, cross-cutting challenges; (2) it is apparent that contributions are necessary from all segments of the science and technology community in order to realize the full potential of nanotechnology R&D; and (3) society's potential return on investment in nanotechnology R&D is immense and of strategic importance. This report proposes a national nanotechnology initiative and outlines its major recommended features. The proposed initiative builds on previous and current nanotechnology programs, including early NSF initiatives on nanoparticles, specialized instrumentation, and functional nanostructures; Department of Defense (DOD) programs supporting its Nanoscience Strategic Research Objectives; and other targeted nanoscience programs of the Department of Energy (DOE), the Department of Commerce (DOC), and the National Institutes of Health (NIH). IWGN workshop participants and contributors addressed the roles that academe, the private sector, the U.S. Government, and professional societies should play in this national nanotechnology initiative.

1. Academe

Role. Universities will continue to play a key role in the development of nanoscience and technology. If there is one signature characteristic of nanoscience, it is its highly transdisciplinary character. This poses difficulties for universities, which mainly are structured in traditional departments. Every effort must be made to foster multidepartmental centers for nanotechnology on campuses. The most successful research efforts will be those that can create new infrastructure (for example, materials preparation and characterization facilities) for these centers.

Recommendations

- Promote interdisciplinary work involving multiple departments.
- Foster on-campus nanotechnology centers for greater interaction.
- Develop new educational paradigms. Introduce nanoscience and engineering in existing and new courses. Include courses on surface science, molecular dynamics, quantum effects, and manufacturing at the molecular scale in curricula at both the undergraduate and graduate levels. Take an integrative science and engineering approach; technology programs cannot be developed without strong supporting science programs because of the scale and complexity of the nanosystems.
- Create or connect "regional coalitions" that involve industry/technology generation.
- Ease intellectual property restrictions to improve information flow with industry.
- Establish graduate and postdoctoral fellowships for interdisciplinary work.

2. Private Sector

Role. The major commercialization opportunities from nanotechnology are probably 10 to 15 years in the future. Much about nanostructures and nanoprocesses is not yet fully measurable, replicable, or understood, and it will require many years to develop corresponding technologies. Industry will invest heavily in nanotechnology only when the underlying capabilities have been developed to the point that products can be foreseen within 3-5 years. Although fundamental nanotechnology research may not be supported by private industry because of the inability of individual companies to restrict and capitalize on basic knowledge, the potential technological and economic benefits that could flow from basic knowledge in nanotechnology are too large for the private sector to ignore. There are critical areas of research and development that can be guided by small industrial teams working within larger consortia of researchers from universities, national laboratories, and other industries. These consortia, perhaps along the lines of the Semiconductor Research Corporation, can provide the critical mass to which companies can afford to contribute. Those that do participate will be in the best position to capitalize on the total research effort and be the first to reach the marketplace with new products derived from nanotechnology.

Recommendations

- Build up investment by maintaining in-house research activities in nanotechnology.
- Join, contribute to, or lead regional coalitions with universities, Government laboratories, and other companies for precompetitive nanotechnology research and information dissemination. The resulting regional centers can encourage niches of common interests, e.g., biotechnology and computers, for jointly developing technologies unlikely to be developed by any single company.
- Sponsor technology start-ups/spin-offs.
- In general, buy into the entire field by investing in nanotechnology research in a variety of ways including training and cross-fertilization among industrial areas.

3. Government R&D Laboratories

Role. Government laboratories can provide many of the large-scale facilities and infrastructure required for fundamental research in nanotechnology, and can serve as technology incubators and provide a stable environment for researchers in the field during the incubation process.

Recommendations

- Pursue applications of nanotechnology in support of respective agency missions.
- Join regional coalitions with universities and industry, and cultivate information flow.
- Provide unique measurement and manufacturing capabilities at nanoscale facilities (synchrotrons, microscopy centers, etc.).
- Provide measurement standards for the nanotechnology field.

4. Government Funding Agencies

Role. Investments must be made in the basic science and technologies that will enable scientists and engineers to invent totally new technologies and stimulate U.S. industrial competitiveness in the emerging nanotechnology areas. The Federal Government should invest in the infrastructure necessary for the United States to lead and benefit from the revolution that is coming. It should support expansion of university and Government/national laboratory facilities, help to build the workforce skills necessary to staff future industries based on nanotechnology, encourage cross-disciplinary networks and partnerships, ensure the dissemination of information, and encourage small businesses to exploit commercial opportunities.

Recommendations

- Undertake a national initiative as part of the fiscal year 2001 budget. The initiative, "National Nanotechnology Initiative (NNI) - Leading to a New Industrial Revolution," should approximately double the Federal Government's annual investment in nanoscience, engineering and technology research and development from the approximately $255 million it spent in fiscal year 1999.

- Address the following priority areas for funding in the initiative:

  A. Long-term fundamental nanoscience and engineering research. The goal is to build fundamental understanding and to discover novel phenomena, processes, and tools for nanotechnology. This commitment will lead to potential breakthroughs and accelerated development in areas such as medicine and healthcare, materials and advanced manufacturing, computer technology, environment and energy. It will refocus the Government's investment that led to today's computer technology and biotechnology.

  B. Synthesis and processing "by design" of engineered, nanometer-size, material building blocks and system components, fully exploiting molecular self-assembly concepts. This commitment will generate new classes of high-performance materials, bio-inspired systems, and efficient, affordable manufacturing of high-performance products. Novel properties and phenomena will be enabled as control of structures of atoms, molecules, and clusters becomes possible.

  C. Research in nanodevice concepts and systems architecture. The goal is to exploit nano-derived properties in operational systems and combine building-up of molecular structures with ultraminiaturization. New nanodevices will cause orders of magnitude improvements in microprocessors and mass storage, create tiny medical tools that minimize collateral damage, and enable uninhabited defense combat vehicles in fully imaged battlefields. There will be dramatic payback to other programs with national priority in many fields, including information technology, nanobiotechnology, and medical technology.

  D. Application of nanostructured materials and systems to manufacturing, power systems, energy, environment, national security, and health. Basic research is needed in advanced dispersions, catalysts, separation methods, and consolidated nanostructures. Also needed are means for increasing the pace of knowledge development and technology transfer.

  E. Education and training of a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology.

- Design a balanced investment strategy that supports a mix of research themes and modes of support, emphasize single principal investigators and small interdisciplinary teams (about two-thirds of the funds on average in all themes), but also support approximately ten R&D centers and networks, such as the existing National Nanofabrication Users Network. Specific agencies should develop project- and disciplinary-oriented activities that focus on education and training; modeling, simulation, and computational science and engineering; infrastructure and facilities; development of partnerships between government, industry, and academia; technology transfer; and international collaboration. Vertical integration activities, pursuing concurrently fundamental research, directed research technology development and prototype construction or clinical evaluations in a collaborative setting, should become a priority for Government R&D laboratories and university- or industry-led consortia. Include support in the initiative for a variety of R&D themes and research modes:

  – In support of *fundamental research*, fund single investigators and small groups (30% of the additional investment).

  – In support of *grand challenges research*, fund interdisciplinary research and education teams, including those in centers and networks, that have major, long-term objectives (30%).

  – In support of *centers and networks of excellence*, fund ten centers for about $5 million each for 5 years, with opportunity for one renewal after review (18%).

  – In support of *research infrastructure*, fund development of metrology, instrumentation, modeling and simulation, and user facilities (18%).

  – In support of *education and training*, fund student fellowships, traineeships, and curriculum development (4%). Support nanoscience and engineering fellowships that are not tied to one discipline.

  – In support of *Small Business Innovative Research (SBIR) and Small Technology Transfer Research (STTR)*, fund focused program announcements on nanotechnology.

- Focus the agencies' programs contributing to the initiative as follows:

DOC	NIST, TA	Measurements and standards; industry-led ventures
DOD	lab and acad.	Information technology; high performance materials; chemical/biological detection
DOE	lab and acad.	Energy science; environment; non-proliferation
DOT	lab and acad.	Smart, lightweight, affordable materials
NASA	lab and acad.	Lighter, smaller spacecraft; radiation-hard electronics
NIH	lab and acad.	Therapeutics; diagnostics; biomaterials; miniaturized tools
NSF	acad.	Science and engineering fundamental knowledge; instrumentation; education

- Direct additional funding toward priority infrastructure requirements.

  A major objective is to create a balanced, predictable, strong, and flexible U.S. infrastructure in nanoscale science, engineering, and technology. This kind of infrastructure is required for the nanotechnology initiative to stimulate further rapid growth of the field. Ideas, concepts, and techniques are developing at an exceedingly rapid pace, such that the field needs coordination and focus with a national perspective. Demands are being made on universities and Government to continue to evolve this science and to bring forth the changes in technology that are expected from the field. Even greater demands are on industry to exploit new ideas, protect intellectual property, and develop appropriate products. This field has major transdisciplinary aspects, which are difficult to coordinate. It is imperative to address these kinds of issues; at stake may be the future economic strength, quality of life, and national security of the United States.

- Provide nanotechnology investigators with ready access to user-friendly, moderately priced analytical tools in order to carry out state-of-the-art research.
- Help establish centers with multiple grantees or laboratories where more expensive analytical tools can be made available. These centers should also sponsor the diverse research teams that will be effective in different scientific disciplines. Also, consider ideas concerning remote access and use of these facilities.
- Use university grants to encourage work among research groups to make maximum use of concepts and ideas being developed in other disciplines. It will be necessary to fund training and fellowships that will attract top quality students. Attention should also be paid to the open exchange of information in multidisciplinary meetings and through rapid publication of research results.
- Support efforts that will inspire high school students to consider careers in science and engineering and specifically in nanotechnology.

• Promote international collaborations for cost-sharing and joint centers/networks of excellence, where appropriate, for fundamental studies.

• Provide national leadership.

The Federal Government should provide leadership and maintain coordination and cooperation through an interagency working group to review research thrusts at least annually and promote cooperative efforts. The rapid pace of advances in the field makes this a necessity. This action by the Government will also assist in reducing unwanted redundancy and will make maximum use of appropriated funds.

5. Professional Societies

Role. The science/engineering/technology of nanostructures will flourish best in an interdisciplinary environment with a liberal mix of government, academic and industrial researchers. Professional science and engineering societies must consciously seek to develop appropriate forums that reach beyond their traditional membership and encourage the desired mixing. The societies must also reach out into the international community to assure that U.S. researchers are aware of global advances in nanotechnology.

Recommendations

- Establish interdisciplinary fora that effectively mix academic, government, and industrial researchers, that accelerate progress in research and development in nanoscience, engineering and technology, and facilitate the transition into other fields and technologies.
- Convene groups of scientists and engineers who have not collaborated traditionally.
- Reach out into the international communities to help ensure that worldwide science/engineering advances in nanotechnology are known to the U.S. community.
- Develop symposia to explore educational opportunities at K-12, undergraduate, and graduate levels.
- Invite industrial players to interview prospective scientists and engineers for nano-related openings.

On behalf of the
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INTRODUCTION TO NANOTECHNOLOGY FOR NONSPECIALISTS

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What is nanotechnology?

Nanotechnology is (1) the creation of useful materials, devices, and systems through the control of matter on the nanometer-length scale, and (2) the exploitation of novel properties and phenomena developed at that scale.

What is a nanometer?

A nanometer is one billionth of a meter (10^{-9} m). This is roughly four times the diameter of an individual atom. A cube 2.5 nanometers on a side would contain about a thousand atoms. The smallest feature in an integrated circuit of today is 250 nanometers on a side and contains about one million atoms in a square layer of atomic height. Proteins, the molecules that catalyze chemical transformations in cells, are 1 to 20 nanometers in size. For comparison, a typical nanometer-scale feature size of about 10 nanometers is 1,000 times smaller than the diameter of a human hair.

Why is this length scale so important?

The wave-like (quantum mechanical) properties of electrons inside matter and atomic interactions are influenced by material variations on the nanometer scale. By creating nanometer-scale structures, it is possible to control fundamental properties of materials like their melting temperature, magnetic properties, charge capacity, and even their color, without changing the materials' chemical composition. Utilizing this potential will lead to new, high-performance products and technologies that were not possible before.

Systematic organization of matter on the nanometer length scale is a key feature of biological systems. Nanotechnology will allow us to place components and assemblies inside cells and to make new materials using the self-assembly methods of nature. In self-assembly, the information necessary for assembly is on the surface of the assembling nanocomponents. No robots or devices are needed to put the components together. This powerful combination of materials science and biotechnology will lead to entirely new processes and industries.

Nanoscale structures such as nanoparticles and nanolayers have very high surface-to-volume ratios, making them ideal for use in composite materials, chemical reactions, drug delivery, and energy storage. Nanostructured ceramics are often both harder and less brittle than the same materials made on the scale of microns, which are 1,000 times larger than nanometers, but still just barely visible to the human eye. Nanoscale catalysis will increase the efficiency of chemical reactions and combustion, at the same time significantly reducing waste and pollution. More than half of therapeutically useful new medicines are not water soluble in the form of micron-scale particles, but they probably will dissolve in water if they are nanometer sized; thus nanostructuring greatly increases the chances of finding new drugs that can be rendered in usable forms.

Since nanostructures are so small, they can be used to build systems that contain a much higher density of components than micron-scale objects. Also, electrons will require much less time to move between components. Thus, new electronic device concepts, smaller and faster circuits, more sophisticated functions, and greatly reduced power consumption can all be achieved simultaneously by controlling nanostructure interactions and complexity.

These are just a few of the benefits and advantages of structuring materials at the nanometer scale.

Is this really new? Don't existing materials already use the nanometer-length scale?

Many existing technologies do already depend on nanoscale processes. Photography and catalysis are two examples of "old" nanotechnologies that were developed empirically in an earlier period despite their developers' limited abilities to probe and control matter at the nanoscale. These two technologies stand to be improved vastly as nanotechnology advances. Most currently existing technologies utilizing nanometer-scale objects were discovered by serendipity, and for many, the role that the nanometer scale played was not even appreciated until recently. For instance, we know now that adding certain inorganic clays to rubber dramatically improves the lifetime and wear properties of tires because the nanometer-sized clay particles bind to the ends of the polymer molecules, which are "molecular strings," and prevent them from unraveling. This is a simple process, but the dramatic improvement in the properties of this composite material, part rubber and part clay, demonstrates the great potential of nanotechnology as it is rationally applied to more complex systems. An example of such a system would be a structure designed to be extremely hard but not brittle, capable of self-repair if minor cracks appear, and easily broken down into its component parts when it is time to recycle the materials.

The ability to specifically analyze, organize, and control matter on many length scales simultaneously has only been possible for about the past ten years. For over a century, chemists have had the ability to control the arrangement of small numbers of atoms inside molecules, that is, to synthesize certain molecules with length scales of less than 1.5 nanometers. This has led to revolutions in drug design, plastics, and many other areas. Over the last several decades, photolithographic patterning (the primary manufacturing process of the semiconductor industry) of matter on the micron length scale has led to the revolution in microelectronics. With nanotechnology, it is just becoming possible to bridge the gap between atom/molecular length scale and microtechnology, and to control matter on every important length scale, enabling tremendous new power in materials design. It is important to remember that the most complex arrangements of matter known to us, living organisms, require specific patterning of matter on the molecular, nanometer, micron, millimeter, and meter scale all at once.

By tailoring the structure of materials at the nanoscale, it is possible to systematically and significantly change specific properties at larger scales—to engineer material behavior. Larger systems constructed of nanometer-scale components can have entirely new properties never before identified in nature. It is also possible to produce composites, i.e., mixtures of different nanoscale entities, that combine the most desirable properties of different materials to obtain characteristics that are greatly improved over those supplied by nature or that appear in combinations not produced by nature. Thus, nanotechnology encompasses a revolutionary set of principles, tools, and processes that will eventually become the foundation for such currently disparate applications as inks and dyes, protective coatings, medicines, electronics, energy storage and use, structural materials, and many others that we cannot even anticipate.

What will be the benefits of nanotechnology?

The new concepts of nanotechnology are so broad and pervasive that they may be expected to influence science and technology in ways that are unpredictable. We are just now seeing the tip of the iceberg in terms of the benefits that nanostructuring can bring (Figure I.1). Existing products of nanotechnologies include wear-resistant tires made by combining nanometer-scale particles of inorganic clays with polymers; nanoparticle medicines with vastly improved delivery and control characteristics; greatly improved printing brought about by utilizing nanometer-scale particles with the best properties of both dyes and pigments; and vastly improved lasers and magnetic disk heads made by precisely controlling layer thicknesses. Many other applications are already under development or anticipated, including those listed below.

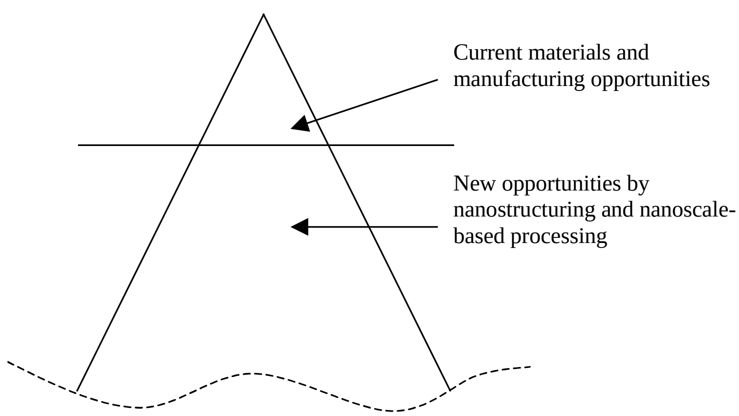

Figure I.1. Current nanotechnology-related materials and manufacturing opportunities.

- *Automotive and aeronautics industries:* nanoparticle-reinforced materials for lighter bodies, nanoparticle-reinforced tires that wear better and are recyclable, external painting that does not need washing, cheap non-flammable plastics, electronics for controls, self-repairing coatings and textiles
- *Electronics and communications:* all-media recording using nanolayers and dots, flat panel displays, wireless technology, new devices and processes across the entire range of communication and information technologies, factors of thousands to millions improvements in both data storage capacity and processing speeds—and at lower cost and improved power efficiency compared to present electronic circuits
- *Chemicals and materials:* catalysts that increase the energy efficiency of chemical plants and improve the combustion efficiency (thus lowering pollution emission) of motor vehicles, super-hard and tough (i.e., not brittle) drill bits and cutting tools, "smart" magnetic fluids for vacuum seals and lubricants
- *Pharmaceuticals, healthcare, and life sciences:* new nanostructured drugs, gene and drug delivery systems targeted to specific sites in the body, biocompatible

replacements for body parts and fluids, self-diagnostics for use in the home, sensors for labs-on-a-chip, material for bone and tissue regeneration

- *Manufacturing:* precision engineering based on new generations of microscopes and measuring techniques, new processes and tools to manipulate matter at the atomic level, nanopowders that are sintered into bulk materials with special properties that may include sensors to detect incipient failures and actuators to repair problems, chemical-mechanical polishing with nanoparticles, self-assembling of structures from molecules, bio-inspired materials and biostructures
- *Energy technologies:* new types of batteries, artificial photosynthesis for clean energy, quantum well solar cells, safe storage of hydrogen for use as a clean fuel, energy savings from using lighter materials and smaller circuits
- *Space exploration:* lightweight space vehicles, economic energy generation and management, ultra-small and capable robotic systems
- *Environment:* selective membranes that can filter contaminants or even salt from water, nanostructured traps for removing pollutants from industrial effluents, characterization of the effects of nanostructures in the environment, maintenance of industrial sustainability by significant reductions in materials and energy use, reduced sources of pollution, increased opportunities for recycling
- *National security:* Detectors and detoxifiers of chemical and biological agents, dramatically more capable electronic circuits, hard nanostructured coatings and materials, camouflage materials, light and self-repairing textiles, blood replacement, miniaturized surveillance systems

Additional details on ongoing nanotechnology R&D results may be found in chapters 4-10 of this report. A modified Delphi survey of experts on nanotechnology taken in May 1999 suggests that the probability of commercial applications of these and other nanotechnology processes and products in the next 15-25 years is between 50 and 100 percent, with the majority of applications ranging from 90 to 100 percent probability of commercialization (Gutmanis 1999).

What should Government do to ensure the United States can enjoy the envisioned benefits?

Government can play the key role to assure that the United States realizes the enormous benefits of nanotechnology. The goals of nanotechnology research are too fundamental, long-term (greater than ten years), transdisciplinary, and high-risk for industry to take an immediate leadership role, although there is high level of industry interest. Given the expectations of U.S. investors and the competitiveness of the global marketplace, U.S. industry is unable to invest significantly in long-term and thus risky research that takes many years to develop into products. In the United States, the university and government research systems must fill this gap.

Because of its transdisciplinary nature, nanotechnology will require teams of physicists, chemists, biologists, and engineers to develop its viability as a field. Government agencies will need to foster this teamwork. A worldwide competition is already underway in this area, and the U.S. response to date is fragmented in comparison to the approaches of European and Asian countries (see Siegel et al. 1999, NSTC report).

Moreover, new infrastructure at universities and the national labs is needed for the field to develop. The increasing pace of technological innovation and commercialization demands continual compression of the discovery-invention-development time scales, which in turn requires parallel and coordinated work in both basic research and commercial product development. The requirements for and from nanotechnology transcend anything that can be supplied by traditional academic disciplines, national laboratories, or even entire industries. For all of these reasons, a Federal initiative is critical to establishing an effective national effort in nanotechnology.

Looking to the future: lessons from the past

Although there is always considerable uncertainty in predicting future benefits, this report attempts to anticipate some that will occur within the next few decades. A significant lesson of the 20th century is that predictions of the state of a particular technology several decades in the future often fall far short of what is actually accomplished. One famous example of such a prediction was that made in the March 1949 edition of *Popular Mechanics*, in which several experts confidently predicted that the computers of the future would add as many as 5,000 numbers per second, weigh only 3,000 pounds, and consume only 10 kilowatts of power. Although at the time this was a bold forecast, it seems quaint now, when there are laptop computers that can add several million numbers per second while using only about a watt of power. Another famous prediction from the 1950s was that the total world market for electronic computers would be fewer than 10, whereas now there are about a billion microprocessors operating as the key components of computers, cellular telephones, automobiles, games, medical imaging instruments, and many more applications. The computer industry is one of the largest and healthiest in the United States, providing a substantial volume of exports and high-paying jobs. It has also spawned other enormous and important industries, such as computer software, that were not even envisioned fifty years ago.

The reason that the sages of *Popular Mechanics* could not foresee the advent of the information industry was that they anticipated only evolutionary change. Their predictions for the future of computers would probably have been correct if computers were still built with vacuum tubes and relays. However, a technological revolution was already beginning: the transistor had been invented in 1947. Along with the integrated circuits that appeared a decade later, this discovery ushered in a new industrial era, the age of silicon and information. The new epoch was born and nurtured in the United States because of the broad fundamental and applied research base that existed here at that period and the sustained Federal investments that went into training the people, building the scientific infrastructure, and creating the culture in which ideas could flow within a broad community of scientists and engineers from academe and industry. One can only speculate what life would be like in the United States today if this technological revolution had originated in a different country or if it had not occurred at all.

The total societal impact of nanotechnology is expected to be much greater than that of the silicon integrated circuit, because it is applicable to many more fields than just electronics. Significant product performance improvements and manufacturing advances will lead to many industrial revolutions in the twenty-first century. Nanotechnology has the potential to change the nature of almost every human-made object, because control at the nanoscale means tailoring the fundamental properties, phenomena, and processes exactly at the scale where electronic, chemical, and biological properties and phenomena are defined. A major question is how can we embrace and facilitate the nanotechnology revolution to maximize the benefit to all U.S. citizens.

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