Nanotechnology Research Directions:
IWGN Workshop Report

National Science and Technology Council (NSTC)
Committee on Technology (CT)
Interagency Working Group on Nanoscience, Engineering and Technology
(IWGN)

Nanotechnology Research Directions: IWGN Workshop Report

Vision for Nanotechnology R&D in the Next Decade

On behalf of NSTC/CT/IWGN
Edited by M.C. Roco (IWGN Chair),
R.S. Williams (private sector), and P. Alivisatos (academe)

KLUWER ACADEMIC PUBLISHERS
DORDRECHT / BOSTON / LONDON

Library of Congress Cataloging-in-Publication Data

ISBN 0-7923-6220-9

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Sold and distributed in North, Central and South America
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

Reprinted 2001

Printed on acid-free paper

This report was prepared under the guidance of NSTC/CT. Any opinions, conclusions or recommendations expressed in this material are those of the Interagency Working Group on Nanoscience, Engineering and Technology, and do not necessarily reflect the views of the Administration or individual funding agencies.

International Technology Research Institute, World Technology (WTEC) Division

This document is available on the Internet at
http://itri.loyola.edu/nano/IWGN.Research.Directions/

Printed in the Netherlands

Nanotechnology Research Directions

Preface to the Reprinted Version

The first edition of this book was intended to provide strategic guidance for the United States R&D community as a new technology develops out of scientific and engineering advances at the nanometer scale. It was utilized as the basis for the U.S. National Nanotechnology Initiative (NNI), and it has influenced R&D strategy discussions in many other countries as well. Nanoscience and engineering was defined beyond just the study of small things: new properties and functions of matter emerge at the nanoscale, and thus nanotechnology will require that matter be intentionally crafted to control composition, size, shape and position at length scales from the nanometer to macroscopic dimensions. The book presented a snapshot of the various disciplines influenced by nanoscale science at the beginning of 1999. The rate of discovery in these disciplines has accelerated dramatically since the reports were compiled, and potential applications are now better defined. The establishment of national research and educational priorities for nanoscience and nanoengineering in virtually all industrialized countries in the past few years is a sign of the broad recognition of the potential scientific, technological and societal benefits of this emerging field. Nanotechnology is joining molecular biology and information technology as the key technologies for the 21st Century.

This report is the synthesis of opinions from about 150 leading experts almost equally distributed among academic, industrial, and government scientists, including those from research laboratories and funding agencies. It identified challenges and opportunities in nanoscale science and engineering research and development, and addressed key issues in order to develop a wide range of commercial applications. The report makes specific recommendations on how to develop a balanced infrastructure for nanotechnology R&D, advance critical research areas, and nurture the scientific and technical workforce for the future. These recommendations stood as the basis of the National Nanotechnology Initiative announced by President Clinton in January 2000, and approved by U.S. Congress in November 2000.

The book was written in a modular fashion to allow readers with any background to learn something useful about Nanotechnology and its scientific, educational, commercial and societal implications. It has twelve chapters, covering fundamental scientific issues, investigative tools, synthesis and processing of nanostructures, key areas for commercial utilization, research infrastructure needs, and strategies for funding agencies. These topics have relevance to researchers and educators, as well as to industrial and government policy makers. The basic concepts and illustrations maintain their relevance since the publication of the first edition.

M.C. Roco, R.S. Williams and P. Alivisatos

THE WHITE HOUSE

WASHINGTON

September 27, 1999

Dear Colleague:

In August 1999, the National Science and Technology Council's (NSTC) Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN) released its first report, entitled *Nanostructure Science and Technology*. That document provided a basis for the Federal government to assess how to make strategic research and development (R&D) investments in this emerging field of nanotechnology through the formulation of national R&D priorities and a strategy for state, local, and Federal government support.

This IWGN Workshop Report, *Nanotechnology Research Directions*, builds upon the foundation provided in the first report and incorporates a vision for how the nanotechnology community -- Federal agencies, industries, universities, and professional societies -- can more effectively coordinate efforts to develop a wide range of revolutionary commercial applications. It incorporates perspectives developed at a January 1999 IWGN-sponsored workshop by experts from universities, industry, and the Federal government. This report identifies challenges and opportunities in the nanotechnology field and outlines the necessary steps on how advances made in nano-science, engineering, and technology can help to boost our nation's economy, ensure better healthcare, and enhance national security in the coming decade.

Preparing for the challenges of the new millennium requires strategic investments. *Nanotechnology Research Directions* will help our nation develop a balanced R&D nanotechnology infrastructure, advance critical research areas, and nurture the scientific and technical workforce of the next century.

Sincerely,

Neal Lane

Neal Lane
Assistant to the President
for Science and Technology

Nanotechnology Research Directions: IWGN Workshop Report

About the National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. This cabinet-level council is the principal means for the President to coordinate science, space and technology policies across the Federal Government. NSTC acts as a "virtual" agency for science and technology (S&T) to coordinate the diverse parts of the Federal research and development (R&D) enterprise. The NSTC is chaired by the President. Membership consists of the Vice President, Assistant to the President for Science and Technology, Cabinet secretaries and agency heads with significant S&T responsibilities, and other White House officials.

An important objective of the NSTC is the establishment of clear national goals for Federal S&T investments in areas ranging from information technologies and health research, to improving transportation systems and strengthening fundamental research. The Council prepares R&D strategies that are coordinated across Federal agencies to form an investment package that is aimed at accomplishing multiple national goals.

To obtain additional information regarding the NSTC, contact 202-456-6100 or see the NSTC Web site at
http://www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/NSTC_Home.html.

Interagency Working Group on Nanoscience, Engineering and Technology (IWGN)

Chair: M.C. Roco, NSF
White House IWGN Co-chair: T.A. Kalil, Special Assistant to the President, W.H. Economic Council
Vice-chair: R. Trew, DOD
Executive Secretary: J.S. Murday, NRL
Members:
White House: T.A. Kalil
OSTP: K. Kirkpatrick
NSTC: J. Porter
OMB: D. Radzanowski
DOC: P. Genther-Yoshida, M.P. Casassa (NIST), R.D. Shull (NIST)
DOD: R. Trew, J.S. Murday (NRL), G.S. Pomrenke (AFOSR)
DOE: I.L. Thomas, R. Price, B.G. Volintine
DOT: R.R. John, A. Lacombe (Volpe Center)
DoTREAS: E. Murphy
NASA: S. Venneri, G.H. Mucklow, M. Meyyappan (NASA Ames), T. Krabach (JPL)
NIH: J.A. Schloss, E. Kousvelari
NSF: M.C. Roco, T.A. Weber, M.P. Henkart
Public Affairs Consultant: J. Canton

International Technology Research Institute, World Technology (WTEC) Division, Loyola College

R.D. Shelton, ITRI Director
G.M. Holdridge, WTEC Division Director and ITRI Series Editor

P. Johnson, Editorial Assistant

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)

Dr. P. Alivisatos, University of California, Berkeley (representing academe)

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 one dimension under the "critical scale length" of 100 nm. Nanostructures offer a new

---

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

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).

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