SOCIETAL IMPLICATIONS OF
NANOSCIENCE AND NANOTECHNOLOGY

March 2001
National Science Foundation

At the request of the National Science and Technology Council (NSTC), Subcommittee on Nanoscale Science, Engineering, and Technology (NSET), the National Science Foundation organized a workshop on September 28-29, 2000. This report incorporates the views of leading experts from academia, private sector and government expressed at the workshop.

NSTC is the principal means for the U.S. President to coordinate science, space and technology policies across the Federal Government.

About the cover: Polymer rods embedded with cadmium selenide nanocrystals, fluorescing at various wavelengths (M. Bawendi et al.; photograph by Felice Frankel — copyright reserved). This photograph suggests the broad societal implications of nanoscience and nanotechnology.

Logistical, Editing and Management Assistance by:

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

R.D. Shelton, ITRI Director
G.M. Holdridge, WTEC Division Director and Series Editor
R. Horning, IT Director, Web Administrator
Societal Implications
of Nanoscience and Nanotechnology

NSET Workshop Report

Edited by Mihail C. Roco and William Sims Bainbridge
National Science Foundation

March 2001
Arlington, Virginia

This report was prepared under the guidance of NSET. Any opinions, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Government.
# SOCIETAL IMPLICATIONS OF NANOSCIENCE AND NANOTECHNOLOGY

## Table of Contents

**EXECUTIVE SUMMARY** ......................................................... iii

1. **INTRODUCTION** ............................................................... 1
  - National Nanotechnology Initiative ........................................... 1
  - NSET Workshop on “Societal Implications of Nanoscience and Nanotechnology” .............................................................. 2

2. **NANOTECHNOLOGY GOALS** ........................................... 3
  - Knowledge and Scientific Understanding of Nature ......................... 4
  - Industrial Manufacturing, Materials and Products ......................... 5
  - Medicine and the Human Body .................................................. 5
  - Sustainability: Agriculture, Water, Energy, Materials, and Clean Environment ................................................................. 6
  - Space Exploration ...................................................................... 8
  - National Security ..................................................................... 8
  - Moving into the Market ............................................................ 9

3. **NANOTECHNOLOGY AND SOCIETAL INTERACTIONS** ....... 10
  - The Interactive Process of Innovation and Diffusion ....................... 10
  - Unintended and Second-order Consequences ................................ 10
  - Ethical Issues and Public Involvement in Decision Making ................. 12
  - Education of Nanoscientists, Nanotechnologists, and Nanofabrication Technicians ................................................................. 13
  - Education of Social Scientists .................................................. 13

4. **SOCIAL SCIENCE APPROACHES FOR ASSESSING** ......... 14
   Nanotechnology’s Implications .................................................. 14
  - Social Science Research Approaches and Methodologies .................. 14
  - Institutional Infrastructure for Societal Implications Research .......... 15

5. **RECOMMENDATIONS** ..................................................... 16
  - Other Measures ...................................................................... 17
  - Specific Areas for Research and Education Investment ................... 17
  - Recommendations to Organizations .......................................... 18
  - With an Eye to the Future ....................................................... 19

6. **STATEMENTS ON SOCIETAL IMPLICATIONS** .................. 20
   6.1 Overviews
     - National Nanotechnology Initiative (T. Kalil — transcript) ............ 20
     - The Age of Transitions (N. Gingrich) ....................................... 23
     - Technological Implications of Nanotechnology: Why the Future Needs Us (J. Armstrong) ......................................................... 28
     - Don’t Count Society Out - A Response to Bill Joy (J.S. Brown) ...... 30
     - National Needs Drivers for Nanotechnology (G. Yonas and T. Picraux) ................................................................. 37
     - Nanotechnology and Societal Transformation (M.M. Crow and D. Sarewitz) ................................................................. 45

   6.2 Focus on Economic and Political Implications of Potential Technology
     Impact of Nanotechnology on the Chemical and Automotive Industries (J.M. Garces and M.C. Cornell) ........................................ 55
Societal Implications of Nanoscience and Nanotechnology

Information Technology Based on a Mature Nanotechnology: Some Societal Implications (T. Theis) ................................................................. 60
Societal Implications of Scaling to Nanoelectronics (R. Doering) .................. 68
Future Implications of Nanoscale Science and Technology: Wired Humans, Quantum Legos, and an Ocean of Information (P. Chaudhari) ................. 75
Implications of Nanotechnology in the Pharmaceutics and Medical Fields (D.A. LaVan and R. Langer) ................................................................. 79
We’ve Only Just Begun (S. Williams and P. Kuekes) ..................................... 83
An Economist’s Approach to Analyzing the Societal Impacts of Nanoscience and Nanotechnology (I. Feller) ....................................................... 87
The Strategic Impact of Nanotechnology on the Future of Business and Economics (J. Canton) ........................................................................... 91
Nano-Science and Society: Finding a Social Basis for Science Policy (H. Etzkowitz) ...................................................................................... 97

6.3 Focus on Science and Education Implications
Implications of Nanoscience for Knowledge and Understanding (G. Whitesides and C. Love) ................................................................. 104
Nanotechnology, Education, and the Fear of Nanobots (R. Smalley) ............. 116
Mathematical Challenges in Nanoscience and Nanotechnology (G. Forest) .... 117
Implications of Nanotechnology for the Workforce (S. Fonash) .................... 138
Societal Impacts of Nanotechnology in Education and Medicine (V. Vogel) ... 143
Technological and Educational Implications of Nanotechnology: Infrastructural and Educational Needs (J. Merz) .................................................. 148
Dynamics of the Emerging Field of Nanoscience (H. Glimell) ...................... 156

6.4 Focus on Medical, Environmental, Space Exploration and National Security Implications
Challenges and Vision for Nanoscience and Nanotechnology in Medicine: Cancer as a Model (R. Klausner) ..................................................... 161
Nanotechnology in Medicine (S. Stupp) ......................................................... 161
Lifecycle/Sustainability Implications of Nanotechnology (L.B. Lave) ............. 162
Implications of Nanotechnology for Space Exploration (S. Venneri) ............. 169
Security Aspects of Nanotechnology (W. Tolles) ........................................... 173

6.5 Focus on Social, Ethical, Legal, and Cultural Implications
Social Science Research Methods for Assessing Societal Implications of Nanotechnology (J.S. Carroll) ......................................................... 188
Ethical Issues in Nanotechnology (V. Weil) .................................................... 193
Social Acceptance of Nanotechnology (P.B. Thompson) ............................... 198
Social, Ethical and Legal Implications of Nanotechnology (R. Smith) ............ 203
Envisioning Life on the Nano-Frontier (M. Suchman) .................................... 211
Societal Implications of Nanotechnology (M. Heller) .................................... 216
Socio-economic Research on Nanoscale Science and Technology: A European Overview and Illustration (M. Meyer) ........................................... 217
Nanotechnology and Unintended Consequences (E. Tenner) ......................... 241
A Cultural Ecology of Nanotechnology (B. Nardi) ........................................ 246
Envisioning and Communicating Nanotechnology to the Public (F. Frankel) ... 251

BIBLIOGRAPHY ........................................................................................................... 254

APPENDICES
A. List of Participants and Contributors ................................................................. 256
B. Selected Endorsements of NNI ................................................................. 262
EXECUTIVE SUMMARY

Advances in nanoscience and nanotechnology promise to have major implications for health, wealth, and peace in the upcoming decades. Knowledge in this field is growing worldwide, leading to fundamental scientific advances. In turn, this will lead to dramatic changes in the ways that materials, devices, and systems are understood and created. The National Nanotechnology Initiative (NNI) seeks to accelerate that progress and to facilitate its incorporation into beneficial technologies. Among the expected breakthroughs are orders-of-magnitude increases in computer efficiency, human organ restoration using engineered tissue, “designer” materials created from directed assembly of atoms and molecules, and the emergence of entirely new phenomena in chemistry and physics.

The study of the societal implications of nanotechnology must be an integral part of the NNI. An interagency effort within the U.S. Government, the NNI supports a broad program of nanoscale research in materials science, physics, chemistry, and biology; it explicitly seeks to create new opportunities for interdisciplinary work. It is balanced across five broad activities: fundamental research; grand challenges; centers and networks of excellence; research infrastructure; and, the ethical, legal, and social implications, including educational and workforce programs.

This report outlines some potential areas for research into societal implications of nanotechnology. It has been prepared just as the NNI is commencing, when there is greater opportunity to affect the NNI investment strategy. Research on societal implications will boost the chances for NNI’s success and help the nation take advantage of new technology sooner, better, and with greater confidence. Moreover, sober, technically competent research on the interactions between nanotechnology and society will help mute speculative hype and dispel some of the unfounded fears that sometimes accompany dramatic advances in scientific understanding.

Toward this end, the National Science and Technology Council (NSTC), Committee on Technology (CT), Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) — the Federal interagency group coordinating the NNI — sponsored a workshop on “Societal Implications of Nanoscience and Nanotechnology.” Held September 28–29, 2000 at the National Science Foundation, this workshop brought together nanotechnology researchers, social scientists, and policy makers representing academia, government, and the private sector. Their charge was to: (1) survey current studies on the societal implications of nanotechnology (educational, technological, economic, medical, environmental, ethical, legal, etc.); (2) identify investigative and assessment methods for future studies of societal implications; (3) propose a vision for accomplishing nanotechnology’s promise while minimizing undesirable consequences.

This report sponsored by NSF incorporates fully the views, opinions and presentations contributed by workshop participants and other leading experts. The NSET report to the NSTC Committee on Technology presents a more concise perspective. The workshop participants offered recommendations to: (a) accelerate the beneficial use of nanotechnology while diminishing the risks, (b) improve research and education, and (c) guide the contributions of key organizations. These recommendations, summarized below, serve as a basis for both the NNI participants and the public to begin addressing societal issues of nanotechnology:

- Make support for social and economic research studies on nanotechnology a high priority. Include social science research on the societal implications in the nanotechnology research centers, and consider creation of a distributed research center for social and economic
research. Build openness, disclosure, and public participation into the process of developing nanotechnology research and development program direction.

- The National Nanotechnology Coordination Office (NNCO) should establish a mechanism to inform, educate, and involve the public regarding potential impacts of nanotechnology. The NNCO should receive feedback from the nanotechnology community, social scientists, the private sector, and the public with the goals of (a) continuously monitoring the potential societal opportunities and challenges; and (b) providing timely input to responsible organizations.

- Create the knowledge base and institutional infrastructure to evaluate nanotechnology’s scientific, technological, and societal impacts and implications from short-term (3 to 5 year), medium-term (5 to 20 year), and long-term (over 20 year) perspectives. This must include interdisciplinary research that incorporates a systems approach (research-technology development-societal impacts), life cycle analysis, and real time monitoring and assessment.

- Educate and train a new generation of scientists and workers skilled in nanoscience and nanotechnology at all levels. Develop specific curricula and programs designed to:
  
a. introduce nanoscale concepts into mathematics, science, engineering, and technological education;

b. include societal implications and ethical sensitivity in the training of nanotechnologists;

c. produce a sufficient number and variety of well-trained social and economic scientists prepared to work in the nanotechnology area;

d. develop effective means for giving nanotechnology students an interdisciplinary perspective while strengthening the disciplinary expertise they will need to make maximum professional contributions; and

e. establish fruitful partnerships between industry and educational institutions to provide nanotechnology students adequate experience with nanoscale fabrication, manipulation, and characterization techniques.

- Encourage professional societies to develop forums and continuing education activities to inform, educate, and involve professionals in nanoscience and nanotechnology.

Over the next 10 to 20 years, nanotechnology will fundamentally transform science, technology, and society. However, to take full advantage of opportunities, the entire scientific and technology community must set broad goals; creatively envision the possibilities for meeting societal needs; and involve all participants, including the general public, in exploiting them.