Small Wonders, Endless Frontiers

A Review of the National Nanotechnology Initiative

Committee for the Review of the National Nanotechnology Initiative
Division on Engineering and Physical Sciences
National Research Council

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Front cover: Three-dimensional scanning tunneling microscope image of a man-made lattice of cobalt atoms on a copper (111) surface. Courtesy of Don Eigler, IBM Almaden Research Center.

Back cover: A nanoscale motor created by attaching a synthetic rotor to an ATP synthase. Reprinted with permission of the American Association for the Advancement of Science from Soong et al., *Science* 290, 1555 (2000). © 2000 by AAAS.

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Preface

Not only did microtechnology during the second half of the 20th century lead to computers and the Internet, but it also brought us to the beginning of an exciting scientific revolution we now call nanotechnology. In addition to the information technologies currently enjoyed throughout the world, microtechnology has helped develop scientific instruments that make it possible for the first time to image, manipulate, and probe objects that can be more than 1,000 times smaller than the microcircuits of the most advanced computers. These objects have dimensions on the scale of nanometers, 1/100,000 the width of a human hair, hence the term "nanotechnology." In recent work it has been discovered that these tiny objects can have electrical, mechanical, magnetic, and optical properties completely different from those of the same material in bulk form. These discoveries could lead to powerful devices with new capabilities and also new materials that will impact all sectors of technology, from advanced electronics to advanced medicine.

Scientists have recently gained the understanding that biology works through highly synchronized interactions among nanoscale objects. For this reason, nanoscale science and technology offer the opportunity to understand life processes at a deeper level, cure and prevent disease, heal injured bodies, and protect society against chemical and biological weapons. At the same time, nanotechnology will point the way to the design of synthetic devices with some of the amazing capabilities of living systems. This prospect is nothing short of astounding, and it places the importance of nanoscale science and technology research into the right perspective.

Science and engineering at the nanoscale demand interdisciplinary research. To make, manipulate, and probe matter on this size scale requires chemical knowledge and also a deep understanding of physical phenomena. Furthermore, the organization of nanoobjects into useful products is a monumental task for engineers. To realize the potential of nanoscale science and technology in advanced medicine will require research at the interface between engineering, the physical sciences, and biology. For all these reasons, the development of nanoscale science and technology will require generations of interdisciplinary scientists and engineers who can learn and operate across traditional boundaries.

How should the country respond to the scientific and societal challenges posed by nanoscale science and technology? All parts of our government—the White House, Congress, federal agencies, and state and local governments—need collectively to implement an effective plan to galvanize the development of nanoscale science and technology in the United States, with advice from experts in our nation's universities, industries, and national laboratories. This plan must also foster strategic alliances with other countries engaged in nanoscale science and technology development.

This review of the National Nanotechnology Initiative (NNI) was initiated by the National Research

Council (NRC) at the request of officials at the White House National Economic Council during the Clinton administration and of agencies participating in the NNI. In reviewing the NNI, the NRC agreed to consider the following questions:

- Does the NNI research portfolio address the skills and knowledge that will allow the United States to fully benefit from the new technology? Is the balance of the research portfolio appropriate?
- Are the available U.S. resources (people, infrastructure, and funding) being applied appropriately within the portfolio? Are the correct seed investments being made now to provide needed infrastructure for future years (to 2005 and beyond)? Are partnerships (government-industry-university, international) being used appropriately to leverage the public investment in this area?
- Is the portfolio of programs being coordinated in such a way as to maximize the effectiveness of the investment? (Is the whole greater than the sum of the parts?)
- Does NNI give sufficient consideration to the societal impact of advances in nanotechnology?
- Are the processes for evaluating the effectiveness of the NNI (determination of metrics, milestones, etc.) appropriate and meaningful? How should the program be evaluated in light of the long-term (10- to 20-year) nature of many of its research goals?
- What are some important areas for future investment in nanotechnology?

The committee offers the following report in response to these questions, and in the hope that its efforts will help the United States to capture the enormous potential benefits of advances at the nanoscale.

Samuel I. Stupp, *Chair*
Committee for the Review of the National Nanotechnology Initiative

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Andreas Acrivos, City College, City University of New York,
A. Paul Alivisatos, University of California, Berkeley,
Louis Brus, Columbia University,
Michael M. Crow, Columbia University,
Alan B. Fowler, IBM Corporation,
Yury Gogotsi, Drexel University,
Evelyn L. Hu, University of California, Santa Barbara,
Royce W. Murray, University of North Carolina,
Mark A. Ratner, Northwestern University, and
J. Fraser Stoddard, University of California, Los Angeles.

Although the individuals listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Alan Fowler, IBM Thomas J. Watson Research Center (emeritus). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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