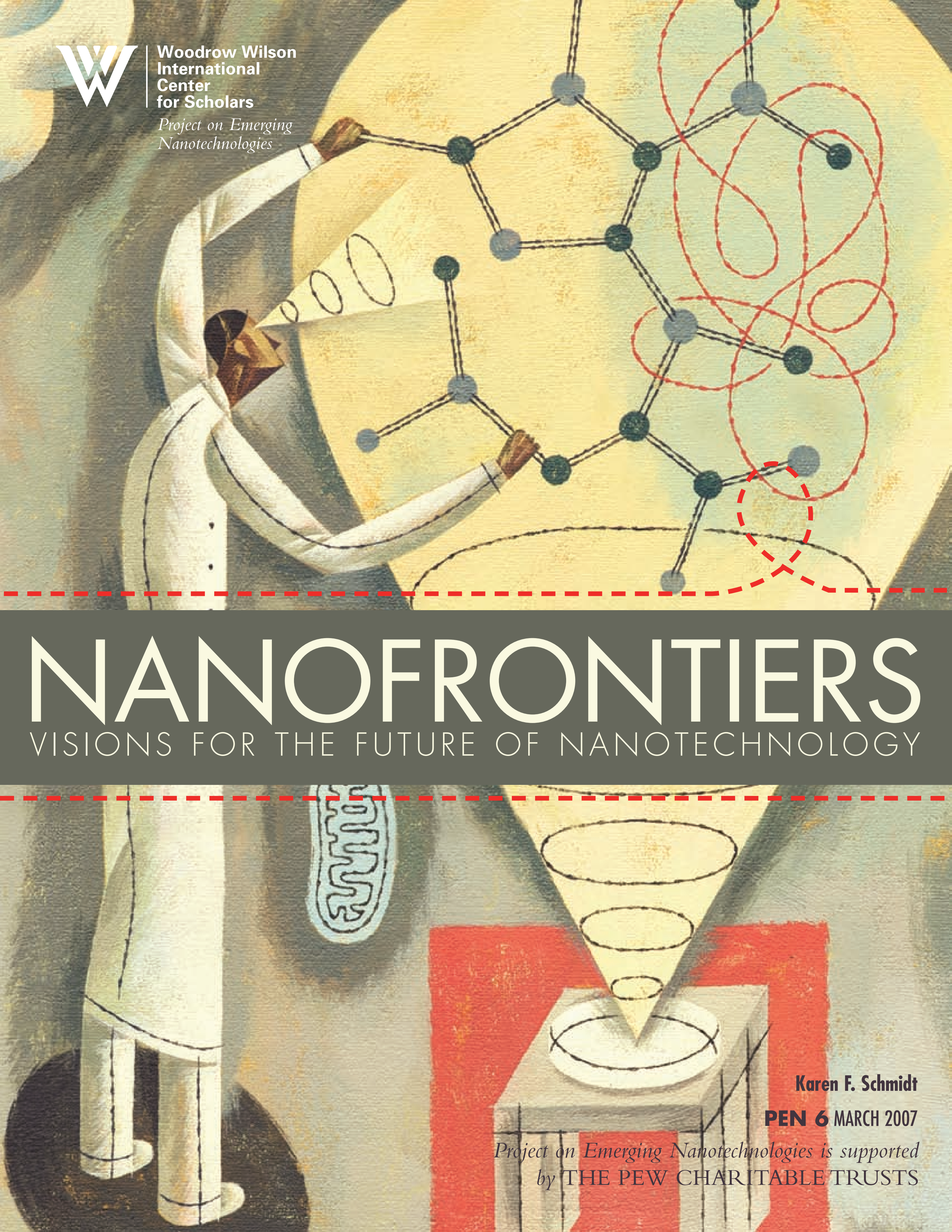
Woodrow Wilson International Center for Scholars
Project on Emerging Nanotechnologies



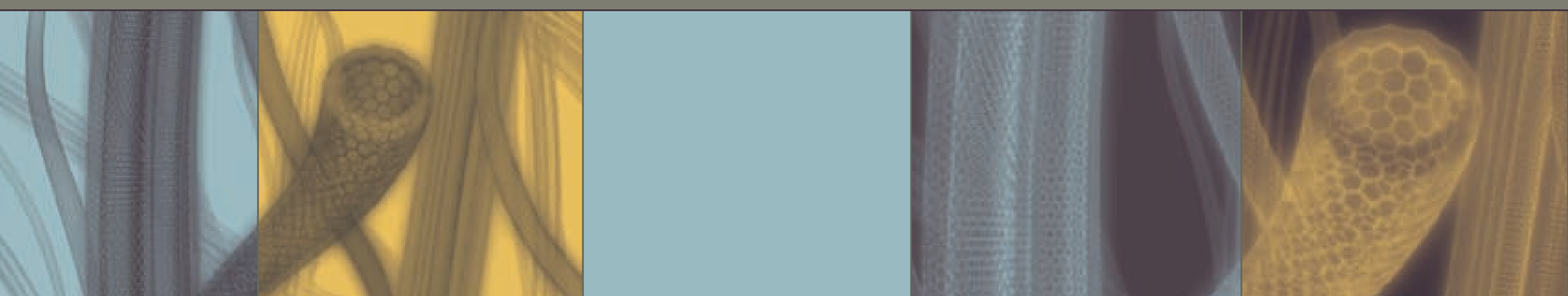
NANOFRONTIERS

VISIONS FOR THE FUTURE OF NANOTECHNOLOGY

Karen F. Schmidt

PEN 6 MARCH 2007

Project on Emerging Nanotechnologies is supported by THE PEW CHARITABLE TRUSTS



contents

About the Author 2

Acknowledgements 2

Preface 3

Introduction: A Glimpse into Nanotechnology's Future 5

Critical Research Areas 9

- THE NANO TOOLSHED 9
- THE NANO LIBRARY 15
- THE NANO WORKSHOP 19

Critical Applications 24

- USING NANOTECHNOLOGY TO HELP SOLVE THE ENERGY CRISIS 24
- USING NANOTECHNOLOGY TO REVOLUTIONIZE MEDICINE 29
- USING NANOTECHNOLOGY TO PRODUCE CLEAN WATER 37

Conclusion: A Final Note from the Nanofrontier 42

Appendix 43

- LIST OF INTERVIEWEES 43
- LIST OF PARTICIPANTS 43

Woodrow Wilson International Center for Scholars
Project on Emerging Nanotechnologies

NANOFRONTIERS

Visions for the Future of Nanotechnology

PEN 6 MARCH 2007

KAREN F. SCHMIDT

The opinions expressed in this report are those of the author and do not necessarily reflect views of the National Science Foundation, the National Institutes of Health, the Woodrow Wilson International Center for Scholars or The Pew Charitable Trusts.

ABOUT THE AUTHOR

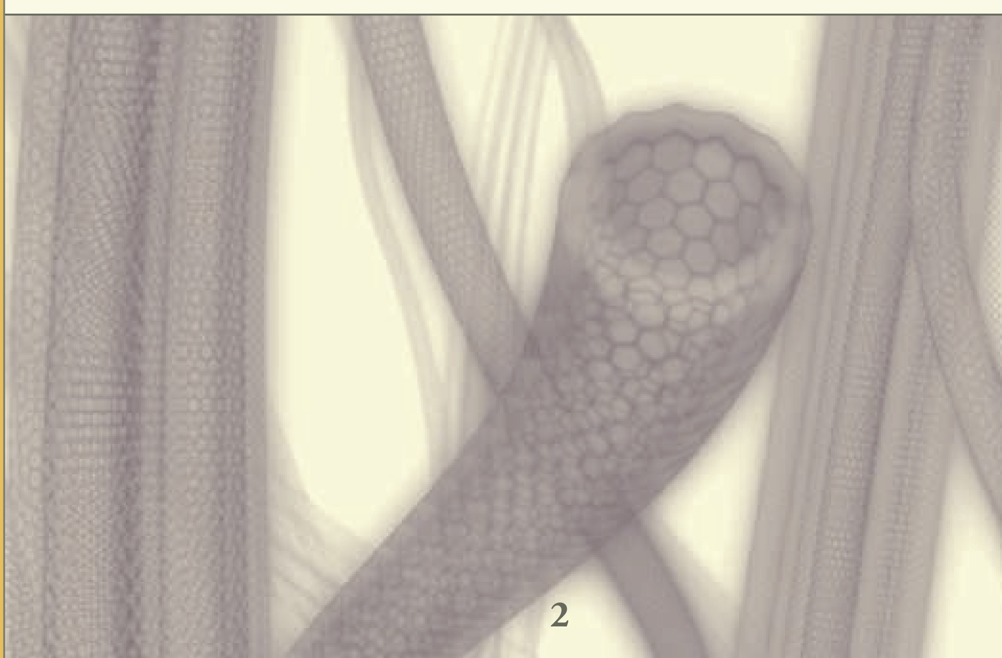
Karen F. Schmidt is a freelance journalist and science writer based in California. Her articles have appeared in numerous national and international magazines and journals, including *New Scientist* and *Science*. Her writing focuses on biology, nanotechnology and toxicology, as well as on research and policy issues related to human health and the environment.

She is a former beat reporter, covering chemistry, for *Science News* and a former science features writer for *U.S. News & World Report*, both based in Washington, D.C. At *U.S. News & World Report*, Schmidt authored a major cover story on the biology of aging. She began her journalism career as a features writer for the *Santa Cruz Sentinel* in California. She is currently collaborating with a physicist to write and produce a series of podcasts on nanotechnology for The Exploratorium Museum in San Francisco.

Schmidt graduated with a B.S. degree in chemistry/biochemistry, with great distinction, from San Jose State University. She holds a graduate certificate in science writing from the University of California, Santa Cruz. Schmidt has also taught news reporting and writing. Her honors and awards include a Scripps Howard Institute on the Environment Fellowship (2002), a Fulbright Senior Scholar Fellowship in Journalism (2000–2001) and a Society of Environmental Journalists Arizona Fellowship (1996).

ACKNOWLEDGEMENTS

We would like to thank all the interviewees and participants who contributed their time and expertise to the NanoFrontiers Workshop. Special thanks to Michael Lesnick of the Meridian Institute for facilitating the dialogue and to the National Science Foundation and the National Institutes of Health for their co-sponsorship and financial and technical support. Finally, thanks to the staff of the Project on Emerging Nanotechnologies at the Wilson Center for editing, designing and producing this document.



PREFACE

For centuries, science has explored and continually redefined the frontiers of our knowledge. For the past decade, one part of that frontier has moved inward, reaching ever smaller dimensions by penetrating to the nanoscale—one billionth of a meter. Having entered the nanoscale world, scientists and engineers are gaining increasing control over the properties of matter and are creating novel applications that have the potential to transform everything from manufacturing to medicine to energy production.

For many non-scientists, however, the nanofrontier remains clouded, inaccessible and, in many cases, almost incomprehensible. Yet it is becoming more important for policy makers, the press, non-governmental organizations and citizens to understand that future landscape where scientific aspirations and public awareness will meet and how the boundaries of innovation may be defined.

This document is the result of an unusual meeting that took place in Washington, D.C., on February 9 and 10, 2006, that involved a visit to the nanofrontier. The premise of the meeting was simple: to explore the scientific and technological advancements and promises of nanotechnology with a wide range of experts from various disciplines. This document is, in effect, the resulting trip report—a report we hope can be understood and appreciated by an audience that goes beyond the scientific community.

In our effort to map that long-term future landscape, we encouraged a range of scientists and engineers to share their visions with each other, with researchers from other disciplines and with the broader policy-making community. Given the inevitable convergence of nanotechnology and biotechnology, this workshop also included researchers and engineers from both the physical and biological sciences and brought together two government agencies responsible for supporting cutting-edge research in these areas—the National Science Foundation and the National Institutes of Health. Also in the room were social scientists, ethicists, historians of science and public policy makers. There were no expectations of consensus at the workshop, yet many of the ideas and recommendations discussed during those two days converged around two areas: tools and transformative applications.

The report uses the metaphor of the tool—for observing, for manipulating and for measuring—to discuss the research that will be needed to advance our knowledge and use of nanotechnologies in the future. How such innovative tools might be used for the good of humankind and the planet is discussed in the second half of the report, which explores potential applications of nanotechnology to address societal needs relevant to sustainable sources of energy, personalized medicine and clean water. The report also raises questions that must be addressed to ensure that as the field moves forward, the long-term benefits of nanotechnology clearly outweigh its risks.

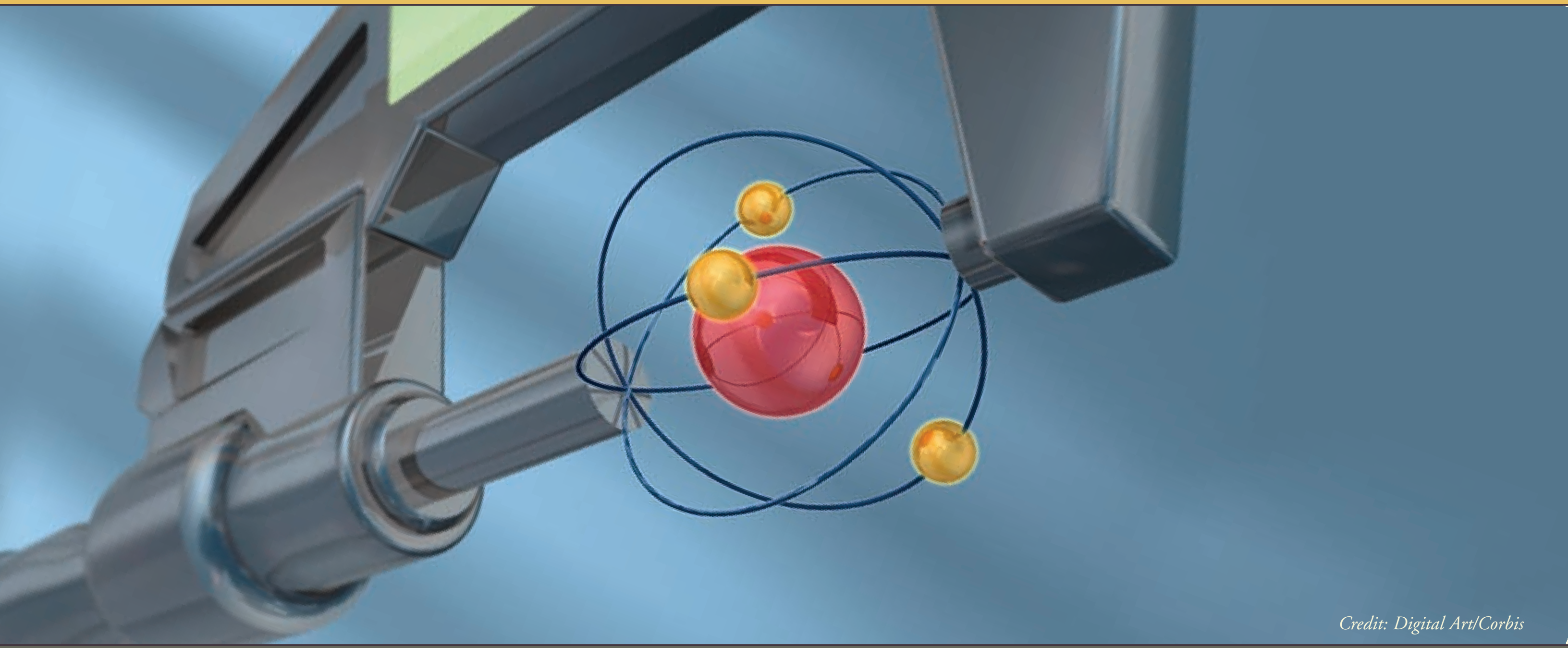
Written from the perspective of a science journalist, this report offers the reader a unique and imaginative perspective on how scientists think about and address the complexities of the future of nanotechnology. We hope that it will provide a glimpse into a vast new world of technological possibilities and that it will stimulate a broader discussion of the goals and vision for nanotechnology in both the scientific and the public realms.

—The Planning Committee

Mihail C. Roco, National Science Foundation
Lynn Hudson, National Institutes of Health
David Rejeski, Woodrow Wilson International Center for Scholars

WHAT IS NANOTECHNOLOGY

Nanotechnology entails the measurement, prediction and construction of materials on the scale of atoms and molecules. A nanometer is one-billionth of a meter, and nanotechnology typically deals with particles and structures larger than 1 nanometer, but smaller than 100 nanometers. To put this into perspective, consider that the width of human hair is approximately 80,000 nanometers. A nanometer-size particle is twice the diameter of a gold atom and a very small fraction of the size of a living cell. Such a particle can be seen only with the most powerful microscopes.



Credit: Digital Art/Corbis

INTRODUCTION

A Glimpse into Nanotechnology's Future

Imagine being invited to sit amongst a group of top chemists, physicists, biologists, electrical engineers, social scientists and government planners and to listen to them talk about the most cutting-edge scientific research and where it is leading us. These experts make bold statements about what is important, enthuse about finding solutions to critical problems, argue about what is possible, express frustrations about what is practical, admit concerns about how society might be changed and laugh occasionally about their difficulty in communicating with each other. You get the chance to hear what researchers are discovering, testing and dreaming. You get a peek at the future.

I was given just such an invitation when I was asked to participate in the NanoFrontiers Workshop, co-sponsored by the Project on Emerging Nanotechnologies at the Woodrow Wilson Center, the National Science Foundation (NSF) and the National Institutes of Health (NIH). As a science journalist, I saw this as a great opportunity to get a deeper understanding of nanotechnology and its potential applications. I had attended other conferences on the subject and had heard about stunning new developments in manipulating matter at the nanoscale, about the potential environmental and health impacts of new nanomaterials, about the promises of nanomedicine and about the ethical concerns raised by this new technology. I knew very well that both risks and benefits would emerge, as happens with any new technology.

"I have a lot of hope that nanotechnology can get governments to put structures in place—nationally and internationally—that are more adaptable, so that the public could decide it wants the technology and then we could go for it."

—Peter Grutter, physicist, McGill University

What made nanotechnology so fascinating to me, though, was a theme I kept hearing underlying the discussion. The people at these meetings were earnestly looking ahead and trying to get a handle on the risk-benefit equations well in advance. They were keenly aware of past mistakes associated with introducing new technologies to the public and were eager to avoid them. While scientists were gaining precision in their ability to use nanotechnology, they were—for the first time—also trying to gain precision in their forecasts about its societal implications.

It remains to be seen whether this ambitious experiment will succeed—that is, whether nanotechnology will, on balance, be steered toward making the world a better place. The NanoFrontiers Workshop seemed a reasonable way to try to increase the odds. At the opening of the February meeting, participants were urged to put their minds together and to think as one brain about how to prepare for the future. And they were asked to be courageous in putting forth their most creative ideas. But this was not to be an exercise in science fiction, and there was no mention of Hollywood-inspired "gray goo" or out-of-control "nanobots." As the organizers put it, "We want to be visionary, but not detached from reality—the ideas must be anchored in logic."

My task was to listen to the discussion, ask questions and analyze a variety of visions for the future of nanotechnology. I began by reading papers written by 15 participating scientists, each laying out his or her ideas on the future of nanotechnology. Then I talked with 15 researchers by phone. Where will we likely be in 5 years, 10 years? What obstacles remain? What unanticipated developments—wild cards—might come into play? Which applications will be important? In February, I attended the two-day NanoFrontiers meeting and observed the lively brainstorming of 50 attendees, as well as the more informal discussions of smaller breakout groups. Finally, after the meeting I called up 12 people to ask additional questions and to collect their afterthoughts.

The result is a report that is my interpretive summary of these many conversations, with some background research included. This summary does not give voice to all possible visions and viewpoints on the future of nanotechnology. However, the conversations were with researchers from many disciplines, so a broad variety of visions was sampled. In the end, the 50 participants agreed that moving nanotechnology forward will require more attention to three critical research areas: tools, informatics and nanoscale building. Advances in these areas could help solve three important problems with broad societal impacts: the energy crisis, the need for better medical treatments and the demand for clean water. This document is organized along those lines.

"It is important for the earliest uses of nanotechnology to be thoughtful and attractive. The public is looking for control of their lives. Could you, for example, use nanotechnology to empower people to practice healthy behaviors?"

—Thomas Murray, bioethicist and President, The Hastings Center

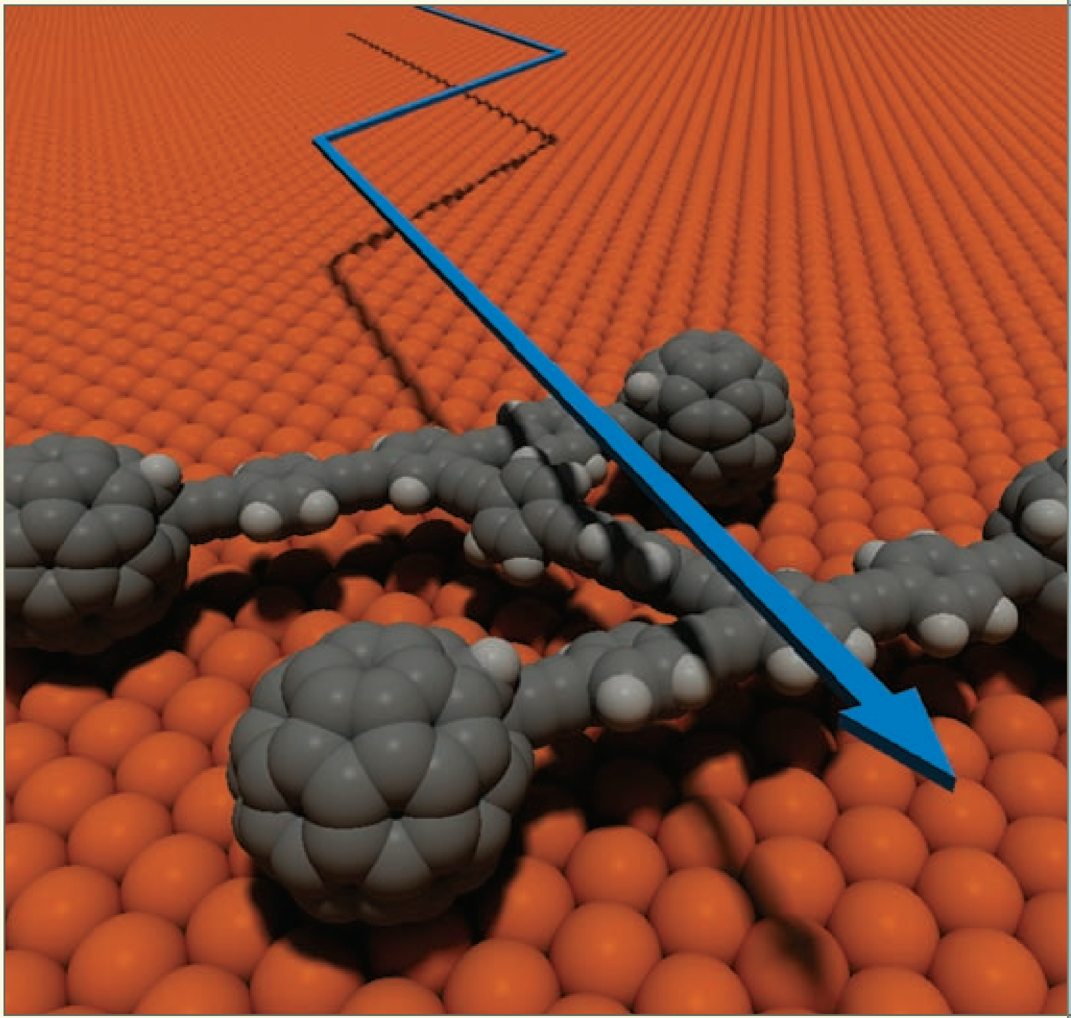
In truth, nanotechnology is much more than what will be discussed here. When new properties of matter are discovered and exploited, the applications are almost limitless. That is why nanotechnology is called a "platform" technology: it readily merges and converges with other technologies and could change how we do just about everything. NanoFrontiers participants focused on the key areas where they expect nanotechnology to have big impacts soon. The effects of nanotechnology on many other areas—such as textiles, paper production, food manufacturing and agriculture—were not explored as deeply. Advances in computing and electronics are humming along, but these applications of nanotechnology were also not chosen as a focus of this meeting.

How does one begin to think about fundamental scientific research that could blossom into myriad technological possibilities? In some sense, this is an old and familiar story. As many scientists will tell you, they are not doing anything radically new. They are simply continuing their tradition of making tools, investigating how the natural world works and manipulating that world at ever-smaller scales. Early humans worked in the macroscopic world, learning how to work with rocks and minerals and how to domesticate plants and animals for useful purposes. Scientists of the 20th century tinkered in the microscopic world, figuring out how to make novel chemicals, such as plastics and pure versions of medicines. Now, researchers have the potential to reach down to the nanoscale and to do revolutionary things with atoms. On the simplest level, I think about it this way: nanotechnology is about domesticating atoms and harnessing them to serve our needs.

What is new is the nanoscale world itself. It clearly differs from the macroscopic and microscopic worlds, and much of it is *terra incognita*. Scientists are still making discoveries about the behavior of atoms as singletons, as clusters and as parts of molecules (which are like structured, mixed communities of atoms). Yet researchers are already beginning to get groups of atoms to do remarkable and highly specific tasks—for instance, to ferry drug molecules, sense a change in the environment and assemble into membranous structures that trap pollutants. Recently, scientists created a functional nanoscale car with chassis, wheels and motor driven by ultraviolet light. Another group of researchers just built the first complete integrated circuit using a single carbon nanotube, which is 50,000 times thinner than a human hair.

"If you look historically at tensions over the introduction of new technologies, they tend to be resolved when a public good or benefit is created and shared. The public was initially resistant to blood transfusions, but soon realized how important they could be in saving the lives of soldiers."

—Elias Zerhouni, Director, National Institutes of Health



Nanocar: proof-of-concept demonstration

Credit: Y. Shirai-Rice University
Scale: width is 3–4 nanometers across

Nanotechnology is now beginning to enable scientists to domesticate atoms, but at the same time, this capability is raising health and safety issues. Like many other chemicals that were created in the past—plastics, pesticides, flame retardants—nanomaterials could turn out to cause unexpected harm to the environment and human health. Many future surprises might be avoided by carefully testing nanomaterials up front in order to gauge their toxicities and to predict how easily they could spread in water, air and soil. We, as a society, could then choose to work with the new materials that appear most useful and benign and to avoid the riskier ones.

Right now is an exciting time to envision how researchers might harness atoms to serve society's most pressing needs. There is certainly no shortage of important problems to solve. Yet the dream of using nanotechnology to make the world a better place will come true only if scientists engage the public and set a course that is both safe and smart.

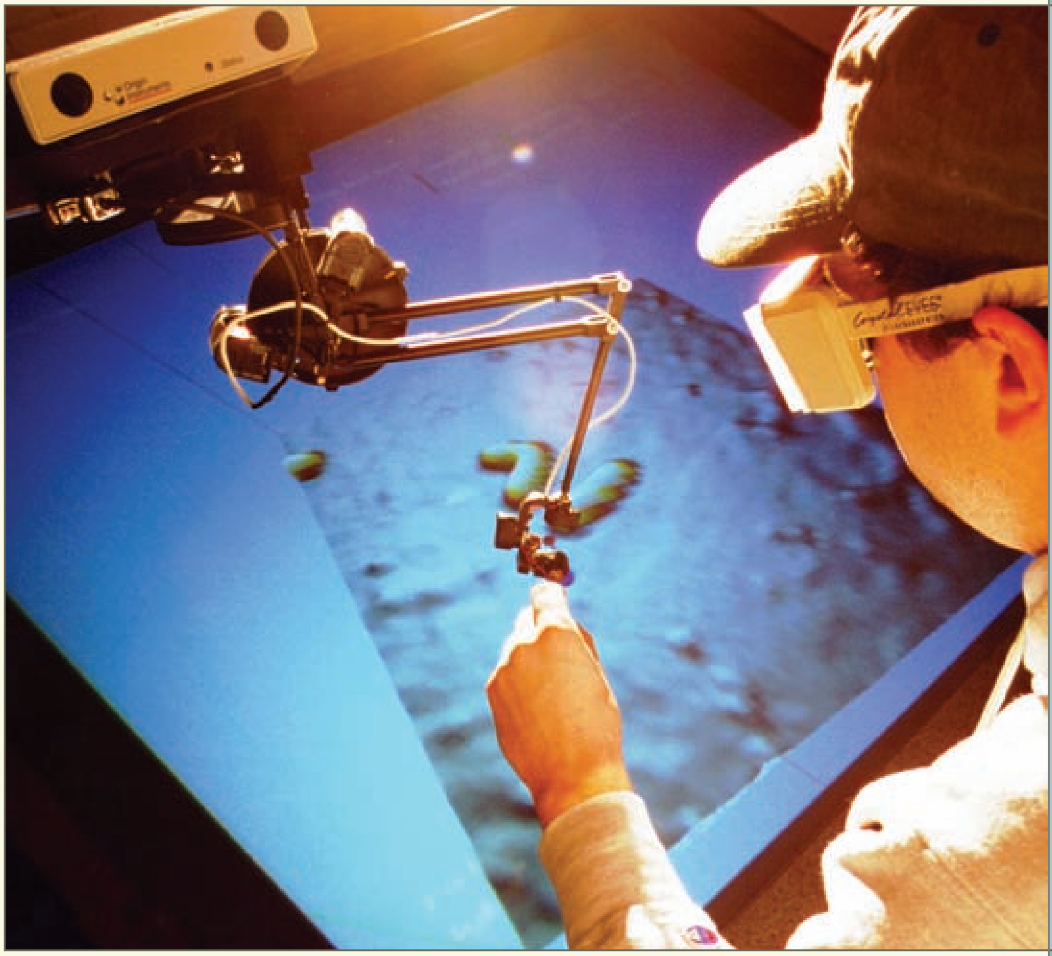
Practical applications of nanotechnology for consumer products

Credit: David Hawxhurst – Woodrow Wilson Center, 2006

The Nano Toolshed

Nanotechnology would not exist if there were not tools for working at this otherwise invisible scale. Nanotools have not been around long. In the late 1960s, researchers at the U.S. National Bureau of Standards—now the National Institute of Standards and Technology—developed the Topografiner, an instrument for scanning and visualizing the surfaces of materials on a microscopic scale. That helped lead in the 1980s to a groundbreaking nanotool, the scanning tunneling microscope (STM). The STM enabled scientists to better control the position of the scanning tip and, for the first time, see things just 1 nanometer in length.

The STM has since spawned a variety of microscopes for imaging, probing and studying nanoscale properties of materials, and these have been particularly useful in developing smaller and faster computer chips. But such microscopes are also opening up new explorations. Consider the nanoManipulator, a microscope with a virtual reality interface that gives scientists the sense of being shrunk a million times as they interact with the nanoworld, probing viruses, DNA and clot-forming proteins called fibrin. These kinds of innovative nanotools are just the beginning. The Nano Toolshed is still relatively empty.



nanoManipulator

Credit: UNC Nanoscale Science Research Group, www.nanomanipulator.org

Asking the 50 NanoFrontiers participants to imagine the tools of the future turned out to be a bit like asking kids what they wanted for their birthdays. Scientists from all disciplines were bursting with ideas for devices that could fill their toolshed. “We define nature by the tools that we use,” one engineer suggested, hinting that new tools would bring big paradigm shifts. “What physical processes do we want to measure, but cannot?” His answer: how information flows through systems and how emergent properties arise with complexity.

He was not the only one with grand questions in mind. An electrical engineer admitted that he did not know exactly which tools to wish for, but that they should be used to find answers to deep scientific questions that matter: Is room-temperature superconductivity possible? Can matter be assembled from the bottom up, as nature does it? Can we build cognitive machines? Are matter, information and energy really one and the same? A life scientist pondered the interface between living and non-living systems. “To what degree can we poke and disturb a cell and still maintain homeostasis?” he asked. “What happens when we merge a cell with nanotechnology, or merge nanotechnology with a cell?”

“We now have a huge opportunity to combine and integrate tools, and that will lead to new science.”

—Dawn Bonnell, materials scientist, University of Pennsylvania

This brainstorming session on tools, which bounced between the lofty and the mundane, seemed to strike a chord for everyone. That is probably because new tools often do lead to revolutionary insights—the “Aha!” moments that scientists live for. “Most scientists make tools because they are trying to discover new phenomena,” noted one materials scientist, who suggested that recent breakthroughs in measuring the spin of a single electron could lead to nanotools that shed light on the fundamental behavior of matter. Researchers who were clearly driven by curiosity acknowledged, however, that they found it next to impossible to predict where such leaps in understanding would take us.

“We need to exploit the intersection of neuroscience and nanotechnology to better understand the synapse—it’s just 40–50 nanometers across that gap and still an unknown area. We should find out how to turn neural networks on and off, to learn how neurological diseases happen.”

—Xiang Zhang, engineer, University of California, Berkeley

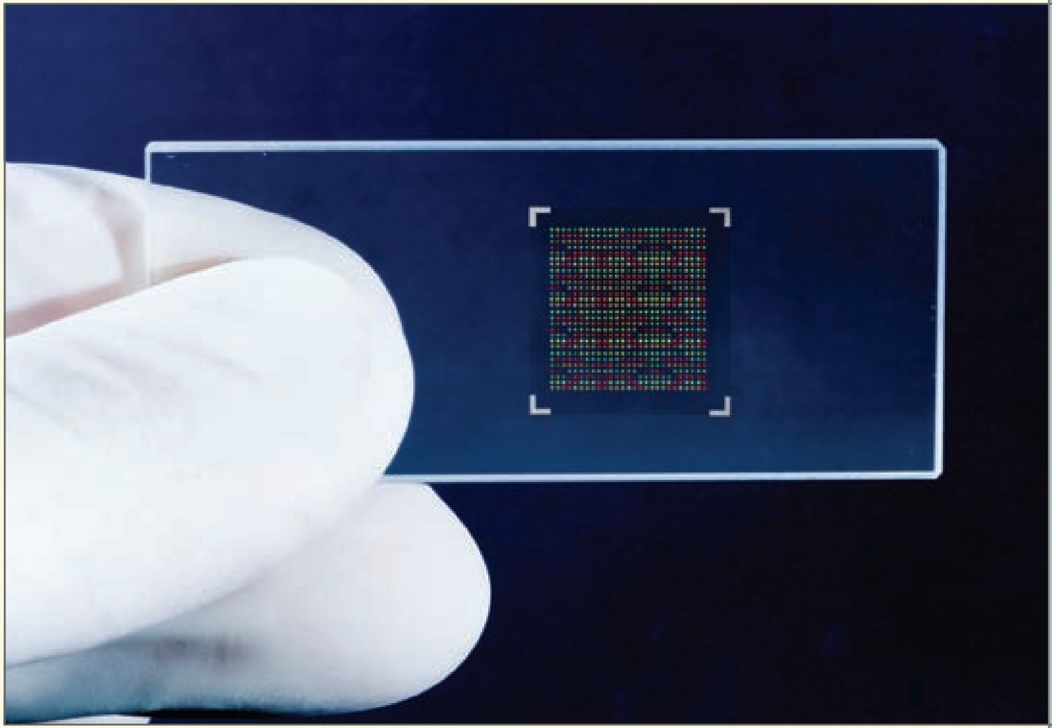
Taking a more practical view, other scientists considered how new tools could help them get around vexing roadblocks, which varied by discipline. One renowned chemist mentioned troubles with controlling the synthesis of tailored materials. “We have no idea what is going on in real time as a nanomaterial forms.” He scoffed, “Nanoscale imaging? There is none!” A physical scientist focused not on time but on obstacles to understanding spatial structure: “We can see only averages; we need to see nanostructures in 3-D.”

Many life scientists mentioned the need for probes that do not harm or disturb living cells and tissues. “The big problem is measuring in vivo biology and understanding living systems in an integrative way,” one biologist suggested. A health scientist argued that the biology section of the Nano Toolshed should include devices for monitoring human exposure to nanomaterials and for studying their effects on organisms. Another life scientist noted, "The complexity of our knowledge and data is reaching the point that we cannot do much without better simulation and modeling."

In short, these scientists came up with a long list of tools that would be needed to truly domesticate atoms. This new generation of nanotools that they were envisioning could be categorized according to their purpose:

Imaging. Chemists, physicists, engineers and biologists all said they wanted better methods for seeing things at the nanoscale. For instance, imaging of cells and tissues in the body could potentially be done on a finer scale using nanoparticles as contrast agents. The detailed structures of nanomaterials and of single proteins, and even the catalytic sites of enzymes, might be better visualized using new kinds of optical probes and microscopy.

Measuring. The researchers noted that anyone who aims to manipulate a material must understand its physical—and sometimes biological—properties. Nanomaterials can behave in unexpected ways, so it is important to understand them well before they are widely used in products. To fully characterize these materials, new kinds of probes are needed to measure electrical conduction, surface reactivity, strength, magnetic properties and so on. Other measurement tools that exploit nanoscience, such as "lab-on-a-chip" devices, hold promise for detecting and quantifying specific molecules of



Nanotechnology may lead to the next generation of "lab-on-a-chip" devices

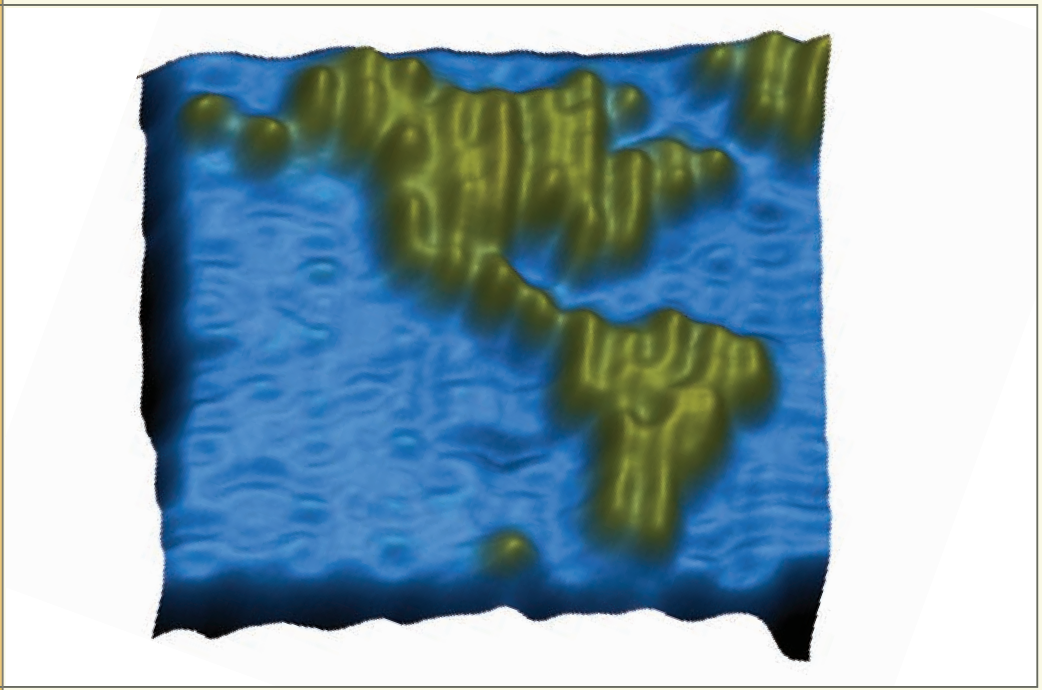
Credit: Andrei Tchernov

interest in water and blood. Likewise, devices with nanopores could enable rapid and cheap sequencing of DNA.

Integrating. NanoFrontiers participants were particularly excited about combining two or more tools within a single device. These could allow researchers to integrate multiple kinds of data and to get a fuller picture of the nanoworld in 3-D and in real time. Such tools would be essential for understanding complex nanosystems, measuring changes in nanostructures and observing molecular interactions. For example, new methods for "nanotomography" (similar to computed axial tomography, or CAT scanning) might combine an optical probe with a physical probe to make a "movie" of how molecules interact with one another.

Manipulating. To work at the nanoscale, scientists will need tools for putting atoms where they want them to go. Adaptations of scanning probing microscopy and new lithography methods for creating nanoscale patterns hold promise, as do nanotweezers and nanosize machines for moving around atoms. But once researchers develop more advanced methods for manipulating atoms, they will still need additional tools to do this efficiently on a larger scale. Such tools for nanomanufacturing are of particular interest to computer chip makers, but eventually all kinds of nano-enhanced industries will need them.

Modeling. The nanoworld is beyond the realm of human intuition, so researchers must pump their data into computers and generate models of this alien landscape. Simulations will be crucial for understanding nanosystems, testing hypotheses and pre-



Nanoscale pattern created by manipulating DNA using new research tools

Credit: Paul Rothemund, California Institute of Technology dicting behavior. Many NanoFrontiers participants commented that the computational tools needed to make these complex simulations require new mathematical concepts that have not yet been developed.

From this discussion, the Nano Toolshed sounded like it could be a great big toy box for scientists. And yet there were hints and suggestions of plenty of beneficial real-world applications that could spin off from these basic tools. Consider:

Medical applications. Imaging and measuring tools could lead to advanced methods for diagnosing disease earlier and more accurately. Integrating and modeling tools used in basic research could reveal new insights about how diseases develop and how to halt their progression, and could clarify how complex systems, such as the brain, work. Manipulating tools could be used to construct new kinds of artificial tissues, drugs and medical implants.

Environmental health and safety. Measuring tools could lead to new methods for assessing human exposure to toxic substances, monitoring the extent of water pollution and evaluating the safety of nanomaterials. Manipulating tools could lead to mass production of new kinds of environmentally benign materials, green technologies and more-effective therapeutics.

Education. Computer simulations of the nanoworld could be adapted for use as educational tools to help teach science concepts and prepare young people for careers in high-tech industries. One such program, called NanoHub and funded by the NSF, could be replicated for the life sciences, for instance, to explore and teach how physical probes interact with living systems.

Of course, multiple government agencies, as part of the U.S. National Nanotechnology Initiative, are already supporting research on nanotools and their applications. And the science agencies of many other countries—from Japan and the European Union to Mexico and South Africa—are doing the same. A natural question for these scientists was, "Is the development of nanotools being hindered in any way?" One chemist highlighted challenges in his lab. "The sophisticated tools we need must be made by teamwork, with physicists, engineers, biologists and chemists, but the sociological barriers between us are enormous!" Some suggested that a lack of information about the properties of nanomaterials was stalling the development of many tools and devices, but several argued that this hesitation was unwarranted. "Engineers never wait—if they did, you would not have a computer!" said a computer scientist, to much chuckling. Others lamented a lack of interest in companies to commercialize nanotools. "The transfer of new information and ideas to industry is slow; it is worrying," remarked one materials scientist.

"Nanotechnology can be used very effectively to extract critical information about the inception of the disease process at the level of the molecule and the atom, and as such, it presents us with a huge horizon of exploration."

—Elias Zerhouni, Director, National Institutes of Health

The tone grew more somber when participants considered the wild cards that could thwart their efforts to build a Nano Toolshed. One social scientist got to the heart of the technology transfer problem: “You can invent something good, but if no one is willing to market it, it goes nowhere. Without new concepts in the areas of liability and insurance, there will be hang-ups.” Even if a powerfully useful tool made it to commercialization, there could be issues of control—that is, of patents, affordability and access. Certain nanotools—those used for gathering large amounts of information, such as people’s DNA sequences or environmental data—might be viewed dimly by the public, if issues of privacy and consent are not carefully handled. Finally, one chemist worried about the future workforce. “We will need a cadre of well-trained people to operate our tools, to make them sing and dance 24/7.”

But overall, spirits were not dampened. NanoFrontiers participants suggested some ways to get ahead in filling their Nano Toolshed. A strategy for the short term could include:

1. **Push existing tools to their limits.** This includes combining more tools into integrated devices and exploring novel ways to use existing tools—for instance, taking tried-and-true tools used in the electronics and computing industries and adapting them for other purposes. This strategy of adaptation and modification may be most valuable in the short term, until next-generation tools are designed.

2. **Build strong interdisciplinary research teams.** This includes establishing new modes of collaboration both within and between government, university and industry investigators. Methods for rewarding and advancing these institutional partnerships need to be developed.

3. **Explore entirely new approaches for imaging, measuring, integrating, manipulating and modeling.** This includes finding new ways to connect artificial devices to biological systems and to visualize what is happening at the nanoscale. These methods need to be developed for use across multiple disciplines and in multiple applications.

“What is not being tackled is the people problem. We need to invent a new model for research like the old Bell Laboratories. What made them so creative and successful?”

—J. Fraser Stoddart, chemist, University of California, Los Angeles

The Nano Library

Many people feel crushed by information overload, but today's scientists experience it on a particularly extreme level. As new tools allow them to collect reams of data around-the-clock and to link it with data from collaborators around the globe, it is not uncommon to hear them say, "I feel as if I am connected to the New York Stock Exchange." Managing information—organizing it, standardizing it, sharing it, comparing it, analyzing it and even visualizing it—has become an integral part of the scientific endeavor.

Scientists have used several strategies to manage this modern-day glut of data. In the fields of astronomy and high-energy physics, researchers decided several decades ago to train their own information managers. Other fields, such as chemistry and engineering, have come together now and then to set up databases that serve the specific needs of their professions. Most recently, life scientists jumped in and created massive databases and complex mathematical tools for managing and making sense of the genetic-sequence data that flooded out of the Human Genome Project. That has led to a hot new field called "bioinformatics" and to remarkable databases, such as the international Protein Information Resource (PIR) and the BioBricks Foundation's Registry of Standard Biological Parts.

Now, scientists and policy planners have begun thinking about "nanoinformatics," or how to manage accumulating information about the nanoworld. Although it is early, some NanoFrontiers participants suggested that it is a good time to draw up blueprints for the proverbial Nano Library. They argued that a growing interdisciplinary community of researchers in nanotechnology would benefit from a variety of interconnected databases and informatics tools.

Nanoinformatics can manage accumulating information about the nanoworld

Credit: Center for Bioinformatics at the University of North Carolina

Worldwide, tens of thousands of scientists are now working in nanoscience, generating detailed data on everything from the optical properties of various sizes of gold nanoparticles to the chemical reactivity of buckyballs with different atoms attached to their surfaces. The pipeline of data is flowing and will be growing, particularly as the Nano Toolshed comes together. As one engineer put it, "We are not overflowing with information yet, but eventually we will be, as new techniques for gathering data become more widely available."

The Nano Library could be a powerful way to help scientists make sense of all the new nano-information coming in. And ultimately, it could help them find ways to domesticate atoms for specific purposes. One information scientist said that the societal impact of the Nano Library could be huge: "It could lead to a social transformation from the early days of heroic nanoscience pioneers to broadly based research by large numbers of labs pooling their information; it could take us beyond the first barnstorming airplanes to real jetliners and air forces." The Nano Library could also foster transparency by giving the public greater access to information about nanotechnology, particularly about toxicological properties of nanomaterials, said several NanoFrontiers participants. In this way, the Nano Library could encourage the safe development of nanotechnology and its transfer to industry.

"Safety is critical, and industry knows it. We have to address it as nanotechnology develops; you cannot put the cart before the horse."

—Andrew Maynard, physicist, Woodrow Wilson International Center for Scholars

Databases. On the simplest level, the Nano Library might begin as a network of databases that help researchers answer practical questions. For instance, which size iron nanoparticles are best at removing contaminants from water? Which kinds of proteins are likely to stick to gold nanowires and be useful for making transistors? How should a nanostructure be shaped, if its function will be to "turn the key" on a tumor cell membrane and carry a drug inside? Clues, theories and real answers might already be out there, but they are hard to find in the vast sea of scientific data. Information about the nanoworld is mostly scattered in journals, published by many different professions in dozens of countries. The Nano Library could bring together similar kinds of data and create easier access to it. Conversely, in the event a question could not be answered, the query process might identify gaps in data and understanding, and help researchers plan further studies.

Informatics tools. The Nano Library might also be used to spur discovery. Consider, for example, that the Genome Browser used by life scientists has helped them find important new disease genes. One cancer researcher suggested, "Informatics is needed to help us really explore that new frontier of interactions between biomolecules and atoms." By viewing data from studies by physicists and biologists side by side, it might be possible to see patterns that were not apparent before, he explained. Using and manipulating data in this way would require complex informatics tools based on new mathematics. It might also require new computer simulations that integrate different kinds of data. "An experimental part of nanoinformatics could focus on nanosystems," suggested one bioengineer.

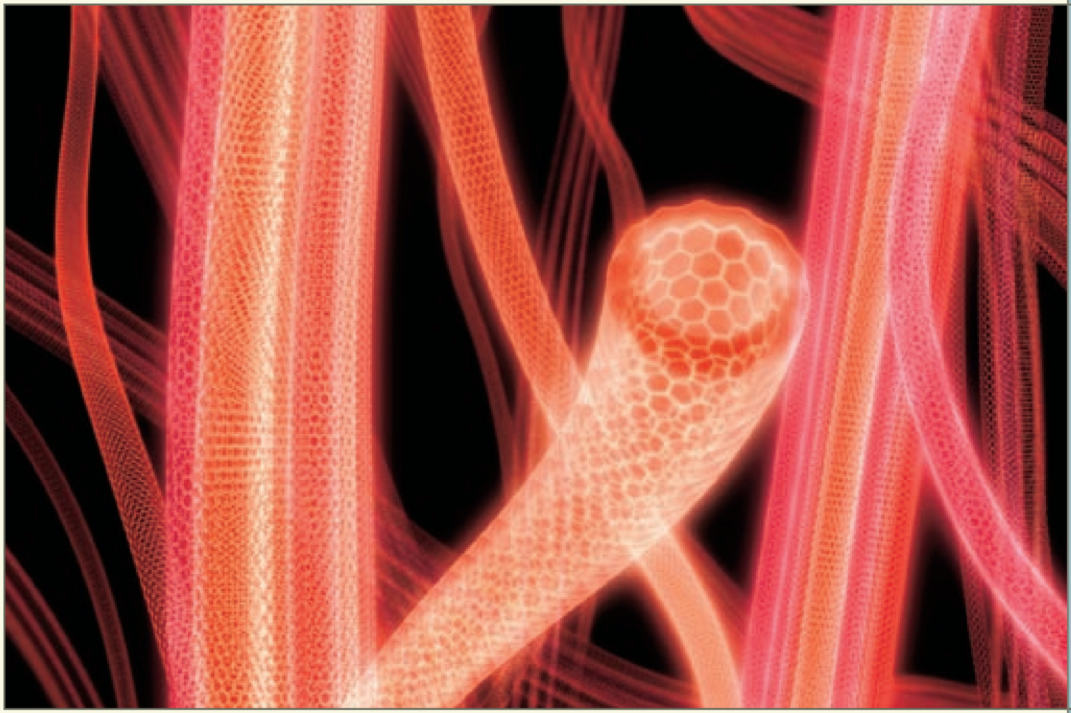
"There is power in a mass of information. We need to use it to learn how to make nanosystems that are functional, complex, reproducible and robust."

—Michael Roukes, Director, Kavli Nanoscience Institute, California Institute of Technology

Collaboratories. The Nano Library could also be extended into the realm of virtual laboratories. New computer-based tools could be used to bring together research groups by allowing them to share data, as well as instruments, remotely. Such "collaboratories"—which are already being pioneered by some groups of scientists—would enable multi-disciplinary and multi-national teams to work together to find nanotechnology solutions to big problems.

It is easy to imagine the benefits of the Nano Library, but not everyone at NanoFrontiers could muster a realistic vision for it. Nanoscience presents some unique challenges for informatics. Emerging data on how matter behaves at the nanoscale is, in a sense, another whole layer of knowledge that needs to interface with many other areas of science. Linking data that is coming out of so many disciplines—each with its own terminology and culture—sounds like "a Herculean task," some NanoFrontiers participants remarked. Several worried that the Nano Library might be oversold and disappointing in the end. "Informatics is important, but it is not sufficient to solve problems," said one chemist. "I am not twiddling my thumbs waiting for it."

When picturing the Nano Library, people often hit a mental block about how to design databases for nanomaterials, which can be difficult to define. Many nanostructures exhibit huge numbers of variations. For instance, in the case of single-walled carbon nanotubes, 20 different structural types can form and their lengths can vary from 5 to 300 nanometers.



Carbon nanotubes

Credit: National Geographic

Four different processes exist for manufacturing them, five methods for purifying them and 10 surface coatings are typically applied. So, there are up to 50,000 different versions of single-walled carbon nanotubes! And they are not expected to all have the same properties.

Moreover, nanomaterials used in living systems would change shape and properties according to surrounding conditions, unlike stable materials used by engineers in devices such as computer chips. "We still hear the classic cry to characterize materials before they are presented to biologists, but that is meaningless," one biologist pointed out. "What we really need is a new kind of physics, mathematics and analytical chemistry that allows us to interrogate a nanoparticle in the biological context."

No one at the NanoFrontiers Workshop suggested that he or she had a blueprint for the Nano Library. In fact, such a library is likely to evolve over time. "We'll have to use instinct, creativity and information science to make it grow with the field—it is not going to be cut and dry," said one information scientist. Several participants argued that its development should be driven by specific needs, in the same way that bioinformatics was. "Informatics can be designed and implemented when needed," suggested one chemist.

The research scientists who considered the idea of a Nano Library did not seem eager to initiate such a project, but two scientists who work in policy and planning did. They suggested that, like the Internet and the Human Genome Project, the Nano Library ought to be spearheaded by government agencies, which are designed to act in the public interest. Said one, "With large amounts of data that have the power to transform society, we cannot leave this job to free enterprise and the private sector."

Indeed, early lessons on how to create a Nano Library are likely to come from the government's first two forays into nano-information management. The National Institute of Occupational Safety and Health recently started a Nanoparticle Information Library, and the National Cancer Institute has begun organizing data from its Nanocharacterization Laboratory.

In summary, NanoFrontiers participants had the following suggestions for how to begin making plans for the Nano Library:

1. **Harmonize the creation of new nanodatabases.** This will allow information to be easily shared and transferred among databases and will link new nanodatabases with important existing ones in other fields. It will require that the nanotechnology community establish universal standards for reporting data.

2. **Organize Nano Library planning workshops.** These meetings would bring together scientific, technical, policy and other user groups and experts to discuss new ways of employing and adopting cutting-edge advances in informatics. The meetings would also help lead to the adoption of standards related to data collection, storage and display.

3. **Develop simulations that connect physical and biological data.** This will lead to more-unified models that incorporate information from the physical and biological worlds. It will also encourage the expansion of existing databases outside the field of nanotechnology to include more data from the nanoscale.

The Nano Workshop

Researchers are enthusiastic about new tools and knowledge, but what really motivates them is the prospect of building novel things at the nanoscale—that is, designing molecular structures, coaxing atoms to go where they want them to and assembling new kinds of materials that perform specific tasks, such as monitoring blood sugar, delivering insulin or harvesting light energy. Creating complex nanostructures that can form nanosystems when put together is the true frontier in domesticating atoms. "Designing new things that do new things—that is the spirit of nano," as one chemist put it. And it is at the center of all potential applications.

"We have about 100 kinds of atoms, and right now 20–25 are frequently used. One should be able to use all of them in various arrangements at the nanoscale, exploiting their properties however we like."

—Mihail Roco, engineer and Senior Advisor for Nanotechnology, National Science Foundation

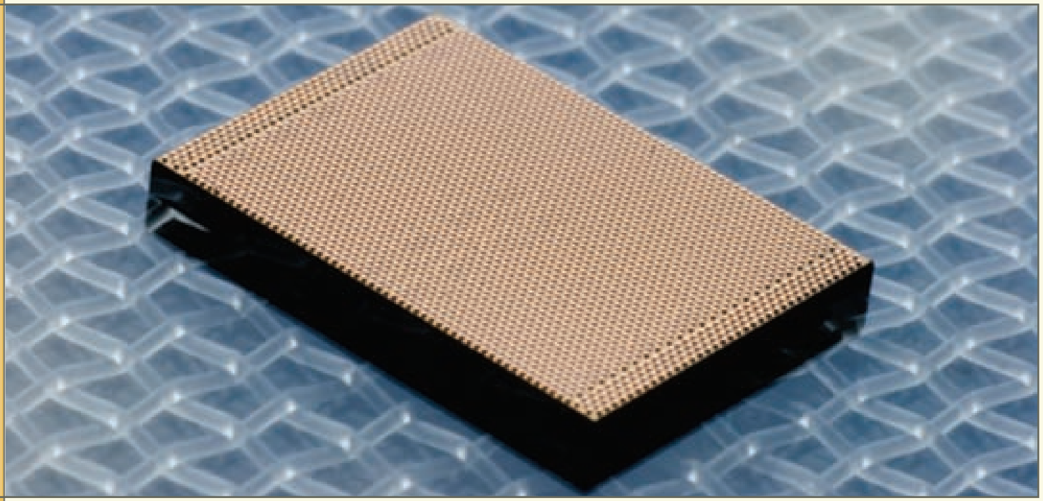
Although participants at NanoFrontiers expressed many views about how far we have come and how far we can go with nanoscale building, nearly all agreed that new capabilities were emerging as the result of a convergence of scientific disciplines. Chemists, who used to concern themselves with the bulk synthesis of materials, are now engineering specific supra-molecular structures. For instance, several laboratories are creating nanofilaments that have biological properties; in experimental animals, these materials appear to make blood vessels sprout and spinal cords grow. Biologists today are exploring ways to link the human nervous system to electronic devices, such as an artificial retina that would restore vision in the blind. Physicists and engineers, who once worked only with inorganic materials, are these days testing biological components—for example, protein microtubules—for use in electronics.

"Electronic devices are built from five simple units; life is built from 20,000 units and has emergent properties that come from its complexity. There is no reason that we cannot make new artificial systems by expanding five Legos to 20,000 Legos."

—Carlo Montemagno, bioengineer, University of California, Los Angeles

There is a synergy happening that is leading to bold new visions in nanotechnology. Toward this end, researchers at NanoFrontiers essentially asked for more Nano Workshops—places where scientists of various skills and perspectives could tinker with myriad pieces and learn how to assemble them into useful three-dimensional nanostructures. Such places could enhance the convergence of disciplines and enable scientists to develop new capabilities.

Using the Nano Toolshed and the Nano Library, a network of Nano Workshops could serve as foundries for producing nanoparticles, as engineering laboratories for designing, modeling and analyzing nanostructures and as prototype factories for manufacturing useful biomolecules and nanomaterials. NanoFrontiers participants noted during discussions of nearly every potential application that at the end of the day, the benefits of nanotechnology would be reaped only if there were breakthroughs in nanoscale building and manufacturing. And those would most likely occur in a Nano Workshop.



Computer chip containing nanomaterials

Credit: David Hawxhurst – Woodrow Wilson Center, 2006

For a start, some Nano Workshops might aim to bridge the gap between academic laboratories and industry by exploring ways to scale up production of nanostructures using cheap, controllable and stable manufacturing processes. Even computer-chip manufacturers—the leaders in making a nanoscale product—have far to go in nanomanufacturing. Several NanoFrontiers participants noted that their colleagues in the computer-chip industry walked past the breakout group on nanoelectronics and headed straight for the discussion on manufacturing. "They voted with their feet," observed one. When asked to explain this choice, one computer engineer replied, "We went to where the gap is—in manufacturing."

Of all scientists and engineers, computer-chip researchers know well the story of where we stand, as well as where we are heading, in nanoscale building and manufacturing. Currently, the most powerful microchips in computers contain a million transistors, and have features just 65 nanometers in size. These chips are made using "top-down" techniques, where materials are laid down on silicon in specific, controlled patterns using lithography. But engineers have now reached the physical limits of this approach. To make chips smaller—and computers more powerful—the industry must come up with additional ways to build at the nanoscale. They are experimenting with smaller parts, such as molecular switches and carbon nanotube wires, and with new ways to create smaller patterns at the nanoscale.

But the big challenge is putting together all the pieces—designing or discovering an architecture that is stable and functional, and assembling the pieces with precision. Part of that challenge is about bridging length scales, so that control at the scale of nanometers is preserved at the scale of centimeters. "It is hard to maintain accuracy over a span of seven orders of magnitude," noted one researcher. Many of the challenges confronting the computer-chip industry could stymie manufacturing of other complex nanoscale products, such as drugs, water filters and solar cells. Indeed, true nanomanufacturing has barely begun.

However, several new and promising approaches to nanomanufacturing are being developed. For instance, nanostructured catalysts might soon be employed to assemble or disassemble complex molecules, and even to work as components in a kind of "nanofactory." Researchers working on catalysis expect such systems to boost the efficiency of chemical reactions and to enable them to more precisely engineer structures at the nanoscale. Also on the near horizon is the ability to mass-produce "custom" nanoparticles with uniform shape. For instance, scientists recently invented one new technique by borrowing and adapting principles used in the electronics industry. Similar to injection molding, the method holds promise for making larger quantities of drug-delivery molecules, imaging agents and other useful nanoparticles as small as 20 nanometers.

"Nature controls shape and size exquisitely—for instance, in red blood cells and viruses. Can we steal those shapes derived from years of evolution and make them with precision and uniformity?"

—Joseph DeSimone, chemist, University of North Carolina at Chapel Hill

More radical advances in nanoscale building and manufacturing will require paradigm shifts in how we approach engineering, NanoFrontiers participants acknowledged. Taking a big step backward, one scientist asked, "To what extent can we *evolve* nanosystems rather than design them?" That is one powerful idea taken from nature, and the participants enthusiastically chattered about many others, including mimicking the cell's nanosystems: hemoglobins for shuttling oxygen, rhodopsins for detecting and responding to light, and ribosomes for assembling proteins. Said one chemist, "We have to understand the chemistry that biological systems use to make things." Said an engineer, "We need to learn how to make lifelike systems that are complex and adaptive."

Flat earth to whole earth. One paradigm shift that NanoFrontiers participants said they wanted to see is a move toward working in three dimensions. In the electronics industry, engineers build devices layer-by-layer on surfaces. They are stuck with a "flat earth" picture and a two-dimensional process. "We get none of the beautiful complexity you see in a tree or a virus; we need breakthroughs in concepts and tools," one chemist noted. Many of the scientists mentioned that they needed a "whole earth" view and the ability to do 3-D building. This would require new tools for studying hierarchical design. Engineers, who created the highly ordered microscopic landscapes of computer chips, might draw some lessons from the more fluid architectures of cells.

Bottom-up building. Many participants envisioned following nature's example by building things from the bottom up, from atoms to molecules to nanosystems. To do this, scientists might need to coax the construction process by creating the right conditions—in other words, by learning how to trigger a natural progression. On the simplest level, it is not unlike figuring out how atmospheric conditions could be manipulated to get the formation of certain kinds of snowflakes. This comes down to chemistry. A computer scientist predicted, "Our manufacturing in the future will definitely involve more sophisticated chemistry, such as this kind of self-assembly." In theory, this more advanced, bottom-up chemistry should be more efficient than top-down approaches and could enable manufacturers to reduce waste of raw materials and energy.

Still, learning how to do this will probably require decades of work in Nano Workshops, if it proves to be possible. Many mysteries remain. "Everyone talks about self-assembly, but no one can see it," lamented one chemist. "It will be very difficult to move into nanomanufacturing without tools to do that." A Nobel Prize winner commented, "We still have no technology to put carbon atoms where we want them. To solve self-assembly, we have a long way to go. It may be feasible, but how?"

Stochastic engineering. Even if researchers could learn to mimic nature's manufacturing methods, another challenge remains: how to achieve precision and minimize errors in the nanosystems they build. After all, products such as medical devices and electronics are not allowed to have many defects. "If we are going to build something that takes advantage of this self-assembly process and make it useful to society, we need to bring to that object reproducibility in how it will behave," noted a physicist. NanoFrontiers participants mulled over the intriguing idea of building systems that are continually changing, rather than static. Called "stochastic engineering," this approach would entail specifically designing nanosystems to function in spite of a relatively high level of defects. "Stochastic engineering is already one of our strategies, inspired by biology," said a computer scientist. "We can win by using redundancy and parallelisms in our components." Still, those may not be the only strategies employed by nature, and many mysteries remain. "Why *do* biological systems work so well, even without high precision?" one engineer pondered.

Adaptability. One answer could be that living things are, by definition, adaptable. So, one way to approach stochastic engineering would be to build devices that can change in response to the environment, and perhaps even evolve. "If we cannot get reproducibility in a device, then we have to make it adaptable," one physicist offered. That is how nature works. "Life is possible because it can be continuously corrected; it has molecular intelligence," a neurobiologist commented. "We do not have that now in our industry; we rely only on the intrinsic qualities of our materials and structures."

"Nature has already worked out solutions that follow well-established rules. We need to harness that, rather than force matter into ways that use a huge amount of energy."

—Martin Philbert, neurochemist, University of Michigan

While achieving adaptability might sound terribly difficult, researchers are making steps in that direction. "Smart" materials that make simple changes in response to the environment—such as becoming more or less porous—are being developed. And at least one research group has found a way to harness catalytic DNA to identify and remove errors—particles of the wrong size—in self-assembled structures made with gold nanoparticles. The next step would be to incorporate smart materials and repair capabilities into complex devices. An engineer suggested, "The key will be to merge sensing, information processing and communicating capabilities on a single platform—one that uses cellular architecture."

Some of these problems are being worked on in Nano Workshops recently established by the NSF at various universities and at national and state laboratories, as well as by private companies. However, some participants suggested that a large variety of workshops will be needed to jump-start advances. For instance, one participant said there is a need for a new kind of state-of-the-art Nano Workshop that marries the “clean room” used in computer-chip manufacturing with the typical organic chemistry laboratory.

NanoFrontiers participants suggested that Nano Workshops strive over the long term to:

1. **Understand how information flows in natural systems.** This will lead to insights regarding how biological systems achieve energy efficiency and will enable researchers to explore ways to harness evolution as a force for design and construction. This understanding will begin to yield new models of nanosystems.

2. **Cultivate new engineering techniques.** This includes an exploration of 3-D hierarchical design and the development of new mathematics to better characterize stochastic (that is, probabilistic) systems. These building techniques will help improve precision across length scales and eventually lead to bridges between the nano-, micro- and macroworlds.

3. **Adapt existing manufacturing methods to make other nanoscale products.** This includes improving interdisciplinary sharing of information and finding crossover uses for different engineering approaches. Over the long term, new techniques for nanomanufacturing, such as ways to increase the purity of nanomaterials used in nanoscale products, will have to be devised.

CRITICAL APPLICATIONS

Using Nanotechnology to Help Solve the Energy Crisis

In thinking about how nanotechnology might benefit society, nearly every NanoFrontiers participant—whether physicist, chemist, biologist or social scientist—pointed to energy applications. If there is to be a Nano Toolshed, a Nano Library and a network of Nano Workshops, it makes sense to use these resources to help meet what is arguably the biggest global challenge of the 21st century: providing a growing human population with reliable, clean, affordable energy. The need for energy bears on all other quality-of-life issues, including healthcare, national security and availability of water resources. If scientists do succeed in domesticating atoms, they could potentially revolutionize how we generate, store, distribute and use energy.

Although the NanoFrontiers meeting took place before U.S. gas prices climbed to more than $3 a gallon, participants discussed the energy issue under the reasonable assumption that the era of cheap fossil fuels was over. In a breakout group, several researchers noted that demand for energy was expected to grow as China and India industrialized; at the same time, global oil production would decline, while the climatic effects of burning fossil fuels would become more pronounced. This brewing crisis would probably lead to more political instability and warfare, they lamented. As one participant noted, energy was likely to become a "gun-to-the-head" issue.

Nanocrystals work as a filter, turning crude oil into diesel fuel

Credit: National Geographic

From this rather bleak scenario, conversations shifted toward the question of whether nanotechnology would likely help us get through the energy crisis and wean ourselves off fossil fuels. The answer was a resounding "yes." One chemist turned the problem around, saying, "High-priced oil will spur us to use nanotechnology to find energy alternatives, and it will pressure us to find ways to manufacture everything, including nanoproducts, using less energy." However, participants noted that nanotechnology alone could not solve the energy problem and that it should not be viewed as a savior. "We cannot afford to be nanocentric. Nanotechnology has to be integrated with everything else to really get at this problem," said one physicist.

"We need people—interdisciplinary teams—to do synthesis, engineering and explore the parameter spaces for each energy research area."

—David Dixon, chemist, University of Alabama

As another physicist put it, "The energy problem is bigger than nano." Societal factors will be crucial, in the view of a social scientist, who said, "A lot of people right now have their heads in the sand; they assume that technology will solve the energy problem, but no one seems to have a clue how to deal with the problem politically." A chemist noted, with exasperation, "We are still evolving a national energy policy; no one has agreed on what it is, and it is hard to see where nanoscience fits in." Others expressed concerns about recruiting and training enough young people for careers in energy research.

Still, participants lit up with hope as they discussed their visions for how nanotechnology could potentially contribute to energy solutions. "We could have talked for hours on this," reported the leader of the breakout group. Several people remembered and drew inspiration from a recently deceased colleague, Richard Smalley, a Nobel Prize–winning chemist who helped launch the field of nanotechnology with his discovery of carbon-60, "the buckyball," and who argued forcefully for confronting the energy crisis. Smalley called for a new "Sputnik generation" of scientists and engineers to come together and work on the "Terawatt Challenge," much as researchers did 50 years ago in response to the launch of the Russian satellite. In 2005, Smalley wrote, "There are three core problems that I think the president ought to address, all of which are connected with and impinge on the major issue of energy prosperity: inspiring the next generation of U.S. scientists and engineers, developing replacements for the dwindling fossil fuel resources that have provided the majority of our energy in the past and finding a solution to global warming. I believe that taking on these challenges would be a deeply moral and wise course of action."

Many NanoFrontiers participants seemed eager to carry forward this mission as they laid out a few possible scenarios. At the very least, most said, they expected new nanotools, knowledge and skills to be gradually absorbed and applied in numerous energy-related technologies, from light bulbs to fuel catalysts to batteries. Some of these advances might occur quietly and unspectacularly, but even small improvements could add up to big savings in energy usage, a historian commented.

High-impact developments could also happen, and perhaps soon. Many research groups and private companies are already exploring a variety of alternative energy sources, such as solar power, wind power, nuclear fusion, hydrogen fuel cells and biofuels and, as one person noted, each considers their approach a strong one. "We should focus on using nanotechnology to solve small problems that work toward all of these bigger goals," this engineer suggested. For instance, nanotechnology might provide a way to safely store hydrogen. "The requirements are well known, but no material we have now fulfills them," explained a materials scientist. "We need new materials with the right properties. By using nanostructures and by doping materials with catalysts, we could get there." Still, no alternative energy sources will probably emerge as the "silver bullet," said one chemist. "There is no one good source of energy; we need to look creatively at all options."

"We need to solve the problem of efficient thermodynamics. There are many examples, such as molecular motors, where biology has demonstrated it. Can nanotechnology allow us to do something similar?"

—Arun Majumdar, engineer, University of California, Berkeley

Eventually, nanotechnology might lead to radical transformations in energy technologies, but these are difficult to foresee. Participants offered several grand challenges to consider working on. An engineer pondered, "Could nanotechnology be directed toward bringing carbon dioxide [the major cause of global warming] back into the energy cycle? Perhaps there's a way to use a photocatalytic process to convert it into methane [which could be used as fuel]?" A chemist mentioned the groundbreaking possibility of efficiently splitting water molecules to generate hydrogen fuel. A physicist noted that perhaps nanotechnology would finally lead to room-temperature superconductivity, and thus, super-efficient wires for transporting energy.

Several others suggested that radically new ideas for how to harness energy would come from studies of living creatures—for instance, from learning about the way plants generate energy from sunlight and the way animals produce energy broadly throughout their bodies using their cells' mitochondria. Indeed, some researchers are already attempting "artificial photosynthesis." A biologist commented that nanotools might help researchers create artificial life forms that resemble simple bacteria and then employ these creatures to produce fuel for human use—another idea currently under investigation.

To begin a journey toward solutions, scientists generally like to break down a problem into well-defined technical challenges. NanoFrontiers participants gravitated toward this approach. They suggested striving for four important research goals: efficient energy conversion, efficient energy storage, efficient energy transmission and efficient energy use. The overarching theme was to reduce energy losses at every step of the way, and they envisioned a short-term and a long-term strategy to accomplish this. For the next 20 years, they said, researchers could aim to maximize the efficient use of fossil fuels and thereby soften the energy crisis. Over the next 50 years, researchers could aim to develop completely new ways of generating, storing and distributing energy efficiently.

Interestingly, these scientists saw themselves standing before a vast frontier, when it came to energy applications. They estimated their knowledge stood at just 10 percent of the total that is relevant, and they said that much exploring remains to be done.

Efficient energy conversion. Energy is all around us, but often inaccessible. We must grab hold of it and convert it into a usable form. Currently, we extract chemical ener-

Solar panels can become more energy efficient using nanotechnology

Credit: David Hawxhurst – Woodrow Wilson Center, 2006

gy from coal, oil and natural gas because these energy-rich materials come in convenient forms. These are also relatively easy to transform into a range of products, including formulated fuels, and into electricity that can be widely distributed by power lines. As fossil fuels grow scarce and increase in value, nanotechnology could be used to reduce losses during energy conversion. For instance, nano-engineered catalysts could improve the conversion of crude oil into various petroleum products, as well as the conversion of coal into clean fuels for generating electricity.

Over the long term, the breakout group suggested that it would be wise to improve our ability to convert sunlight into electricity, the easiest form of energy to use. Common commercially available solar cells have an efficiency of about 12 percent; some laboratory models achieve 30 percent. Researchers are testing many different ways to boost energy conversion by fine-tuning the material properties in solar cells, and it is quite likely that the problem will be solved using nanotechnology. Some prototypes have embedded carbon nanotubes in them, while others take advantage of nanocrystals or clusters of atoms called quantum dots. However, NanoFrontiers participants commented that they still understand little about the fundamental processes behind various energy conversions, including sunlight to electricity, heat gradients to electricity and nuclear fusion to electricity. Said one engineer, "We need tools that will allow us to interrogate our conversion questions."

Efficient energy storage. Once energy has been made available, it must be stored so that it can be used as needed. In the near term, nanotechnology could be used to create appliances and other products that can store energy more efficiently—that is, take up charge and hold it over time. Many research groups are working on better batteries, often using engineered nanomaterials. "Energy storage is a very good problem for nanotechnology to attack in the short term, partly because issues of complexity may not be important," said one physicist.

Batteries as a common means of energy storage are lasting longer with advances in nanotechnology

Credit: David Hawxhurst – Woodrow Wilson Center, 2006

Better batteries might make it possible to store energy that is generated in a widely distributed way, such as within consumer products. That would eliminate the need to ship energy across thousands of miles and solve the problem of losses during transport. This vision of a broadly distributed energy grid captured the imagination of Richard Smalley, who wrote of the need to develop small-scale energy-storage units that could be located in people's homes. He believed that such an appliance might be developed using nanotechnology. With energy-storage units that are small, efficient and affordable, communities could buffer themselves against fluctuations in energy availability, such as when the sun stops shining or the wind stops blowing. "Local energy storage would get us past that problem and give us an extremely robust, terrorist-resistant, delocalized electrical-energy system," Smalley wrote.

Efficient energy transmission. For now, energy is not typically generated right where it is needed, so we must have ways to transmit it. Nanotechnology could be used to create new kinds of conductive materials that lose very little energy as electricity moves down the line. Many research groups are investigating whether nanowires and nanocoatings could reduce losses in electrical-transmission lines. One participant mentioned that "self-cleaning" nanomaterials might be used to keep ice from accumulating on power lines—something that leads to disruptions in power every winter. In the longer term, the need for efficient energy transmission might disappear if energy is converted and stored locally.

Efficient energy use. Nanotechnology could lead to breakthroughs that indirectly conserve large amounts of fossil fuels. A chemist noted that 10 percent of the U.S. oil budget goes toward producing nitrogen fertilizers for agriculture. "Few people realize that we are burning oil in eating," he said. "If we could find a way to fix nitrogen from the atmosphere, we could save huge amounts of fuel." Nanomanufacturing might also enable us to make all kinds of products using less energy. For instance, nanosensors might be used to track energy use and help minimize waste.

In every case, though, new processes, products and alternative energy sources will need to be thoroughly evaluated, the breakout group emphasized. Said one physicist, "It is important to avoid well-meaning but thoughtless applications and to always ask, 'How clean is this new technology?'" The breakout group suggested that it is important to consult with the people who might benefit or bear the costs of a new energy technology.

Using Nanotechnology to Revolutionize Medicine

One of the hottest areas of research is nanomedicine, so it is perhaps no surprise that NanoFrontiers participants pointed to it when asked how nanotechnology could benefit society. Nanotechnology, all agreed, stands a good chance of revolutionizing the practice of medicine. And radical changes might be what are needed to handle an onslaught of aging Baby Boomers—including many of the scientists at the meeting—who will soon need everything from hip replacements to insulin-monitoring kits to Alzheimer's treatments. There is a growing demand for healthcare, and it makes sense to use the Nano Toolshed, Nano Library and a network of Nano Workshops to create a new and improved generation of medical treatments and devices.

If scientists domesticate atoms and molecules, they could harness them for a wide range of medical purposes. For one thing, they could create novel nanostructures that serve as new kinds of drugs for treating common conditions such as cancer, Parkinson's and cardiovascular disease. They could also engineer nanomaterials for use as artificial tissues that would replace diseased kidneys and livers, and even repair nerve damage. Moreover, they could integrate nanodevices with the nervous system to create implants that restore vision and hearing and build prosthetic limbs that better serve the disabled. When you consider that one-third of all Americans are Baby Boomers—and that many others already suffer from degenerative disease—it is clear that advances in nanomedicine could help vast numbers of people maintain their health, their independence and their participation in society.

"The most compelling home run for nanotechnology would probably be in healthcare. Americans believe in technology when it's used in healthcare."

—Davis Baird, philosopher, University of South Carolina NanoCenter

With nanotechnology, drugs can target specific cells in the body

Credit: Belinsky Yuri

A large contingent of scientists who came to the NanoFrontiers meeting joined an animated conversation about future scenarios for nanomedicine. There was plenty to talk about, because medical applications of nanotechnology—more so than energy applications—are already rapidly developing. Many companies, including pharmaceutical giants, medical-device makers, biotech companies and start-up ventures, are now exploring and using nanotechnology for healthcare applications.

Indeed, in January 2005 the first drug to employ nanotechnology was approved by the U.S. Food and Drug Administration (FDA). Called Abraxane, this nanomedicine was made by loading the drug Taxol into nanoparticles of albumin, a protein that is plentiful in human serum. In this formulation the drug appears to be less toxic than regular Taxol and more effective in treating metastatic breast cancer. The FDA is now reviewing another 130 or so nano-enhanced drugs in the pipeline. Like Abraxane, these first-generation nanomedicines are mostly reformulations of existing drugs, and they often use new methods of delivery within the body. Researchers are currently testing everything from buckyballs to nanocapsules to dendrimers as vehicles for efficiently ferrying drugs in the body, particularly for delivering chemotherapy agents to tumors.

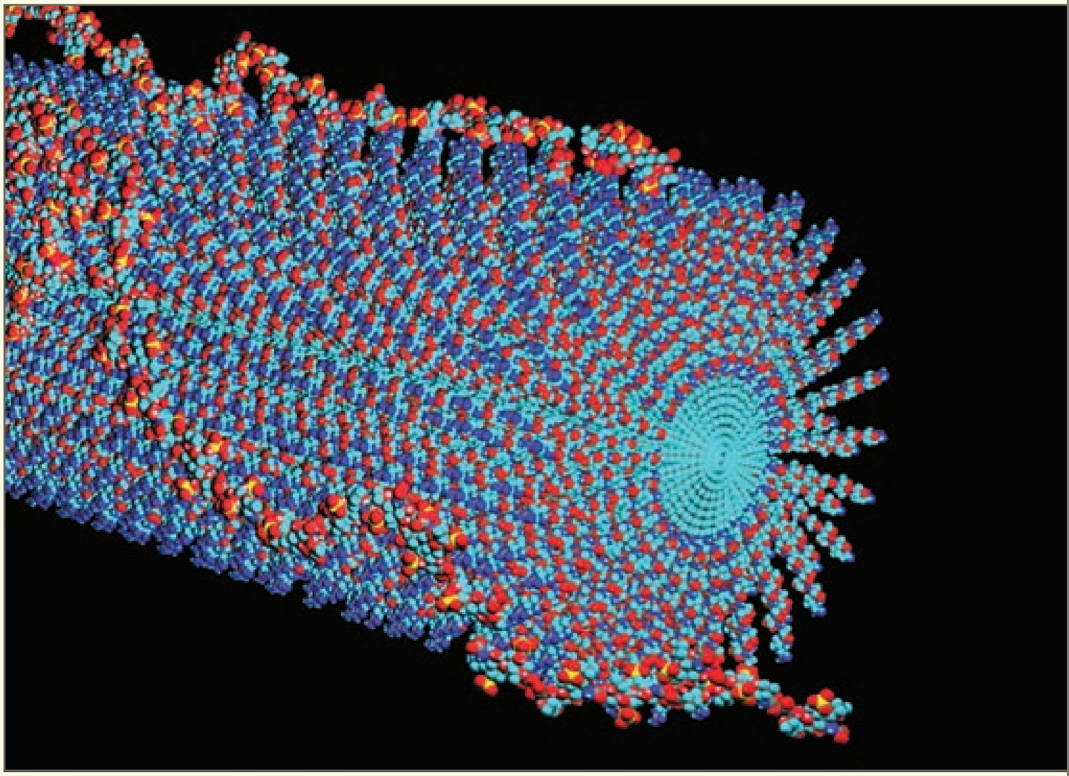
Given this starting point, the question before the NanoFrontiers group was not so much whether nanotechnology could or would have an impact on medicine, but rather how all the developments might add up to alter the practice of medicine. To answer that question, it is helpful to look at a time line of likely advances, and NanoFrontiers participants laid these out. First on the horizon, they said, they foresee a broad array of new methods for disease diagnosis based on nanotools for imaging tissues and for analyzing blood. "The critical 10-to-15-year challenge will be to start doing disease diagnosis using biomarkers and imaging, and to do it earlier," said one clinical investigator. For instance, a diagnostic kit that employs gold nanoparticles is being tested in hospitals for use in detecting prostate cancer early, at a stage when the numbers of protein biomarkers in the blood are quite low. Nanoparticles are also useful as high-resolution contrast agents; using them in tissue imaging will enable doctors to spot tumors and other kinds of trouble with greater precision. New nanobased diagnostic tests could save lives, as early diagnosis of any disease increases the chances of a patient's survival.

In two decades perhaps, NanoFrontiers participants predicted that kits would become available for continual monitoring of certain biomarkers, for instance, LDL cholesterol—the bad kind that clogs arteries—in patients who have had heart attacks. A life scientist described a second-generation device for diabetics: "You will be able to non-invasively monitor glucose status in real time and make nanoscale adjustments in response, in real time." During this same time period, artificial tissues could become important for treating disease. For instance, researchers have engineered a variety of scaffolds made from nanotubes and nanofibers that can be used to grow lifelike networks of cells from the liver, bladder, kidney, bones and cardiovascular system. These artificial tissues could be developed into new therapies for patients with diseased or damaged organs.

> "There is always a push by innovators and a pull by users. Technologies that succeed cross that chasm."
>
> —Mostafa Analoui, Senior Director of Global Clinical Technology, Pfizer Inc.

Further out in the future, expect to see entirely new kinds of treatments, including drugs designed from the bottom up, one chemist said. "To interact effectively with the body, you need crafted, artificial nanostructures," he said. Such molecules could potentially target a specific problem in the body with much greater accuracy than current small-molecule drugs. Although the research is still exploratory, several groups of scientists are beginning to build novel nanostructures that mimic complex biomolecules. Some of these appear to have regenerative powers and might lead to therapies for untreatable conditions such as Alzheimer's, nerve injury and brain damage from stroke.

Quite a few decades from now, several researchers noted, it will probably become possible to create interfaces between the nervous system and electronic devices. These nanoscale links would make it possible to essentially "plug in" human-made machines to the body—for instance, prosthetic legs that truly function like one's own. "A lot of soldiers with injuries could benefit from this, because the treatments we now have are not very good," said one neuroscientist. "Learning how to stimulate muscles more effectively would be a superb breakthrough," he noted, but it will also take advances in robotics and information science to generate intelligent walking properties. An engineer mentioned his goal of understanding signal processing in the nervous system. Such breakthroughs might seem hard to imagine, but they are expected to happen because many research groups from a variety of disciplines are working on these problems. And we already have the cochlear implant to restore hearing in the deaf, so perhaps it is not so far-fetched to develop an artificial retina to restore vision, which several groups are trying to develop. "I do not see any reason why we can not figure all this out," said an engineer.

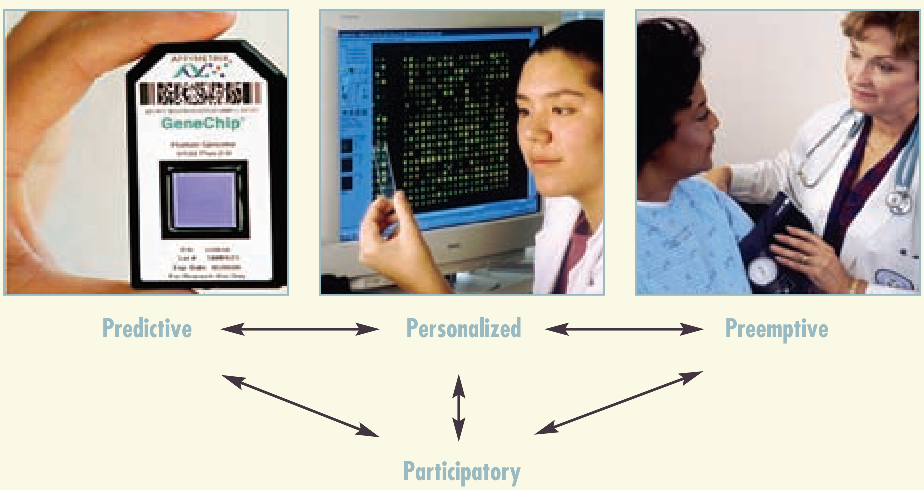


Computer model of a nanomotor

Credit: Samuel Stupp, Northwestern University

In this most distant scenario, interfaces between neurons and electronic devices would also make it possible to develop a wide variety of brain implants. At first, these would undoubtedly serve to improve treatment of diseases with root causes in the brain, such as Parkinson's disease and epilepsy. Implants might also be developed to replace parts of the brain damaged by stroke or injury, or to fine-tune imbalances that cause severe depression and other mental illnesses. Eventually, implants might be used to enhance normal brain function—for example, to boost memory and learning. At each step there is likely to be a lot of soul searching and debate about the ethics of these interventions and about what it means to be human, several participants noted. "People accept that you can use a piece of metal to replace bone, but the public might not be ready for replacements affecting the higher orders of brain function," noted an engineer.

Underlying these conversations about nanomedicine—from the present to the far future—some themes emerged. NanoFrontiers participants often referred to four distinct revolutions in medicine, and envisioned that nanotechnology could play a role in driving any or all of them. That is, nanotechnology could be used to make medicine more predictive, preemptive, personalized and participatory (regenerative).



Nanotechnology may aid these four visions for the future of medicine

Credit: Elias Zerhouni, NIH

Predictive medicine. In this vision, which participants discussed in great detail, nanotechnology would help doctors predict the major diseases that an individual is likely to develop. The goal would be to routinely and cheaply analyze several hundred substances in a patient's blood and estimate disease risks with a relatively high degree of accuracy. Viewed from another angle, this panel of tests would provide a window on a person's overall state of health. Several research groups are in fact working on developing a "lab-on-a-chip" device—using nanotechnology—to perform a comprehensive analysis of a drop of blood. The blood analysis would alert the doctor to early precursors of disease that reflect both genetic predispositions and environmental factors, such as diet, exercise, stress and exposure to air pollution.

Predictive medicine sounds incredibly promising, but developing such a comprehensive test might prove to be exceedingly challenging. First, researchers would have to identify the 200 or so most important disease biomarkers. That is a challenge, but given current advances, probably doable. Next, although scientists would not have to understand every last detail about each biomarker and its role in disease, they would have to know how the levels of each biomarker vary normally and in various stages of disease. Those patterns could be identified only by trolling though huge amounts of data collected from a broad population sample. And the computations would be extraordinarily high level, requiring fancy mathematical tools that have not yet been invented. "I think we are underestimating the complexity here," noted one clinical investigator.

Some NanoFrontiers participants suggested that predictive medicine might also prove to be unpopular. "When it comes to predictive medicine, researchers may love it, but it often looks like surveillance to the public," a bioethicist noted. Another social scientist offered the opinion that the American public would never support the widespread gathering of personal data on their health risks because the information could be used to deny them health insurance. Universal healthcare, suggested a proponent of predictive medicine, might help get around this problem.

"If the rate of information acquisition outpaces the rate of therapy development, you come to a big problem, a reality crush. You will find out your health risk and then be depressed the rest of your life. If we do not make an equal investment in therapies, we will be doing the wrong thing."

—Samuel Stupp, chemist, Northwestern University

Others argued that predictive medicine stops short, because not enough therapies would be available. That problem already vexes some patients today. For instance, a genetic test can tell you that you are at high risk for Huntington's disease, but you cannot do much to stop the progression of this incurable neurological disease. Said one neurochemist, "What if nanotechnology allowed us to extract vast amounts of information that we will not know what to do with? That would be completely disenfranchising."

In fact, this scenario might be just around the corner. An expert on instrumentation suggested that new nanopore devices are poised to make complete genome sequencing rapid, cheap and widely available. That means it will be possible for individuals to find out the sequences of all their genes, including those linked to disease. "If I had to single out one big impact of nanotechnology that is coming soon, rapid DNA sequencing is it," he said. "It will totally change medicine, raising issues of how to handle genetic and risk information." It remains to be seen whether or not the public will embrace personal genomic sequencing, and whether or not it might pave the way for predictive medicine or derail it.

"We need to transform medicine by making healthcare more predictive, preemptive and personalized."

—Elias Zerhouni, Director, National Institutes of Health

Preemptive medicine. This vision focuses more on early intervention, but also requires early diagnosis. Here the idea is to help doctors detect treatable diseases earlier so that they can help patients preempt the full-blown development of illness or at least manage it effectively over a lifetime. Nanotechnology can enhance the development of more- sensitive diagnostic tests, as well as devices for health monitoring and disease management.

NanoFrontiers participants were very interested in preemptive medicine, and mentioned diabetes care as one obvious and important area that would stand to benefit from it. Consider that if new, nanobased diagnostic tests could detect in you the earliest stages of insulin resistance, you could make changes in your diet and exercise to slow the progression of the disease. A health-monitoring device at home could help you maintain your regimen by providing positive feedback on your blood sugar levels. Perhaps you could even delay or completely prevent the onset of diabetes. But if you did at some point need to take insulin, home monitoring could also help you manage the dosage and timing more effectively.

Similarly, preemptive medicine might be used to help a large portion of the population more effectively deal with cardiovascular disease and hypertension. This model could be expanded and used to manage many chronic diseases—say, for example, lupus or arthritis—as new diagnostic tests, monitoring capabilities and therapies became available.

"Drugs of the future will be three, four or five compounds that will manipulate networks of systems in the body."

—Leroy Hood, biologist and founder, Institute for Systems Biology

Personalized medicine. The vision to make medicine more personalized comes from the notion that information about an individual can be used to specifically tailor his or her treatment. A doctor has a much greater chance of coming up with an effective medical strategy if he or she knows something about a patient's disease subtype, metabolism (particularly as it relates to drugs), liver status and risk for other diseases, for example. Nanotechnology could provide new tools for gathering detailed information about variations in disease states and about unique parameters of treatment.

Perhaps more important, nanotechnology could spur the personalized-medicine revolution by helping bring about real-time, sensitive monitoring of drug therapies. With more frequent feedback, a doctor could easily adjust drugs and dosages to personalize a patient's therapy. Indeed, treatments are expected to become more complex in the future, several participants at NanoFrontiers noted. For instance, a doctor might prescribe a cocktail of several different drugs in calculated proportions—perhaps 10 percent of drug A, 50 percent of drug B and 40 percent of drug C. Nanobased monitoring devices could give doctors the ability to adjust the drug cocktail to suit the individual patient.

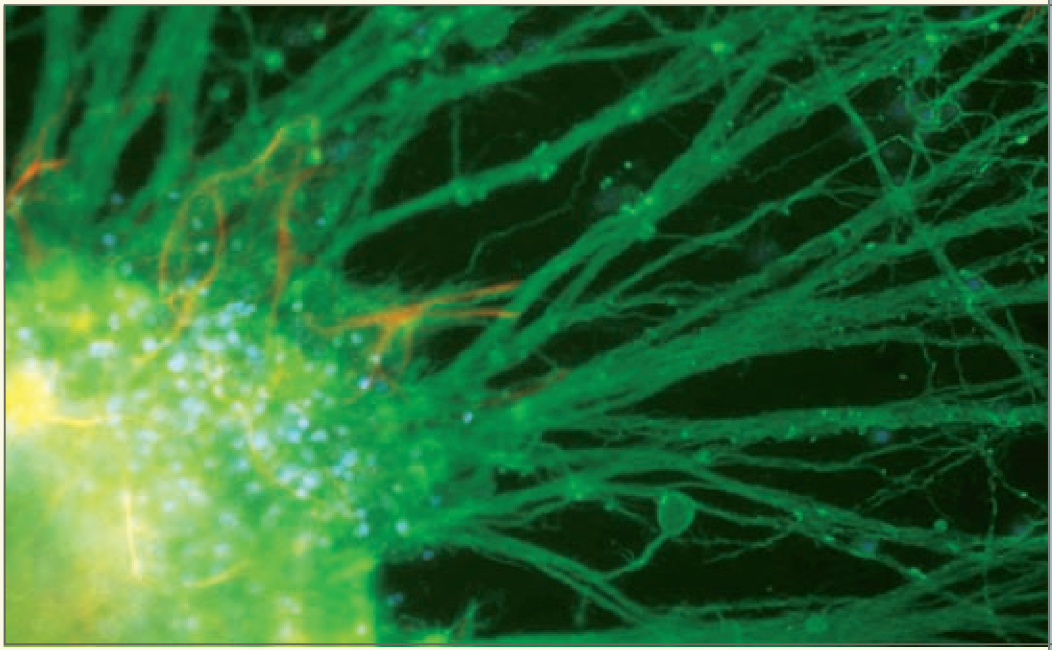
"Personalized medicine will probably be expensive. Who is going to pay for it? Who will benefit from it?"

—John Ryan, physicist and Director, Bionanotechnology Interdisciplinary Research Centre, Oxford University

Participatory (regenerative) medicine. Excitement about the potential for regenerative medicine has generally focused on stem cells, but nanotechnology could also lead to radically new treatments for spinal cord injury, macular degeneration, type 1 diabetes and other dysfunctions. The goal, in all these cases, is to regenerate a part of the body that has been injured or has deteriorated as the result of disease, genetic defects or normal aging. Whether stem cells can be coaxed to rebuild tissues and restore function remains to be seen, but an equally promising approach is to employ nanostructured artificial tissues.

It is still early, but many laboratories are experimenting with a wide variety of nanomaterial scaffolds that can be infused with cells to form artificial tissues, such as bone and liver. It appears possible to repair damaged nerves by injecting them with nanomaterials that form bridge-like lattices. Other nanostructures show promise as foundations for growing three-dimensional networks of blood vessels.

Regenerating damaged tissues is one approach, but lost function might also be restored using nano-enhanced replacement parts for the body—devices that hook right into the nervous system. Although science fiction writers and moviemakers have explored this idea in many colorful ways, NanoFrontiers participants discussed a more serious vision that could indeed become reality as the result of rapid advances in nanotechnology, microelectronics, robotics, information science and neuroscience.



Nano-scaffold for nerve regeneration

Credit: Samuel Stupp, Northwestern University

No one doubts that new and better prosthetic devices for the disabled are on the horizon, and that tools for helping people walk, communicate, hear and see again are worthwhile aims of nanotechnology. But we will eventually cross into murky territory, where it is no longer clear that we are fixing what is broken. Then there will be important questions for societies to debate: Which parts of the body are acceptable to replace, and which are not? Should people be allowed to acquire super-human capabilities, such as infrared vision? Would a brain implant change who a person is? Would we still be human if we boosted our ability to learn?

"One of the highest callings of humankind is to develop prostheses that improve the quality of life for our fellow human beings who have been disabled."

—Ralph Cavin, engineer, Semiconductor Research Corporation

Many NanoFrontiers participants expressed concerns that public discussion about these issues will be difficult. Several voiced worries that some groups in society might embrace personal enhancement or have much greater access to enhancement technologies, while other groups would resist them or not be able to afford them. This could create new divisions between "haves" and "have nots." A government scientist noted, "No country—of 27 surveyed—has any regulations or laws in place regarding converging technologies and human enhancement." A public conversation about enhancement seems inevitable, but has not yet begun in earnest.

For now, a large percentage of Americans do seem to be hoping for new therapies that repair the body and restore lost function, according to public opinion polls and as suggested by the fact that Californians voted to support investment in an Institute for Regenerative Medicine. It seems that the sky is the limit on what might one day be accomplished with nanostructured artificial tissues and nano-enhanced prosthetic devices. In the meantime, researchers developing them will have to grapple with concerns about biocompatibility—that is, making sure that the materials are not toxic and do not trigger harmful immune reactions. Some participants at NanoFrontiers expressed confidence that these challenges could be surmounted and that nanotechnology would help bring about a golden era of regenerative medicine.

Using Nanotechnology to Produce Clean Water

Nano-enhanced technologies can generate clean water for safe drinking at point of use

Credit: Karen Kasmauski

A subgroup of NanoFrontiers participants argued that nanotechnology could potentially revolutionize clean-water technologies and that this will be a critical application. These scientists pointed out that water resources are essential to life and crucial to our standard of living, greatly affecting our ability to maintain health, grow food and build vibrant industries. One engineer noted that water and energy issues were intertwined: "In the First World, people tend to focus more on the energy crisis, but in the Third World they focus more on the water crisis," he said. "At a certain point, these will intersect. If you address the energy problem, it can also help you solve the water problem, and vice versa."

The researchers said they see fresh opportunities to create nano-enhanced technologies that will help generate more clean water for the world's growing population. With a Nano Toolshed, a Nano Library and a network of Nano Workshops, scientists could launch innovative efforts to improve water purification, prevent water pollution and clean up tainted groundwater, lakes and streams. If scientists domesticate atoms and molecules, they would be able to efficiently corral pollutants and drive them out of water and into places where they do no harm. Even better, nanotechnology could be used to transform these unwanted materials—essentially atoms and molecules in the wrong place—into something harmless or useful.

This NanoFrontiers breakout group began its deliberations by reviewing the argument that clean water is an urgently needed resource. Demand for water outstrips supply in many parts of the world, even fueling war at times. The United Nations estimates that one-fifth of the world's population lacks access to safe drinking water. Climate change is expected to further strain water resources by shifting precipitation patterns and causing severe drought in some regions; indeed, much of the central United States is currently experiencing a record-breaking drought. A climate model from the U.S. Pacific Northwest National Laboratories recently estimated that by the next century, mountains in the Sierras, Cascades and Rockies would maintain only 57 percent of their snow pack, the main source of drinking water for the western United States. At the same time, many communities that rely on groundwater are withdrawing it faster than it can be recharged, particularly in the midwestern agricultural belt.

Water woes also afflict communities with plentiful supplies. In these places, the problem is poor water quality. Consider, for instance, Washington, D.C., where old pipes have leached unsafe amounts of lead into the water that flows from the treatment plant to taps in homes and schools. Groundwater—prehistoric in origin and as pristine as water gets—has also been widely contaminated; for instance, perchlorate used by southern California's aerospace industry seeped underground and spread throughout aquifers. Removing contaminants from water is now a routine, but costly and imperfect, process.

Clean water is also vital to industry, and not just to food and beverage manufacturers. The computer and electronics industries require ultra-pure water to make their high-tech products. Many chemical and pharmaceutical manufacturers have been reducing their use of toxic solvents and turning to water-based processes. And as one participant noted, "Nanomanufacturing is also going to require more pure water. How will they manufacture nanoparticles? They will do it using water. If anyone suggested using toxic solvents, they would be run out of town."

To many NanoFrontiers participants it seemed clear that a powerful strategy for boosting the availability of clean water would be to exploit nanotechnology. A physicist suggested that there were three goals that could be tackled: "We could use nanotechnology to determine if water is clean, to enable the filtration of dirty water and to reduce water use, particularly in industrial processes." A chemist added a fourth goal: using nanotechnology to clean up polluted bodies of water.

Researchers can already point to nanomaterials that could be harnessed to enhance existing water-purification processes. Because nanosize particles have a high surface area and can be chemically tailored, many show great potential as sorbents, materials that latch on to pollutants and pull them out of solution. For instance, multi-walled carbon nanotubes have been shown to take up lead, cadmium and copper more effectively than does activated carbon, a commonly used sorbent. Some nanoparticles also act as potent catalysts and could be used to render pollutants harmless. Nanosize iron, for example, can detoxify organic solvents, such as trichloroethylene. Other nanoparticles that are bioactive, such as silver and magnesium oxide, can kill bacteria and might be used in place of chlorine to disinfect water.

Perhaps most impressive would be if nanotechnology led to new water-treatment capabilities—a goal that looks to be well within reach. Nano-engineered membranes and filtration devices could be used to detect and remove viruses and other pollutants that are difficult to trap using current technologies. For instance, a preliminary technique employs imprinted polymer nanospheres to detect pharmaceuticals—a kind of pollution coming from households that is difficult to spot in waterways and was only recently discovered. Such nanoscale sensors might be helpful for real-time monitoring of these pollutants—everything from chemicals in Prozac to hormones in birth control pills—at water-treatment plants and industrial sites. Eventually, "smart" membranes with specifically tailored nanopores might be designed to both detect and remove such pollutants. With greater ability to filter out unwanted materials, industrial wastewater—and even the ocean—could become available to boost the supply of clean water.

"Nanotechnology offers the promise of cleaning up pollution problems from the past. But its biggest impact could be in pollution prevention—in helping us to do and make things in a clean and green way."

—Barbara Karn, chemist and visiting scientist, Woodrow Wilson International Center for Scholars

Several scenarios for the future of nanobased water technologies were laid out. In the near term, participants said they expected to see new techniques for remediation of water pollution. Many exploratory projects have already been launched with research grants from the U.S. Environmental Protection Agency (EPA) and the NSF. One of the most promising examples is zero-valent nano-iron, which is being tested for use in removing solvents from pumped groundwater. Another new method may prove valuable for cleaning up polluted lakes and streams. Titanium dioxide nanoparticles could potentially be sprinkled into a contaminated body of water, where they would be activated by sunlight to degrade PCBs and dioxins.

In another decade or so, nanotechnology is expected to have an impact on water treatment, beginning with nanosorbents and bioactive nanoparticles that could be integrated into existing purification systems. These first hybrid technologies would eventually be replaced by entirely new kinds of devices that use nanotechnology to improve the efficiency of filtration, remove more kinds of contaminants and add functions, such as water-quality sensors. Research groups are currently investigating a wide variety of nanomaterials—including carbon nanotubes, zeolites, dendrimers and metal-oxide nanoparticles—for use in such devices. Ultimately, a single membrane might be made to perform multiple tasks—for instance, detect, separate out and detoxify a contaminant. If researchers could develop a suite of smart membranes that perform many different filtration tasks, water-treatment plants could mix and match them to address specific needs. To achieve this, participants said, basic research to develop new and improved catalysts and membranes must be pursued over the long term.

Additional research challenges also need to be met before nanomaterials could be successfully used in water treatment. First, the nanomaterials would have to be fully evaluated for safety, including examining their toxicity, their transport, and their fate in the environment. If a nanomaterial passed the safety test, then it would need to be available in large quantities so that it could be incorporated into filtration devices. Methods for efficiently scaling up production of these key nanomaterials are not yet available, and that could put the brakes on clean-water technologies, some NanoFrontiers participants suggested. Moreover, the manufacture of nanomaterials, the use of the new water technology and finally the disposal of the removed contaminants will all need to be energy efficient and generate few, if any, additional pollution problems. NanoFrontiers participants acknowledged that those are big challenges, which might cause clean water technologies to arrive after, rather than before, many other nanotechnology applications.

Nevertheless, participants described several compelling visions for using nanotechnology in clean water technologies:

Desalination. One way to expand the availability of drinking water in coastal communities is to turn to the sea. Technologies for removing salt from seawater already exist, with desalination plants operating in the Middle East and one nearly ready to start up

Nanotechnology energy application may improve water desalination capabilities

Credit: Flip Chalfant

in Tampa, Florida. New plants are also being planned for several sites in California. The trouble with desalination is that it currently requires a lot of energy, so it is costly and all but guaranteed to grow more expensive in the future.

There is a critical need to design alternative desalination methods that are more efficient. That is why the U.S. Bureau of Reclamation and Sandia National Laboratories have announced a key long-term goal in their Desalination and Water Purification

Roadmap: by 2020, they aim to develop smart membranes with antimicrobial surfaces and embedded sensors that can automatically adjust membrane performance. Nanotechnology is likely to play an important role in meeting that challenge. New energy technologies that exploit nanotechnology might also have an impact on desalination.

Personal water treatment. To really have a global impact on the availability of clean drinking water, new technologies will be needed to treat water at its point of use. That is, people should have at hand a device that enables them to purify water at the tap, at the well, or in their residences. The idea is to dismantle the current model of centralized water-treatment plants and to replace it with small, strategically placed treatment systems that meet the water needs of population clusters. Such satellite treatment systems would be particularly useful in developing countries, where big plants are still rare and there is a tremendous need for cost-effective ways to bring clean drinking water to communities. Small-scale water-treatment systems, it has been suggested, would also make less attractive targets for bioterrorists than would big plants.

Community-based water treatment would be most effective if it could be customized to remove the specific contaminants found in a local water source. That would most likely require nanotechnology. Nanosorbents, nanocatalysts, smart membranes, nanosensors and other kinds of nanotechnology could serve as the basis for new, small-scale water treatment systems. The goal of personal water treatment might actually prove easier to reach than the goal of integrating nanotechnology into existing centralized water treatment plants operated by public utilities, one participant noted.

"This is my dream: a novel water-treatment system for personal use and which could be made cheaply and distributed throughout the world. Something like that cannot be done without nanotechnology."

—Mamadou Diallo, engineer, California Institute of Technology

Emerging pollutants. Unfortunately, new kinds of pollutants are being continually discovered in water resources, even while we still deal with old problems such as lead, pesticides and *E. coli*. Waterways now contain trace quantities—which have obviously added up—of personal-care products such as sunscreens, medicines of all kinds and flame retardants and plastic residues that slough off consumer products. Some of these materials have been shown to have deleterious effects on fish and other wildlife, and they might also cause subtle health effects in people.

Water-filtration technologies have not kept pace with emerging pollutants; no methods are currently available to remove most of them. Nano-enhanced water filtration could be developed to target these new contaminants. Moreover, as one physicist put it, "This could become even more important to do if new, nanomedicine-based pollutants started to enter the water supply." Advanced methods of water purification using nanotechnology might prove to be the only viable strategy for keeping a wide variety of nanomaterials off the growing list of emerging pollutants.

CONCLUSION

A Final Note from the NanoFrontier

At the end of the NanoFrontiers meeting (and in conversations afterward), I sensed that many of the researchers felt renewed excitement about the future of nanotechnology. They were eager to get back to their labs, make new discoveries about the nature of matter and explore the possibility of applying their knowledge and skills to solve important societal problems. Participants expressed delight at the opportunity they had been given to meet colleagues from other fields, to have a sincere dialogue with the director of NIH and to discuss future research directions. I got the impression that many researchers would continue talking with one another to plan and share their dreams.

I was astonished by the realization that nanotechnology is based upon a new kind of science. It is being done by a pool of people who have diverse talents and training and who are working together to advance the field. I was particularly intrigued by one participant's comment that we know very little about the world of atoms and also very little about the world of ecosystems, the planet and the universe. I would add that human behavior—especially on the scale of globalized societies—is also one of those big unknowns. It is fascinating to consider the possibilities that harnessing the power of matter at the smallest scale may help us successfully deal with the challenges of the larger world—whether in clarifying our understanding of brain and behavior or in determining how best to provide energy, healthcare and water to a burgeoning population.

Perhaps what now seems almost like science fiction will one day seem like a historic paradigm shift that helped us solve some of our most pressing and complex problems. I do not think that I, or anyone else, can quite imagine how all the pieces of our expanding knowledge of nanotechnology will fit together. Likewise, it is impossible to imagine what will emerge as researchers, engineers and social scientists continue to interact with one another. Nanotechnology will almost certainly evolve in ways that we cannot predict, it will change our world and it will become a key part of the advance of human potential.

—Karen F. Schmidt

APPENDIX

List of Interviewees

Pre-Meeting

Ralph Cavin—electrical engineering
Cees Dekker—instrumentation
Peter Grutter—physics
Horst Hahn—materials science
Leroy Hood—systems biology
Harry Kroto—chemistry
Rodolfo Llinas—neuroscience
Carlo Montemagno—bioengineering
Wolfgang Porod—electrical engineering
Mihail Roco—engineering
Michael Roukes—biology and physics
Fraser Stoddart—chemistry
Horst Stormer—physics
Sandip Tiwari—instrumentation and physics
James Tour—chemistry

Post-Meeting

William Bainbridge—NSF information science
Davis Baird—philosophy
Dawn Bonnell—instrumentation
Joseph DeSimone—chemistry
Mamadou Diallo—chemical engineering
David Dixon—chemisty
Greg Downing—NIH medicine
Arun Majumdar—electrical engineering
Tom Murray—ethics
Martin Philbert—public health, neurology
Samuel Stupp—chemistry
Tom Theis—electrical engineering

List of Participants

Mostafa Analoui (Pfizer)
Phaedon Avouris (IBM)
William Bainbridge (National Science Foundation)
Davis Baird (University of South Carolina)
Yoshio Bando (Tsukuba University)
Dawn Bonnell (University of Pennsylvania)
Ralph Cavin (Semiconductor Research Corporation)
Harold Craighead (Cornell University)
Cees Dekker (Delft University of Technology)
Joseph DeSimone (University of North Carolina at Chapel Hill)
Mamadou Diallo (California Institute of Technology)
David Dixon (University of Alabama)
Greg Downing (National Institutes of Health)
Leon Estrowitz (National Science Foundation)
Peter Grutter (McGill University)
Horst Hahn (Forschungszentrum Karlsruhe GmbH)
Naomi Halas (Rice University)
James Heath (California Institute of Technology)
Leroy Hood (Institute for Systems Biology)
Lynn Hudson (National Institutes of Health)
Barbara Karn (Woodrow Wilson International Center for Scholars)
Angus Kingon (North Carolina State University)

Gerhard Klimeck (Purdue University)

Harold Kroto (Florida State University)

Michael Lesnick (Meridian Institute)

Arun Majumdar (University of California, Berkeley)

Andrew Maynard (Woodrow Wilson International Center for Scholars)

Evan Michelson (Woodrow Wilson International Center for Scholars)

Nancy Miller (National Institutes of Health)

Carlo Montemagno (University of California, Los Angeles)

Julia Moore (Woodrow Wilson International Center for Scholars)

Thomas Murray (The Hastings Center)

Alex Parlini (Woodrow Wilson International Center for Scholars)

Martin Philbert (University of Michigan)

Wolfgang Porod (University of Notre Dame)

David Rejeski (Woodrow Wilson International Center for Scholars)

Mihail Roco (National Science Foundation)

Michael Roukes (California Institute of Technology)

John Ryan (Oxford University)

Karen Schmidt (Independent Writer)

David Schwartz (National Institutes of Health)

Paul Sieving (National Institutes of Health)

Lana Skirboll (National Institutes of Health)

J. Fraser Stoddart (University of California, Los Angeles)

Horst Stormer (Columbia University)

Samuel Stupp (Northwestern University)

Edward Tenner (Princeton University)

Thomas Theis (IBM)

Sally Tinkle (National Institutes of Health)

Matt Tirrell (University of California, Santa Barbara)

Sandip Tiwari (Cornell University)

James Tour (Rice University)

Carly Wobig (Woodrow Wilson International Center for Scholars)

Elias Zerhouni (National Institutes of Health)

Xiang Zhang (University of California, Berkeley)

The following submitted ideas but were unable to attend the meeting:

David Guston (Arizona State University)

Rodolfo Llinas (New York University Medical Center)

WOODROW WILSON INTERNATIONAL CENTER FOR SCHOLARS

About the Center

The Center is the living memorial of the United States of America to the nation's twenty-eighth president, Woodrow Wilson. Congress established the Woodrow Wilson Center in 1968 as an international institute for advanced study, "symbolizing and strengthening the fruitful relationship between the world of learning and the world of public affairs." The Center opened in 1970 under its own board of trustees.

In all its activities the Woodrow Wilson Center is a nonprofit, nonpartisan organization, supported financially by annual appropriations from Congress, and by the contributions of foundations, corporations, and individuals. Conclusions or opinions expressed in Center publications and programs are those of the authors and speakers and do not necessarily reflect the views of the Center staff, fellows, trustees, advisory groups, or any individuals or organizations that provide financial support to the Center. **www.wilsoncenter.org**

The **PROJECT ON EMERGING NANOTECHNOLOGIES** was launched in 2005 by the Wilson Center and The Pew Charitable Trusts. It is dedicated to helping business, governments, and the public anticipate and manage the possible human and environmental implications of nanotechnology. **www.nanotechproject.org**

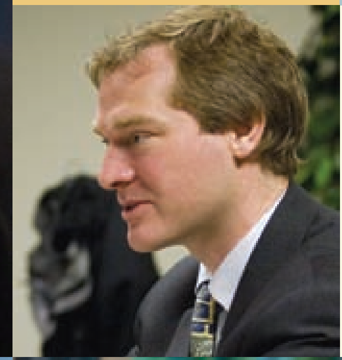
THE PEW CHARITABLE TRUSTS serves the public interest by providing information, advancing policy solutions and supporting civic life. Based in Philadelphia, with an office in Washington, D.C., the Trusts will invest $248 million in fiscal year 2007 to provide organizations and citizens with fact-based research and practical solutions for challenging issues. **www.pewtrusts.org**

Lynn Hudson, NIH

Participants during the nanomanufacturing session

Harold Kroto, FSU

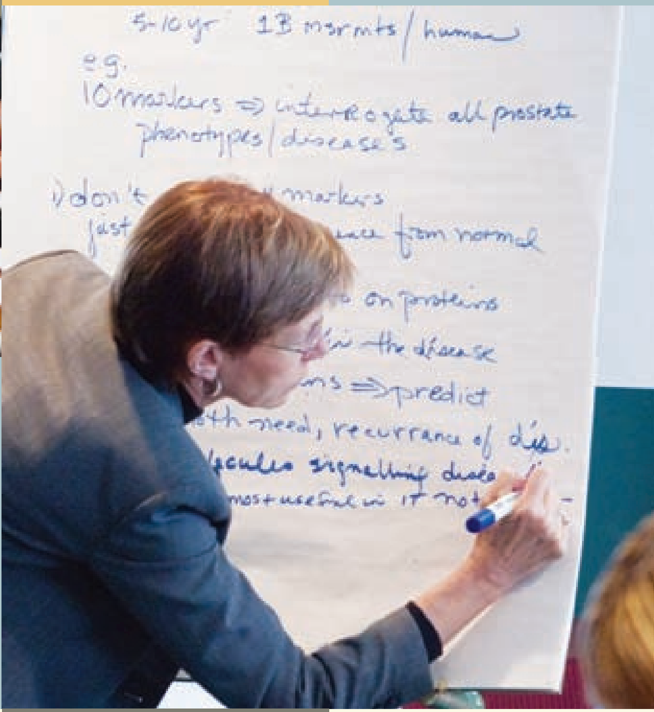
Andrew Maynard, WWICS



Sally Tinkle, NIH

Thomas Theis, IBM

Elias Zerhouni, NIH
Mihail Roco, NSF



Dawn Bonnell, Penn

Harold Kroto, FSU

Greg Downing, NIH

John Ryan, Oxford, addressing the nanomedicine breakout group

Ralph Cavin, SRC

Woodrow Wilson International Center for Scholars

Project on Emerging Nanotechnologies

One Woodrow Wilson Plaza
1300 Pennsylvania Ave., N.W.
Washington, DC 20004-3027

T 202.691.4000
F 202.691.4001
www.wilsoncenter.org/nano
www.nanotechproject.org