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The National Nanotechnology Initiative: Present at the Creation

The U.S. government was a pioneer in supporting nanoscale research; now it must boost funding to maintain the nation's leadership.

The United States, which made a major early commitment to nanotechnology in 2000, has been the world's research leader, but as the promise of nanotechnology has grown the government commitment has flattened. We are concerned that lukewarm support for nanoscale science and engineering (S&E) puts U.S. technological leadership at risk and might prevent the country from realizing the full potential of nanotechnology.

President Clinton unveiled the National Nanotechnology Initiative (NNI) in a major science policy address at Caltech on January 21, 2000. His fiscal year (FY) 2001 budget proposed almost doubling the federal funding for nanoscale S&E from $270 million in FY 2000 to $495 million in FY 2001. The president's speech triggered a wave of primarily positive media coverage of nanotechnology and eventually led to increased investment in nanoscience and nanotechnology by universities, states, venture-backed start-ups, Global 1000 companies, and foreign governments. As two of the primary White House advocates for the NNI, we are delighted by the progress that has been made to date by researchers and entrepreneurs. We believe that this progress justifies continued increases in federal investment in nanoscale S&E, particularly as part of a larger effort to reverse the cuts in funding in the physical sciences and engineering.

Although President Clinton did much to increase public awareness of nanotechnology, the concept can be traced to Richard Feynman's brilliant 1959 lecture "There's Plenty of Room at the Bottom." He urged his audience to consider the possibility that we could eventually "arrange the atoms the way we want; the very atoms, all the way down!" Feynman's vision began to seem less fanciful in 1985, when IBM researchers developed the scanning tunneling microscope. Four years later, IBM researchers used the mi-

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croscope to "write" the letters for IBM with 35 individual xenon atoms. In the 1980s and 1990s, researchers also began to synthesize and characterize nanostructures, such as buckminsterfullerene, carbon nanotubes, quantum dots, and nanowires, with novel and useful properties.

Federal agencies began to launch programs in nanoscale S&E, such as the Defense Advanced Research Project Agency's ULTRA Electronics Program. Beginning in 1996, federal program officers at the National Science Foundation (NSF) and other agencies began to meet and share information on their respective efforts in nanoscale S&E. By 1998, one of us (Lane) testified before Congress that "If I were asked for an area of S&E that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

Our efforts to develop a formal interagency initiative in nanoscale S&E began in earnest in the fall of 1998. An interagency working group was created under the auspices of the National Science and Technology Council. In January 1999, a workshop led by Paul Alivisatos of the University of California at Berkeley and Stan Williams of Hewlett Packard helped develop a detailed research agenda.

Beginning in 1999, we and other members of the administration began an active campaign to have the NNI included as one of the president's initiatives in the FY 2000 budget. We told the science agencies that if they proposed increases in funding for nanoscale S&E above the budget "guidance" they had received from the Office of Management and Budget (OMB), we would fight for those increases. We began to educate other senior White House staffers about the long-term promise of nanotechnology and worked with the research community to identify a series of ambitious but plausible grand challenges (for example, storing the Library of Congress in a device the size of a sugar cube or detecting cancerous tumors before they are visible to the human eye) that would be easy to communicate to the public. We worked closely with OMB professional staff to develop a rationale for increased investment.

Advocates made a number of arguments on behalf of the NNI, which we believe are still valid today. First, nanoscale S&E has the potential to be as important as previous general-purpose technologies, such as the steam engine, the transistor, and the Internet. At a size of 1 to 100 nanometers, materials, structures, and devices exhibit new and often useful physical, electrical, mechanical, optical, and magnetic properties. Second, expanded funding for nanotechnology can help revitalize the physical sciences and engineering, because it builds on disciplines such as condensed-matter physics, materials science, chemistry, and engineering. Third, the NNI will help attract and prepare the next generation of scientists, engineers, and entrepreneurs. Because roughly two-thirds of the funding for the NNI flows to university researchers, it directly supports undergraduates, graduates, and postdocs. Fourth, it is clear that realizing the potential of nanotechnology will require supporting long-term high-risk research that is beyond the time horizons of corporations, which are understandably focused on nearer-term research and product development. As President Clinton noted in his Caltech speech, "Some of these [nanotechnology] research goals will take 20 or more years to achieve. But that is why . . . there is such a critical role for the federal government." Finally, a 1998 technology evaluation concluded that global leadership in nanotechnology was up for grabs. We hoped that the NNI would allow the United States to strengthen its position in this critical technology.

In the late fall of 1999, President Clinton decided to include the NNI as one of his key budget initiatives for FY 2001, making it the centerpiece of a much broader research initiative to address the growing imbalance in federal funding for biomedical research and the physical sciences and engineering. He proposed a nearly $3 billion increase for his 21st Century Research Fund, including an additional $1 billion for university research and an NSF request that was nearly double the largest dollar increase the agency had ever seen. Targeted initiatives such as the NNI helped capture the imagination of the president and his senior advisors, making the potential benefits of increasing overall funding for research much more tangible. The initiatives benefited not only targeted areas such as information technology and nanotechnology, but also a broad range of S&E disciplines.

The NNI included nanotechnology research funding in five categories: fundamental research, grand challenges, centers and networks, research infrastructure, and societal implications and workforce education and training. The original list of grand challenges, which echoed some of Richard Feynman's 1959 predictions, included nanostructured materials by design; nanoelectronics, photonics and magnetics; therapeutics and diagnostics; and other challenges related to the environment, energy, space technology, manufacturing, and instrumentation.

Of course, the NNI was never intended as a vehicle to fund all research at the nanometer scale. Indeed, many disciplines, such as chemistry, condensed-matter physics, and AMO (atomic, molecular, and optical) physics focus on intrinsically nanoscale phenomena. Rather, the NNI emphasizes fundamental new properties and functions of materials, devices, and systems because of their small size; novel phenomena and properties that are nonscalable outside the nanometer domain; the ability to control and manipulate matter at the nanometer scale; and integration along length scales.

Nanotechnology could play a key role in creating new sources of carbon-free energy that are competitive with fossil fuels.

There was very little opposition to the NNI, although Sun Microsystems cofounder Bill Joy warned in a widely read article ("The Future Doesn't Need Us," *Wired*, April 2000) that the confluence of genetics, nanotechnology, and robotics presented society with a dilemma. Unlike nuclear weapons, which require the resources of a nation-state to develop, genetics, nanotechnology, and robotics will be driven by private enterprise and will therefore be low-cost and widely available. Joy argued that, "an immediate consequence of the Faustian bargain in obtaining the great power of nanotechnology is that we run a grave risk—the risk that we might destroy the biosphere on which all life depends." Although most scientists disagreed with Joy's specific scenarios, such as superhuman artificial intelligence with its own agenda and self-replicating assemblers, there is no question that the destructive power available to small groups is increasing over time. Joy's article underscored the importance of considering the unintended consequences of technological advances, and the discussions motivated by Joy's article have continued to this day.

With support from industry, the research community, and even former House Speaker Newt Gingrich, the Clinton administration was able to persuade Congress to provide $422 million in funding for nanoscale S&E. By the fall of 2000, the NNI was officially launched, and a National Nanotechnology Coordination Office was created to help encourage information-sharing and collaboration across the federal government.

Progress since 2000

In the nearly five years since the birth of the NNI, considerable progress has been made. Funding has continued to increase, to over $1 billion. There are now 11 agencies with funding and another 11 agencies that participate in the interagency discussions, although 88 percent of the budget goes to NSF, the Department of Defense, the Department of Energy (DOE), and the National Institutes of Health (NIH). As many as 40 centers and networks have been funded or are in the planning stages; already-funded activities include NSF's Nanoscale Science and Engineering Centers and DOE's Nanoscale Science Research Centers. Congress has passed, and President Bush has signed, the 21st Century Nanotechnology Research and Development Act. This legislation provides multiyear authorization for the NNI, although its primary practical effect to date has been to increase the number of reviews and reporting requirements.

The NNI funding has resulted in an expansion of fundamental understanding of nanoscale phenomena and many research results with potentially revolutionary applications. In widely cited journals such as *Science*, *Nature*, and *Physical Review Letters,* the percentage of journal articles related to nanoscale S&E has increased from 1 percent in 1992 to over 5 percent by 2003. The breadth of activity is impressive. For example, researchers are developing:

- The use of gold nanoshells with localized heating for the targeted destruction of malignant cancer cells, an approach that involves minimal side effects.
- Genetically engineered viruses that can self-assemble inorganic materials such as gallium arsenide.
- Low-cost hybrid solar cells that combine inorganic "nanorods" with conducting polymers.

• A scale that can detect a zeptogram, the weight of a single protein.

• Quantum dots that can "slow light," opening the door to all-optical networks.

• Nanoscale iron particles that can reduce the costs of cleaning up contaminated groundwater.

The increased funding has also triggered broader institutional responses at leading U.S. research universities. Universities are hiring more faculty in this interdisciplinary area, investing in new buildings that are capable of housing 21st-century nanoscience research and creating shared facilities for nanoscale imaging, characterization, synthesis, and fabrication. Colleges and departments are experimenting in educating truly interdisciplinary nanoscientists and engineers, with new courses, lab rotations, and two or more faculty mentors in different disciplines.

The NNI has continued to evolve over time. In response to the concerns about the potential environmental and health risks of nanomaterials, the latest NNI strategic plan identifies "responsible development of nanotechnology" as one of the four principal goals. Several agencies have stepped up their research in this area, although as we argue below, more can and should be done. The National Toxicology Program, for example, is investigating the toxicity of nanotubes, quantum dots, and titanium dioxide. The Environmental Protection Agency (EPA) is supporting research on the fate and transport of manufactured nanomaterials in the environment. The EPA and other regulatory agencies are exploring whether existing laws and regulations such as the Toxic Substances Control Act need to be modified to take into account the size-dependent properties of nanoparticles.

In addition to these federal activities, states, the private sector, start-ups, and foreign governments have also increased their investment in nanotechnology. According to Lux Research, corporations invested $3.8 billion in nanotechnology R&D in 2004. Of the 30 companies on the Dow Jones industrial index, 19 have launched nanotechnology initiatives, and 1,200 nanotechnology-related start-ups have emerged, about half of them in the United States. Companies are moving beyond novelty uses of nanotechnology, such as stain-resistant pants, to begin marketing truly valuable products.

Still, as a commercial enterprise, nanotechnology is in its infancy. For example, companies are still not able to reliably purchase high-quality nanotechnology building blocks such as nanotubes, metal oxide nanoparticles, and fullerenes.

Whither the NNI?

Although the NNI has made significant progress, we are concerned that federal funding for nanoscale S&E has been flat in recent years. The administration's FY 2006 budget, for example, actually proposes a decrease in funding as compared to the level of support provided by Congress in FY 2005.

We believe that there is a compelling case for sustained increases in federal funding for nanoscale S&E, particularly if this is done in the context of increased investments in the physical sciences and engineering more generally. First, federal agencies are still able to fund only a tiny fraction of the meritorious proposals that are submitted. In its most recent solicitation for Nanoscale Science and Engineering Centers, for example, NSF received 48 proposals and could fund only 6. Even when an agency does fund a proposal, the size and duration of the grant are often inadequate. Second, foreign governments are continuing to aggressively ramp up their investments in nanoscale S&E. Given that international leadership in nanotechnology is up for grabs, allowing U.S. funding to stagnate while foreign governments continue to provide double-digit increases seems to us to be an incredibly risky strategy. Third, only the federal government is in a position to support the long-term high-risk research that is beyond the time horizons of companies. Finally, researchers have demonstrated the potential of nanotechnology to make important contributions to a wide range of national goals and key economic sectors, such as health, clean energy, information technology, new materials, national and homeland security, sustainable development, manufacturing, and space exploration. Stagnant or declining budgets will make it difficult to pursue these and other opportunities. Below are just a few of the areas where new and expanded initiatives in nanoscale S&E would make a big difference.

Invest in nanotechnology for clean energy. Experts believe that combating global warming may require the ability to generate 15 to 30 terawatts of carbon-free energy worldwide by 2050. By comparison, today's total global energy consumption is a little less than 15 terawatts. Considering that 85 percent of our current global primary energy consumption is from fossil fuels, this is a daunting challenge. Researchers have identified a variety of ways in which nanotechnology could help solve our long-term energy challenges. These include a dramatic reduction in the cost of photovoltaics, direct photoconversion of light and water to produce hydrogen, and transformational advances in energy storage and transmission. The United States desperately needs an Apollo-type project to reduce the threat of climate change and its dependence on Middle East oil. Nanotechnology could play a key role in creating new sources of carbon-free energy that are competitive with fossil fuels.

The United States should fund research collaborations between U.S. and developing-country researchers on nanotechnology applications.

Extend "Moore's law" with nanoelectronics. In the 1990s, the U.S. economy began to experience significant increases in productivity, the most important determinant of the country's long-run standard of living. Much of this increase could be traced to business investments in information and communications technologies, combined with the managerial and organizational innovations needed to take advantage of the dramatically lower cost of storing, processing, and transmitting information. The semiconductor industry believes that today's technology will approach fundamental performance limits in 2020. If we want the benefits of Moore's law to continue for decades to come, increased investment is needed to explore alternatives such as quantum computing, spintronics, molecular electronics, and computing based on nanostructures such as nanowires and nanotubes.

Establish a "Pioneer Award" for nanoscale S&E. One of the frequent complaints of scientists and engineers is that flat science budgets and proposal pressure have made the peer review process more conservative. Some scientists joke that "you have to do the experiment before you can write the grant." NIH Director Elias Zerhouni is attempting to counteract this trend by providing a Pioneer Award to support exceptional researchers interested in pursuing high-risk high-impact research. Researchers are given $500,000 per year in direct costs for five years, which gives them the time and resources to explore innovative ideas and approaches to challenges in biomedical research. NSF should be given the budget to launch a similar program in nanoscale S&E and possibly other areas as well.

Create nanotechnology-related education and outreach activities that scale. One of the explicit goals of the NNI is to excite young boys and girls about science, particularly the physical sciences and engineering. U.S. trends are troubling, particularly when compared with emerging economic competitors in Asia. Last year, for example, 65,000 U.S. high-school students participated in the local fairs used to select the finalists for the Intel Science and Engineering Fair. In China, that number was 6 million! Currently, agencies such as NSF encourage researchers to engage in education and outreach activities to increase the number of high-school and undergraduate students that pursue careers in S&E and to increase public understanding of science. These activities are worthwhile and praiseworthy, but we believe that the federal government must also experiment with interventions that have the potential to reach millions of children. We would like to see an IMAX movie that would explain the promise of nanotechnology to every middle-school student in the United States, or a video game about nanotechnology that is as engaging as *Halo 2* or *Everquest*.

Understand and mitigate the environmental and human health effects of nanomaterials. As Scott Walsh notes in his article in this issue, our current understanding of the environmental and human health effects of nanomaterials is limited. A failure to understand and manage these health risks could put the nanotechnology revolution on hold. Reinsurance companies such as Swiss Re have made it very clear that they do not wish to be left holding the bag if nanotechnology poses significant risks to human health. Although some research is already being done, increased funding for agencies such as the EPA, the National Institute for

Occupational Safety and Health, and the National Institute for Environmental Health Sciences is clearly needed. Such activities at the EPA now account for less than 1 percent of the total NNI budget.

Promote nanotechnology applications for developing countries. As the article by Peter Singer *et al.* in this issue points out, researchers at the University of Toronto have published a list of the 10 applications of nanotechnology with the most relevance to developing countries. Examples include inexpensive systems that purify, detoxify, and desalinate water more efficiently than conventional bacterial or viral filters; clean energy; and a "lab on a chip" for research on developing-country diseases. The United States should fund research collaborations between U.S. and developing-country researchers to explore these applications.

Promote the interface between bio and nano. The intersection between "nano" and "bio" is an incredibly promising and fertile area. On the one hand, nanotechnology is creating powerful new tools for health care and fundamental biology. On the other hand, nature is serving as a rich source of inspiration for nanoscientists, who are challenged by the performance of biological systems such as rotary motors in the flagella of *Escherichia coli* bacteria. As Caltech's Michael Roukes observed, "The fact that the gene encodes the commonplace, mass-production of such atomically precise devices taunts us, urging us onward in our explorations!" Biological systems routinely assemble individual molecules into large, complex, functional structures, using templated hierarchical self-assembly. The immune system develops millions of extremely similar but critically different structures (antibodies) and rapidly scans them for the desired properties. Furthermore, living systems are self-healing, self-repairing, and fault-tolerant. Unfortunately, there are cultural barriers within the scientific community to research on bio-inspired materials, processes, and devices. Biologists are usually descriptive scientists who focus on understanding the components and operations of existing systems, not the creation of new systems. Although NIH, especially the National Cancer Institute, is beginning to ramp up its activities in nanomedicine, there are many nonhealth applications of bio-inspired nanosystems. At least one federal science agency should be given the budget and the mandate to build a robust research community in this area.

Help nanotechnology start-ups cross the "valley of death." Part of the argument for increased funding for research is that it will eventually fuel the creation of new companies, new industries, and high-wage jobs. Moving ideas from the lab to the marketplace is never easy, particularly in nanotechnology. A big gap exists between showing that a nanostructure has some novel and useful property and demonstrating high-volume cost-effective manufacturing. Although one might argue that venture capitalists should fund this "reduction to practice," most of them are reluctant to invest in early-stage technology development. With institutional investors still counting their losses from the "dot com" era, they are urging venture capitalists to shift to later-stage, less risky investments, reducing the capital available for seed investments in spinoffs from universities and national labs. We believe that the Small Business Innovation Research (SBIR) and Small Business Technology Transfer Program should be used more aggressively to help nanotechnology start-ups cross the chasm between proof of principle and reduction to practice. NIH has done this by increasing the duration and size of its SBIR grants for nanotechnology and allowing entrepreneurs to submit a broad range of ideas for using nanotechnology to help prevent, detect, diagnose, and treat disease. Other agencies should adopt a similar approach in applications of nanotechnology that are related to their mission.

Although the research community and companies involved in nanotechnology must be careful not to overpromise and underdeliver, the technology's long-term potential is awe-inspiring. Although we will inevitably be surprised by the future course of nanotechnology, with continued investments in high-risk research many of the grand challenges that have been established will eventually be met. However, we cannot expect the United States to lead this technological revolution with the current policies that short-change research. It is our sincere hope that we will respond to the growing challenges to U.S. scientific, technological, and economic leadership before it is too late.

GEORGE ALLEN

The Economic Promise of Nanotechnology

Congress must continue to support U.S. leadership in this field as a key component of future national prosperity.

As a U.S. senator, I have championed several initiatives over the past several years to nurture U.S. leadership in innovation. Perhaps none was more exciting than sponsoring the 21st Century Nanotechnology Research & Development Act, which was signed into law by President Bush on December 3, 2003. Together with my hardworking friend and colleague, Senator Ron Wyden (D-Oregon), we were successful in launching the National Nanotechnology Program, which became the single largest federally funded, multiagency scientific research initiative since the space program in the 1960s, securing $3.63 billion over four years.

As a member of the Senate Committee on Commerce, Transportation, and Space, I held the first congressional hearings on nanotechnology. The committee quickly recognized that the fields of nanoscience, nanoengineering, and nanotechnology have the real potential to transform almost every aspect of our lives and commerce. Whether it is related to electronic devices, biotechnology, the health sciences, agriculture, energy, transportation, or national defense, nanotechnology will form the foundation for revolutionary discoveries and advancements in the decades to come, and will soon occupy a major portion of our economy.

Because this country has been the leader in virtually every important and transformative technology since the Industrial Revolution, I have made U.S. competitiveness in nanotechnology a priority in the Senate. Almost every country that supports scientific and technological research has a nanotechnology research program. To ensure that the United States is well positioned to participate and benefit as much as possible from this emerging field of science, this country must take an active role in creating the conditions necessary for our researchers and innovators to compete, contribute, and succeed both domestically and internationally.

As recognized with the passage of the 21st Century Nanotechnology Research and Development Act, the federal government can play an important role in the development of nanotechnology by supporting education and basic research. This legislation provides an organized, coordinated, and responsible approach to nanotechnology research and development (R&D) across the entire federal government. It will catalyze the synergistic interdisciplinary science and engineering research through grants to individual sci-

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