Chapter 9
National Nanotechnology Initiative: A Model for Advancing Revolutionary Technologies

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Fifteen years after the enactment of the legislation establishing the National Nanotechnology Initiative (NNI) (U.S. Congress 2003), it is worth reflecting on the framework and policies that allowed the program to take root and grow. The NNI is a coordinated suite of activities across the federal government including research, regulation, standards, workforce education, and public outreach. Collectively these activities created a foundation that promoted multidisciplinary research and development (R&D) and enabled the results to be transitioned in a responsible manner to practical application and public benefit. A measure of the NNI's success is the increasing number of products—from medical implants to advanced electronics—that incorporate nanotechnology.

Nanoscale science, engineering, and technology, or nanotechnology, is defined by the NNI as the "understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nm, where unique phenomena enable novel applications" (National Nanotechnology Initiative 2019a). Advances in instrumentation were essential to progress in nanotechnology research and development. In 1981, Gerd Binnig and Heinrich Rohrer at IBM invented the scanning tunneling microscope, which made it possible to image individual atoms and for which they were awarded the Nobel Prize in 1986 (Royal Swedish Academy of Sciences 1986). Binnig, Calvin Quate, and Christoph Gerber went on to invent the atomic force microscope, which allows one to view, measure, and manipulate materials with subnanometer precision (Binnig et al. 1986). Perhaps the best known early example of nanoscale control was the demonstration by Don Eigler in 1989, when he spelled IBM by positioning 35 xenon atoms on a nickel surface (IBM 2009).

Nanotechnology emerged from the confluence of advances in the ability to measure and manipulate matter on the scale of atoms and molecules and the recognition of how such capabilities could be used to create new materials, structures, and

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P. M. Norris, L. E. Friedersdorf (eds.), *Women in Nanotechnology*, Women in Engineering and Science, https://doi.org/10.1007/978-3-030-19951-7_9

processes in diverse fields and sectors. Nanotechnology is distinguished from other areas of materials science and technology by the novel behavior that occurs at nanometer length scales. For example, bulk gold melts at 1064 °C; however, the melting temperature decreases exponentially with particle size below approximately 10 nm diameter (Buffat and Borel 1976; Gao and Gu 2016). In addition to size-related properties that occur at the nanoscale, molecular length scales correlate to many biological features and processes. For example, the width of a DNA molecule is approximately 2 nm. These characteristics open whole new areas of research and development, such as engineered nanoparticles that target and attack disease at the cellular level in the body. At the same time, the novel and sometimes unpredicted properties of nanomaterials extend to their interaction with the body and the environment, posing potential risks.

Advances in materials science and engineering were necessary for nanotechnology to be "born" but other actions and factors were involved in it becoming a federal priority and initiative and even a global phenomenon. This chapter reviews people, events, and policies that resulted in the creation of nanotechnology as a new field of science and technology. It is largely based on the author's personal experience while serving as Assistant Director for Technology R&D in the White House Office of Science and Technology Policy (OSTP) from 2003 to 2008.

The signing of the Twenty-First Century Nanotechnology Research and Development Act (the Act) on December 3, 2003, made statutory the NNI. While enactment of the legislation was a major milestone, it was the culmination of key events and the efforts of many individuals in the federal government and the scientific community (National Nanotechnology Initiative 2019b). Starting in the 1990s, federal agencies already were investing, albeit in an uncoordinated manner, in research at the nanoscale. An ad hoc interagency working group was formed, co-chaired by Mihail (Mike) Roco at the National Science Foundation (NSF) and Tom Kalil in the White House National Economic Council, and promoted by key individuals in other agencies, such as James Murday at the US Navy, who served as Executive Secretary. The group held a workshop in 1999 and with input from the broader scientific community published a report (Roco et al. 1999) outlining research opportunities and needs related to advancing nanotechnology. Based on the groundwork laid by the working group, the White House launched the NNI in 2000. The initiative was outlined by President Clinton shortly before leaving office in a speech at the California Institute of Technology that echoed a talk given by Richard Feynman in 1959, also at Cal Tech, entitled "There's Plenty of Room at the Bottom" (Feynman 1959). Feynman envisioned the ability to control matter at the atomic scale and challenged scientists to overcome the barriers. It was several decades, however, before science and engineering advances enabled Feynman's vision to be realized.

Following the launch of the new initiative at the end of the second term of the Clinton administration, the incoming George W. Bush administration embraced the new program. The interagency working group became the Nanoscale Science, Engineering and Technology (NSET) subcommittee of the National Science and Technology Council (NSTC). Starting in 2003, the NNI and nanotechnology were one of a handful of R&D priorities specified in the annual budget guidance memo from OSTP and the Office of Management and Budget (OMB) to departments and agencies (Office of Management and Budget 2003).

When considering how to organize and manage the NNI, those drafting the legislation looked to another successful multiagency federal program, the Networking and Information Technology Research and Development program (NITRD). Several processes and structures used by NITRD were adapted and incorporated in the Act, including a coordination office independent from any participating agency and reporting to OSTP, annual budget reports that include research plans, and a presidentially appointed advisory panel to review and provide expert advice. To ensure more independent assessment of the federal investment in what was an emerging and rapidly advancing field, requirement for a periodic review by the National Academies was also included in the Act.

Interagency Coordination

The NNI has benefited since its inception from strong interagency coordination made possible by a robust interagency body and a coordination office with a clear purpose. The NSET subcommittee has served as the interagency body for such coordination. The subcommittee is co-chaired by OSTP and an agency representative. The agency co-chair rotates among the participating agencies, thereby avoiding any one agency appearing to have greater influence and ensuring support among all participating agencies. The subcommittee formed subgroups or working groups to focus on certain areas deemed essential to achieving the goals of the initiative. Working groups engage individuals with relevant experience and responsibilities at participating agencies and may be established and disbanded as appropriate. In addition, coordinators have been named in cross-cutting areas "to track developments, lead in organizing activities, report periodically to the NSET subcommittee, and serve as central points of contact for NNI information in the corresponding areas" (National Nanotechnology Initiative 2019c). Coordinators also strengthen interagency engagement and interaction in a particular area, such as standards development.

After President Clinton announced the NNI, a coordination office was established, modeled after a similar office that coordinated NITRD. The National Nanotechnology Coordination Office (NNCO) was initially focused on coordinating among the multiple participating agencies; however the Act passed in 2003 enumerated the following additional roles for the office:

1. Provide technical and administrative support to the NSET subcommittee and the advisory panel
2. Serve as the point of contact on federal nanotechnology activities for government organizations, academia, industry, professional societies, state

nanotechnology programs, interested citizen groups, and others to exchange technical and programmatic information
3. Conduct public outreach, including dissemination of findings and recommendations of the advisory panel
4. Promote access to and early application of the technologies, innovations, and expertise derived from activities to agency missions and systems across the Federal Government, and to the US industry, including startup companies

Rather than funding the NNCO through appropriations within a single agency, participating agencies with budgets for nanotechnology R&D agreed to jointly fund the NNCO. The amount each agency contributed to the NNCO budget was determined by its fraction of the total nanotechnology R&D investment. This approach meant that agencies with larger budgets contributed more. It also meant that multiple agencies had "skin in the game" and an interest in seeing value from the office.

The multiagency approach to funding the NNCO also had drawbacks. It required the NNCO to deal with multiple agency contracting offices, a time-consuming effort for both sides. In addition, assessing how much each agency owed posed challenges. The total nanotechnology R&D investment is the sum of a crosscut reported to OMB of each agency's proposed R&D budget for the upcoming fiscal year. Nanotechnology is foundational and crosscutting and typically is not segregated in a single program or budget within an agency. For grantmaking agencies like NSF, a method for determining which grants are for nanotechnology R&D was needed. At a government lab, such as NIST or one of the DOD research labs, it can be difficult to categorize a research project as nanotechnology R&D. Moreover, mission agencies, such as the Department of Defense, invest in research to address mission needs, which may or may not be based on nanotechnology, making it difficult to plan future spending levels. Each agency developed a method to track nanotechnology R&D, which had to be applied consistently in order for the year-over-year estimates to be meaningful. The formula for determining how much each agency paid to support the NNCO, i.e., based on its fraction of the total investment, could incentivize agencies to be conservative when deciding whether to include projects that are only partly focused on nanotechnology R&D or otherwise difficult to categorize. On balance, however, the participating agencies have concluded that the benefits of joint support outweigh the costs.

The 2003 Act called for the NSET to prepare and update every 3 years a strategic plan for the initiative. The first strategic plan was issued in 2004 (National Nanotechnology Initiative 2004) and was organized around the following four goals:

- Maintain a world-class R&D program.
- Facilitate transfer of new technologies into products for commercial and public benefit.
- Develop educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology.
- Support responsible development of nanotechnology.

These overarching goals have remained the guideposts for the NNI. In addition, the strategic plan has identified an evolving set of objectives and actions aimed at each goal. Annual reports state progress toward the objectives through individual and joint agency activities.

In addition to a sound organizational framework and good management processes, a critical element of the NNI's success has been the individuals who serve on the NSET and as the NNCO director. NSET representatives typically are volunteers who take on the duties in addition to their full-time job. The commitment of these individuals to maximizing the advancement and utilization of nanotechnology to achieve their agency mission is evident based on the many years that most representatives serve; some current representatives have been involved since the beginning.

The NNCO director is a key position in the NNI organization. The director must serve the NSET and make sure that the work of the subcommittee is accomplished and be the liaison to OSTP on behalf of all the participating agencies. In addition, the director is the face of the NNI to the broader community. The first full-time NNCO director, appointed in early 2003, was Clayton Teague, a distinguished scientist on assignment from NIST. Teague's background in precision engineering and measurement at the nanoscale and in standards development, as well as his ability to communicate to broad audiences on all aspects of nanotechnology, made him ideally suited to the job, especially at the outset when many had questions about the potential for both good and possible harm of the new technology.

Addressing Risks

It was recognized from the beginning that nanotechnology, like all new technologies, poses certain risks. These fall into two main categories—potential to harm humans or the environment and the potential for nefarious or unethical use. Environment, health, and safety (EHS) concerns stemmed from the novel and sometimes unpredictable properties of nanomaterials and their small size, which made them hard to see and called into question the ability to filter them and to protect workers, consumers, and the environment (National Nanotechnology Initiative 2006). The possible biological applications and concerns about access to benefits in general raised ethical, legal, and societal implications (ELSI). ELSI also was a concern in the Human Genome Project and a percentage of funds appropriated for the project were set aside to invest in ELSI research starting in 1990 (National Human Genome Research Institute 2019). Although a prescribed level of funding was never specified by Congress, the Act explicitly called for the NNI to address these areas within the broad portfolio.

It was unusual when the NNI started for a research initiative to consider potential EHS risks and seek to address those risks in parallel with the basic research to advance fundamental scientific knowledge. Such a proactive approach was considered essential given the myriad applications envisioned, from medicine to food safety to environmental sensing and remediation. Addressing EHS concerns required participation of agencies with relevant expertise and responsibilities, including the Environmental Protection Agency (EPA), Food and Drug Administration (FDA), National Institute for Occupational Safety and Health (NIOSH), National Institute for Environmental Health Sciences (NIEHS), Occupational Safety and Health Administration (OSHA), and Consumer Product Safety Commission (CPSC).

The NSET subcommittee established the Nanotechnology Environmental and Health Implications working group (NEHI) in 2003 to focus on identifying potential EHS risks and the research needed to be able to assess and manage those risks. NEHI has helped to accelerate understanding related to all aspects of EHS, from monitoring exposure and dose to assessing potential toxicity compared to existing chemicals. The transparent and proactive approach was key to ensuring that agencies responsible for protecting people and the environment had accurate data. It also communicated to the broader community the measures being taken to be responsible in the development of the new technologies.

Supporting Commercialization

The name of the initiative intentionally emphasized "technology" with an eye toward the practical applications envisioned. A number of actions taken under the NNI helped to remove barriers and accelerate progress toward achieving economic and public benefits. These included the establishment of intellectual property structure and expertise in the US Patent and Trademark Office (USPTO) and collaboration with industry sectors with a stake in the development of nanotechnology.

The ability to protect intellectual property is essential to the private sector when making investments needed to commercialize a new technology. As a member of the NSET subcommittee, the USPTO kept abreast of research and was able to prepare for the rapid increase in patent applications following the launch of the NNI (Fig. 9.1). To facilitate the examination of these applications, in 2004, the USPTO created a new category for nanotechnology-related patents (Class 977) in its system for grouping patents. Working with counterparts worldwide, international patent classification systems were also modified.

To guide and accelerate nanotechnology R&D toward practical applications, NNI leaders reached out to industry sectors with an interest in nanotechnology, starting with the semiconductor and chemical industries. Convening and consulting among NNI agencies and sector-specific groups allowed the agencies to learn about basic research needs to enable certain applications and industry gained insight on current government investments. Industry interaction led to various positive outcomes.

NNI engagement with the semiconductor industry focused on the technological needs "beyond Moore's law," when scaling the current silicon-based technology to smaller sizes is not possible. The in-depth discussions and exchange of information

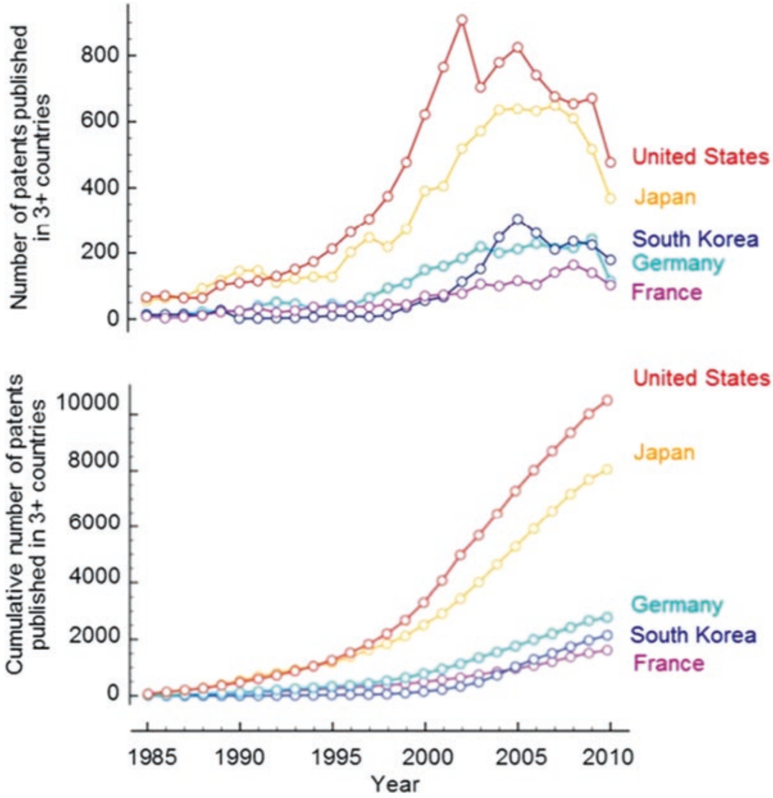

Fig. 9.1 Number of patents published in three or more countries by inventors in the United States and other leading countries in nanotechnology R&D. Source: President's Council of Advisors on Science and Technology (2014)

eventually led to the Nanoelectronics Research Initiative (NRI), a consortium of semiconductor companies that partnered with NSF and NIST to fund university research. The goal of NRI was to create technology options that could extend the performance trends associated with Moore's law into the future. NRI was a subsidiary of the Semiconductor Research Corporation (SRC) and used the SRC approach to define research needs, solicit ideas from university researchers, and connect industry experts with faculty and student researchers to guide projects and transfer results back to the companies.

Vision2020, an organization with broad participation from across the chemical industry, focused on the industry's long-term technology needs and opportunities, and partnered with NNI agencies to develop a R&D roadmap for "nanomaterials by design" (Chemical Industry Vision2020 Technology Partnership 2003). The report published in 2003 outlined research needs for advancing the ability to create nanomaterials with specific properties, including the need to understand EHS implications. It highlighted the need for R&D in manufacturing, tools for synthesis and characterization, standards, and workforce education and training. Elements of the roadmap appeared in NNI programs, including the DOE nanoscale science research centers and NSF programs related to nanomaterials and biological interactions.

A third industry partnership was with the forest product sector, represented by the American Forest and Paper Association. In 2005, the industry engaged with NNI agencies, led by the USDA Forest Service, to publish vision and technology roadmap (American Forest and Paper Association 2005). The document outlines how nanotechnology could impact the industry, e.g., to reduce the energy intensity of paper production, and how the industry could lead to advances in nanotechnology, particularly in the development of new nanomaterials based on lignocellulosic biopolymers, an abundant nanostructured plant-based material.

The hype surrounding nanotechnology in the early 2000s generated both positive and negative publicity. The eventual ability to routinely control matter of all types of matter on the scale of atoms and molecules promised everything from cures for disease to clean water and abundant, cheap renewable energy. On the other hand, the ability also could be used against the United States and its allies, e.g., to create potent chemical and biological warfare agents or hard-to-detect surveillance technologies (Clunan and Rodine-Hardy 2014). One far-off but existential scenario envisioned nanomanufacturing machines that could replicate themselves, thereby creating an exponentially growing “grey goo” (Drexler 1986). Nearer term threats of widespread use and exposure before possible harmful effects were understood seemed more likely, leading to calls for greater investment in risk research and for a precautionary approach (Balbus et al. 2005).

As for all new products that are regulated, including chemicals and materials, drugs, food, and, once available for sale, cosmetics and other consumer products, the responsible agencies act within their authorities based on data and evidence. In general, manufacturers do not want their products to cause harm to workers, customers, the public, or the environment. The potentially novel behavior of nanomaterials, however, meant that data for the same material in bulk may not apply and assumptions used when estimating risks of new chemicals may not be appropriate. Moreover, unlike many large companies, small businesses generally do not have broad in-house industrial hygiene capacity and therefore may not be aware of the latest scientific research. NEHI and the regulatory agencies engaged industry, academic experts, and nongovernmental organizations to inform decisions and raise awareness. The NNI disseminated guidelines (e.g., National Institute for Occupational Health and Safety 2009) and other documents related to EHS (National Nanotechnology Initiative 2019d).

In parallel to the development of appropriate regulations is the need to establish standards, which promote competition in the marketplace and safety of consumers and the environment. Nanotechnology is inherently difficult to define and constrain. The relative importance of quantum versus classical behavior changes gradually with size and is material specific. When does “nanomaterials” include naturally occurring nanosized particles, such as found in soot? In order for researchers, businesses, and government regulators to communicate clearly, terminology needed to be agreed upon. To ensure consistency, characterization methods needed to be established.

In the United States, the American National Standards Institute (ANSI) promotes the development of voluntary, consensus standards through transparent processes that are open to all stakeholders. ANSI also represents US interests at many international standards organizations. At the recommendation of OSTP, ANSI established the Nanotechnology Standards Panel in 2004. In 2005, the International Standards Organization (ISO) established a technical committee on Nanotechnologies (TC 229), with working groups for terminology and nomenclature; measurement and characterization; and health, safety, and environment. ANSI administers the US Technical Advisory Group (TAG) for TC 229. The first TAG Chair was Clayton Teague, who had experience in standards development and was NNCO Director at the time.

ANSI does not create standards itself; it accredits procedures of standard development organizations (SDOs). ASTM and IEEE were the first ANSI-accredited SDOs to establish technical bodies for development of nanotechnology-related standards. ASTM standards include calculation of nanoparticle sizes and size distributions and a test method for analysis of hemolytic properties of nanoparticles (ASTM 2019). ASTM also has published guides for workforce education in various areas of nanotechnology, including health and safety, materials synthesis and processing, and material properties and the effects of size. IEEE standards include test methods for characterization of electronic properties of carbon nanotubes (IEEE 2006) and a standard that is in development for large-scale manufacturing for nanoelectronics (IEEE 2015).

International Collaboration

Although the NNI was the first and largest coordinated national effort, other nations followed with similar programs, spurred in part by competition and the desire to be among the leaders of the anticipated "nanotechnology industry" (Fig. 9.2) and international scientific meetings where research results were presented proliferated. At the same time, the need for cooperation in certain areas was recognized. As mentioned earlier, international cooperation was initiated relatively quickly in the areas of patent classification and standards development.

As those responsible for EHS in counties around the world grappled with the new nanomaterials, US policy makers, led by OSTP and EPA, supported the Organization for Economic Cooperation and Development (OECD) Chemicals Committee as an ideal forum for international coordination in the area. The Chemicals Committee has worked for over four decades to protect human health and the environment while avoiding duplication of efforts, e.g., through sharing of high-quality EHS data.

In 2005, OSTP and the US State Department proposed to address topics related to nanotechnology innovation and commercialization at a government-to-government level through a newly created Nanotechnology Working Party under the OECD Committee on Science and Technology Policy (CSTP). Now part of the Working

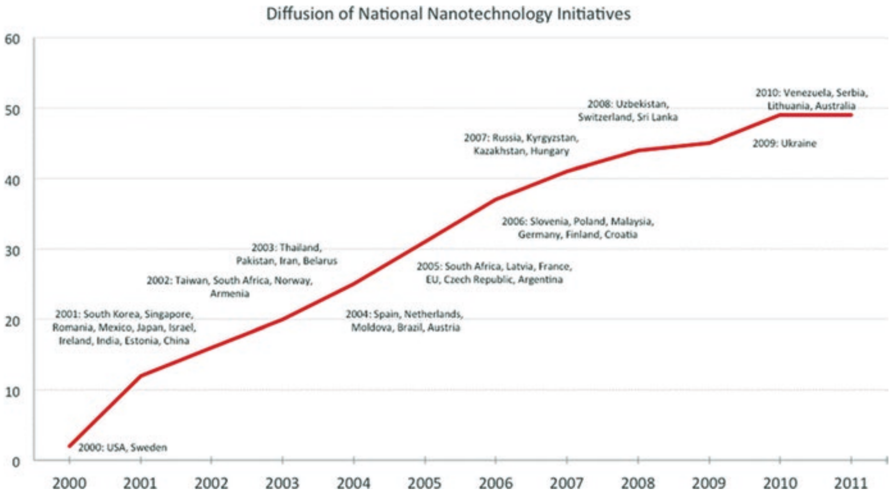

Fig. 9.2 Number of national nanotechnology initiatives established between 2000 and 2011. Source: Clunan and Rodine-Hardy (2014)

Party for Bio-, Nano- and Converging Technologies in the Directorate for Science, Technology and Innovation, the group continues to track key nanotechnology economic indicators, including number of nanotechnology firms and public sector nanotechnology R&D expenditures (OECD 2019).

Oversight and Review

The 2003 Act included provisions for periodic review of the NNI by a presidentially appointed advisory panel and by the National Academies. In July 2004, President Bush signed an executive order designating the President's Council of Advisors on Science and Technology (PCAST) as the National Nanotechnology Advisory Panel (NNAP) created by the Act. According to the Act, the NNAP is to review the NNI every 2 years. Comprising senior leaders and executives from industry and academia, PCAST was able to provide valuable input on managing and directing such a large multiagency initiative. To augment PCAST expertise in key technical areas relevant to nanotechnology, a technical advisory group (TAG) of some 50 experts was created. The "nano TAG" was surveyed and consulted by PCAST to inform its assessment and recommendations. The Obama and Trump administrations also designated PCAST as the NNAP. In addition to the advisory panel review, the Act calls for the National Academies to review the NNI, including 13 specific aspects of the program funding, organization, strategy, and management, every 3 years. The first National Academies review was published in 2006 (National Research Council 2006).

Outside expert assessment and input is a valuable mechanism for keeping a program like the NNI on track. However, by being so specific in what each assessment must address, the advisory panel and National Academies committees are effectively constrained with insufficient time or resources to consider other topics that might be useful for managing and achieving the goals of the program. When the Act was passed in 2003, nanotechnology was new and very dynamic and relatively frequent detailed assessments were appropriate. As the NNI matures, the type of review that can help keep the program on the leading edge will evolve. Legislation enacted in 2017 amended the schedule for NNAP and National Academies reviews to every 4 years and extended the interval to 5 years for updating the strategic plan. However, the nature of the assessment has not been revised or made more flexible.

Concluding Thoughts

The NNI has been a poster child for how a government-led program can accelerate progress in a new area of technology by a coordinated investment in advancing knowledge combined with practical approaches to addressing potential risks and barriers to commercialization. Today, the NNI involves 20 federal agencies that collectively invest approximately $1.5 billion annually. The program's success stemmed from a combination of factors.

- Visionary founders: The NNI benefited from significant contributions by many individuals, and in particular by Mike Roco at NSF, who had vision and was indefatigable in his efforts to create and sustain the initiative. In addition, with his background in precision measurement and experience in related standards development Clayton Teague was the right person at the right time to be the first full-time NNCO director. Support from OSTP and OMB ensured that agencies prioritized nanotechnology in the critical early years.
- Good timing: Technical advances in the ability to characterize and manipulate matter at the scale of atoms and molecules set the stage for individual and coordinated agency investments that could address agency missions.
- Robust coordination: Establishing the NNCO provided essential support for coordination among agencies and between the federal government and other entities, including the private sector and the public.
- Attention to risk: The NNI included research and other activities aimed at understanding EHS and other societal implications of nanotechnology. To accomplish objectives in this area, regulatory agencies were engaged early in the program.

It is difficult to answer the question, "What would have happened if there hadn't been an NNI?" Nanoscale science would have advanced, though perhaps not at the same rate. It can be argued that nanotechnology served as the linchpin for converging multidisciplinary research, along with biotechnology and information technology. The emphasis on multidisciplinary research forced teams of researchers to collaborate. Supporting multidisciplinary programs required funding agencies to allow crossing of silos and boundaries among discipline-based programs and offices.

The NNI was unusual for the breadth of engagement and participation. Among the 20 federal agencies that joined the program are several that do not have significant research budgets but play essential roles in promoting innovation and managing risks. Enduring relationships among NSET representatives led to multiagency programs that would not have happened otherwise. Strategic engagement with industry at an early stage was invaluable in guiding researchers and research programs. To ensure that the United States had the necessary talent, the NNI supported nanotechnology education at all levels—both formal and informal.

What lies ahead for nanotechnology? Some nations have ended their separate nanotechnology programs. In part due to the 2003 Act, the US NNI continues to exist and supports activities aimed at growing nano-enabled technology—through research and education, and by focusing the program in areas where it can have a substantive impact. The NNI has built a foundation of knowledge and capability that can advance new priority areas, such as quantum information science.

There is still "plenty of room at the bottom." The design and creation of complex nanostructured materials and systems is in its infancy. The ability to manipulate atoms precisely remains largely a painstaking process and scaling to industrial manufacturing levels is a challenge. Based on the achievements to date, the power of the NNI to cross boundaries and build coalitions among federal agencies and with the private sector to address challenges—in energy, healthcare, nanoelectronics, aerospace, and myriad other applications—is sure to lead to even greater advances and opportunities in the next 15 years.

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