Development of the US National Nanotechnology Initiative in its First Decade

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This paper traces the development of the constituent base, the objectives and results of the US National Nanotechnology Initiative, primarily over the decade 2000–2009.

Introduction

The purpose of this article is to sketch the development of the United States' National Nanotechnology Initiative, mainly during the initial decade of the 21st century.[1] Starting in 1991, the National Science Foundation had operated a program on nanoparticles. Its next program, the cross disciplinary "Partnerships in Nanotechnology" was funded during 1997–1998.[2] By 1999 the Foundation began to unify complementary fields in nanoscale engineering and science, while an NSF-funded workshop produced this working definition of nanotechnology:[3]

> *Nanotechnology is the ability to control and restructure matter at the atomic and molecular levels in the range of approximately 1–100 nm, and exploiting the distinct properties and phenomena at that scale as compared to those associated with single atoms or molecules or bulk behavior. The aim is to create materials, devices and systems with fundamentally new properties and functions by engineering their small structure. This is the ultimate frontier to economically change materials properties, and the most efficient length scale for manufacturing and molecular medicine. The same principles and tools are applicable to different areas of relevance and may help establish a unifying platform for science, engineering and technology at the nanoscale. The transition from*

[1] The primary reference for this paper is: M.C. Roco, *J. Nanopart Res.* **13** (2011) 427–445, which was excerpted from *Nanotechnology Research Directions for Societal Needs in 2020*, Roco, M.C., Mirkin, C.A. and Hersham, M.C. (eds), National Science Foundation/World Technology Evaluation Center report. Springer (2010).

[2] National Science Foundation (1997) "Partnership in Nanotechnology" program announcement, Arlington, VA, http://www.nsf.gov/nano

[3] Roco, M.C., Williams, R.S. and Alivisatos, P. (eds), *Nanotechnology research directions: Vision for the Next Decade*. Springer (formerly Kluwer Academic Publishers) IWGN Workshop Report (1999). Washington DC: National Science and Technology Council. Also published in 2000 by Springer (http://www.wted.org/loyola/nano/IWGN.Research.Directions).

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single atoms' or molecules' behaviour to collective behaviour of atomic and molecular assemblies is encountered in nature and nanotechnology exploits this natural threshold.

An essential component of the definition (i.e., "*the application of scientific knowledge to manipulate and control matter in the nanoscale range to make use of size- and structure-dependent properties and phenomena distinct from those at smaller and larger scales*") was used by the International Organization for Standardization (ISO) to establish a common vocabulary for scientific discourse.[4] A more recent refinement of the definition of nanotechnology is included in the National Nanotechnology Initiative Strategic Plan for 2011.[5]

Inception of the National Nanotechnology Initiative

The seminal workshop report *Nanotechnology Research Directions* included a ten year R&D nanotechnology blueprint. The definition arrived at in 1999 formed a basis for the US National Nanotechnology Initiative (NNI) which was announced in January 2000 by President Clinton. The NNI is the US Federal Government's interagency program for coordinating research and development and enhancing communication and collaborative activities in nanoscale science, engineering and technology with the goal of pursuing new properties of matter and their practical applications. Over 60 countries, including Japan, the UK, the European Community, Germany, China, Korea and Taiwan, established national nanotechnology programmes in the interval 2001–2004.[6]

Growth of the field was vertiginous. Over the period 2000–2008 the average annual growth rate in the nanotechnology workforce was 25%.[7] Growth in scientific papers included in the Science Citation Index (SCI) was 23% per year.[8] Patent applications grew by 35% annually,[9] new products by 25%, R&D funding by 35% and venture capital investments by 30%.[10]

By 2009 the US Federal government's R&D investment in the NNI had increased to some 1.78 billion dollars, about 6.6 times larger than the expenditure in 2000.[11] It was accompanied by 1.9 billion dollars in industrial R&D funding. Jointly, these investments resulted in $91 billion in products, $18 billion in US tax revenue and 180,000 jobs in the United States. Worldwide government investment in nanotechnology totalled $7.8 billion In 2009. Beginning in 2006, industry R&D investment had exceeded government spending in the US and around the world. By 2010 cumulative funding of the NNI had reached 12 billion dollars, less only than the space program among nonmilitary S&T expenditures. (It is now $18 billion.)

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[4] ISO (International Organization for Standardization) (2010) TC 229 *Nanotechnologies* (re.: nanotechnology definition). http://www.iso.org/iso/iso_technical_committee.html?commid=381983

[5] National Nanotechnology Initiative Strategic Plan (2011), National Science and Technology Committee on Technology—Subcommittee on Nanoscale Science, Engineering and Technology, Washington, DC (http://nano.gov/sites/default/files/pub_resource/2011_strategic_plan.pdf).

[6] Roco, M.C., *AICHE J.* **50** (2004) 890–897.

[7] Roco, M.C., *J. Nanopart. Res.* **5** (2003) 181–189.

[8] Chen, H. and Roco, M.C., Mapping nanotechnology innovations and knowledge. Global and longitudinal patent and literature analysis series. Berlin: Springer (2009).

[9] Dang, Y., Zhang, Y., Fan, L., Chen, H. and Roco, M.C. *J. Nanopart. Res.* **12** (2010) 687–706.

[10] Huang, Z., Chen, Z., Che, Z.K. and Roco, M.C., *J. Nanopart. Res.* **6** (2004) 325–354; Huang, Z., Chen, H.Z., Yan, L. and Roco, M.C., *J. Nanopart. Res.* **7** (2005) 343–376.

[11] See Reference 1 and papers cited therein.

The original participants in the NNI were eight Federal agencies: the Departments of Defense, Energy and Transportation, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Institutes of Health, the National Institute of Standards and Technology, and the National Science Foundation (NSF). By 2010 the NNI was coordinating the activities of 25 Federal departments and independent agencies.

Scientific evolution of nanotechnology was projected to proceed through five phases, from first generation products, (passive nanostructures) in 2000, through active nanostructures (2005), to integrated nanosystems (2010), and molecular nanosystems (2015–2020) leading eventually to converging technologies that would incorporate large complex systems.

The NNI identified five strategic initiatives for investment between 2001 and 2005. These were: (1) support fundamental research; (2) establish priority research areas such as designed materials, healthcare and environmental improvement; (3) institute centres of excellence; (4) create a stable infrastructure; and (5) consider societal implications and develop educational programs.

During financial years (FY) 2006 to 2010 the goals were focused further in successive NNI strategic plans[12] to: (1) advance a world-class R&D program; (2) foster technology transfer into products; (3) develop educational resources, a skilled workforce, infrastructure and tools; and (4) maintain and develop ethical standards *vis à vis* nanotechnology.

NNI Organizational and Functional Evolution

The NNI is a partnership between 27 federal research and regulatory agencies coordinated by the White House's Office of Science and Technology Policy underlying the broad implications of nanotechnology on society. NNI policymakers believed that management of nanotechnology development should have the attributes of being transformative, responsible, inclusive, and visionary. The following examples are offered of the realization of these attributes.

Development of Nanoscale Science and Engineering Centers has been focused on scientific and engineering breakthroughs, while the National Nanomanufacturing Network (NNN) has been focused on transformative nanomanufacturing. Results of the investment in nanotechnology were seen in new instrumentation (Sandia National Laboratories), nanoparticles (DuPont), nanocomponents (General Electric) and carbon nanotube cables and sheets (National Reconnaissance Office).

Recognizing science's obligation to communicate in society, NSF made awards in support of social aspects of nanotechnology. Networks were established, directed at high school and undergraduate nanotechnology education, nanotechnology in society, and informal nanotechnology science education. Also, NNI fostered nanotechnology programs in environmental, health and safety research while maintaining interagency and international collaboration on standards and regulation.

The goal of inclusiveness was met by incorporating diverse stakeholders (i.e., by including all interested Federal agencies in the planning process); by inviting the public to participate in strategy development; by encouraging cross-disciplinary R&D programs; by fostering a network of 34 local, state and regional nanotechnology alliances; and by supporting international conversations and collaborations.

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[12] NSTC/NSET (Nanoscale Science, Engineering and Technology Subcommittee of the National Science and Technology Council Committee on Technology), *The National Nanotechnology Initiative Strategic Plan*. Washington, DC (2004, 2007, 2010) (http://www.nano.gov/html/res/pubs.html).

The organizers of NNI have taken a long, 20-year view in establishing a strategic plan, leading to a formative long-term vision. It is being realized by encouraging the integration of nanotechnology with other long-term technologies (i.e, combining nanotechnology with biology and information technology); developing long-term partnerships such as the Nanoelectronics Research Initiative; through the initial vision of nanotechnology governance; through support from NSF of the Centers for Nanotechnology in Society; and by the setting early on of the "grand challenges" listed below. These were supplemented by discrete challenges for R&D efforts (called "signature initiatives"), also listed.

Grand challenges advanced by the NNI strategy in 2000–2005 are:

- Nanostructured materials by design
- Manufacturing at the nanoscale
- Chemical–biological–radiological–explosive detection and protection
- Nanoscale instrumentation and metrology
- Nano-electronics, -photonics, and -magnetics
- Healthcare, therapeutics, and diagnostics
- Efficient energy conversion and storage
- Microcraft and robotics
- Nanoscale processes for environmental improvement.

Nanotechnology signature initiatives included in the NNI strategy since 2011 are:[13]

- Nanotechnology applications for solar energy
- Sustainable nanomanufacturing—creating the industries of the future
- Nanoelectronics for 2020 and beyond
- Nanotechnology for sensors and sensors for nanotechnology
- Nanotechnology knowledge infrastructure—enabling national leadership in sustainable design.

Conclusions

Ten years since its inception the NNI recognized that some initial objectives had not yet been fully met, while others were entirely "on track", and some had yielded better results than anticipated.

Roco[14] has asserted that, as of 2010, principles and processes for creating "materials by design" were still lacking. Certain sustainable development projects in energy, water purification and climate research were moving more slowly than anticipated. Achieving a better level of public awareness about nanotechnology remained a challenge. On the other hand, interdisciplinary education and research had produced numerous multidisciplinary projects and scientific interactions. As noted above, significant progress was evinced by the impressive production of scientific papers and inventions, growing at 23–35% annually. This was more than twice the average growth rate for all scientific fields. It was mirrored by the rate of growth in US nanotechnology R&D investment.

Certain results stemming from the NNI exceeded expectations. By 2008, major industrial involvement in nanotechnology had led to papers, patents and/or products from more than

[13] See Reference 12 for the 2010 Strategic Plan.
[14] See Reference 1.

5400 US companies. Significant discoveries either involved existing fields or led to the invention of new ones, in plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering and quantum information systems. Creation of the NNI also contributed to the formation and increasing viability of the international nanotechnology community, a constructive and satisfying development.

Future perspectives for nanotechnology include immediate opportunities for R&D in the areas of simulation, theory and measurement. Expansion will take place into relevant areas of science including energy, nanomedicine and engineering. Development is needed in the areas of food and agriculture, textiles, plastics, wood, paper and water purification. Long term opportunities will include the creation of active, multicomponent nanosystems, and the widespread utilization of nanostructured electronics, materials, chemicals and pharmaceuticals.