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EDITORIAL

The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years

Mihail C. Roco

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Abstract A global scientific and societal endeavor was set in motion by the nanotechnology vision formulated in 1999 that inspired the National Nanotechnology Initiative (NNI) and other national and international R&D programs. Establishing foundational knowledge at the nanoscale has been the main focus of the nanotechnology research community in the first decade. As of 2009, this new knowledge underpinned about a quarter of a trillion dollars worldwide market, of which about $91 billion was in US products that incorporate nanoscale components. Nanotechnology is already evolving toward becoming a general-purpose technology by 2020, encompassing four generations of products with increasing structural and dynamic complexity: (1) passive nanostructures, (2) active nanostructures, (3) nanosystems, and (4) molecular nanosystems. By 2020, the increasing integration of nanoscale science and engineering knowledge and of nanosystems promises mass applications of nanotechnology in industry, medicine, and computing, and in better comprehension and conservation of nature. Nanotechnology's rapid development worldwide is a testimony to the transformative power of identifying a concept or trend and laying out a vision at the synergistic confluence of diverse scientific research areas. This chapter provides a brief perspective on the development of the NNI since 2000 in the international context, the main outcomes of the R&D programs after 10 years, the governance aspects specific to this emerging field, lessons learned, and most importantly, how the nanotechnology community should prepare for the future.

Keywords Nanoscale science and engineering · Research opportunities · Research outcomes · Forecast · International perspective · Governance

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M. C. Roco (✉)
National Science Foundation, 4201 Wilson Blvd, Arlington, VA 22230, USA
e-mail: mroco@nsf.gov

The import of a research-oriented definition of nanotechnology

The National Science Foundation (NSF) established its first program dedicated to nanoparticles in 1991 and from 1997–1998 funded a cross-disciplinary program entitled "Partnerships in Nanotechnology" (NSF 1997). However, only in 1998–2000 were fragmented fields of nanoscale science and engineering brought together under an unified science-based definition and a 10-year R&D vision for nanotechnology. These were laid out in the 1999 National Science Foundation workshop report, *Nanotechnology Research Directions* (Roco et al.

1999), which was adopted in 2000 as an official document by National Science and Technology Council (NSTC). These were the significant steps toward establishing nanotechnology as a defining technology of the 21st century. The definition of nanotechnology (see sidebar) was agreed to in 1998–1999 after consultation with experts in over 20 countries (Siegel et al. 1999) and achieved some degree of international acceptance. This definition is based on novel behavior of matter and ability of scientists to restructure that matter at an intermediate length scale. This is conceptually different from the previous definitions used before 1999 that were focused on either small features under a given size, ultra-precision engineering, ultra-dispersions, or creating patterns of atoms and molecules on surfaces. The internationally generated vision published in 1999 provides guidance for nanotechnology discovery and innovation in this cross-disciplinary, cross-sector domain. It has become clear after about 60 countries developed nanotechnology activities by 2004 that without this definition and corresponding long-term vision, nanotechnology would have not been developed on the same accelerated, conceptually unifying and transforming path (Roco 2004).

Definition of nanotechnology (set out in *Nanotechnology Research Directions*, 1999)[1]

Nanotechnology is the ability to control and restructure the 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 single atoms or molecules behavior to collective behavior of atomic and molecular assemblies is encountered in nature, and nanotechnology exploits this natural threshold.

In 2010, the International Standardization Organization (ISO) Technical Committee 229 on nanotechnologies (ISO 2010) issued a definition of nanotechnology that essentially has the same elements as those of the 1999 definition: 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 or larger scales. Full acceptance and use of the ISO definition in the environmental, health, and safety (EHS) community has not yet been resolved (Lövestam et al. 2010). Nevertheless, in 1999 as now, there has been a shared acceptance of the value of clearly defining nanotechnology to support common language and purpose for scientific discourse, engineering, education, manufacturing, commerce, regulation, and tracking of investments. Defining the long-term vision for nanotechnology development is especially critical because of nanotechnology's rapid emergence as a fundamentally new scientific and engineering paradigm and because of its broad implications for societal wellbeing.

The 1999 unifying definition of and long-term vision for nanotechnology paved the way for the US National Nanotechnology Initiative (NNI), announced in January 2000. The main reasons for beginning the NNI were to fill major gaps in fundamental knowledge of matter and to pursue the novel and economic applications anticipated for nanotechnology. Coherent and sustained R&D programs in the field were soon announced by other nations: Japan (April 2001), Korea (July 2001), the European Community (March 2002), Germany (May 2002), China (2002), and Taiwan (September 2002). Over 60 countries established programs at a national level between 2001 and 2004, partially inspired or motivated by the NNI. However, the first and largest such program was the NNI itself. Its cumulative funding since 2000 of more than $12 billion, including about $1.8 billion in 2010, places the NNI second only to the space program in the US civilian science and technology investments. This 2010 international study, involving experts from over 35 countries, aims to redefine the goals for nanotechnology development for the next decade.

Indicators of nanotechnology development globally, 2000–2020

Six key indicators, described below and in Table 1, help portray the value of investments in nanotechnology development and associated science breakthroughs and technological applications. These indicators show

[1] (Roco et al. 1999).

Table 1 Six key indicators of Nanotechnology Development in the World and the US

World */US/*	People primary workforce	SCI papers	Patent applications	Final products market	R&D funding public + private	Venture capital
2000 (actual)	**~60,000** */25,000/*	**18,085** */5,342/*	**1,197** */405/*	**~$30 B** */$13 B/*	**~$1.2 B** */$0.37 B/*	**~$0.21 B** */$0.17 B/*
2008 (actual)	**~400,00** */150,000/*	**65,000** */15,000/*	**12,776** */3,729/*	**~$200 B** */$80 B/*	**~$15 B** */$3.7 B/*	**~$1.4 B** */$1.17 B/*
2000–2008 (average growth)	**~25%**	**~23%**	**~35%**	**~25%**	**~35%**	**~30%**
2015 (2000 estimate)[a]	**~2,000,000** */800,000/*			**~1,000 B** */$400 B/*		
2020 (extrapolation)	**~6,000,000** */2,000,000/*			**~$3,000 B** */$1,000 B/*		

Global figures are indicated in *bold*; US figures are indicated in *italics*. SCI papers and patent applications were searched by title-abstract keywords, using the method described in Chen and Roco (2009). Venture capital estimations were made by Lux Research; see Chapter 13, Sect. 13.8.11

[a] Roco and Bainbridge (2001)

average annual growth rates worldwide of approximately 25% between 2000 and 2008. The average growth rates of all indicators fell by more than half worldwide during the financial crisis of 2009. They appear to be returning to higher rates in 2010 compared to 2009, but with significant differences between countries and domains of relevance.

1. *The number of researchers and workers involved in one domain or another of nanotechnology* was estimated at about 400,000 in 2008, of which about 150,000 were in the United States. The estimate made in 2000 that there would be 2 million nanotechnology workers worldwide by about 2015 (800,000 in the United States) would have been realized if the 25% rate growth had continued. The initial 2000 estimation for quasi-exponential growth in the nanotechnology workforce (Roco 2003a) held up to 2008, and because of new generations of nanotechnology products envisioned to enter the market within the next few years, it is expected to continue.
2. *The number of Science Citation Index (SCI) papers* reflecting discoveries in the area of nanotechnology reached about 65,000 in 2008 as compared to 18,085 in 2000, based on a title–abstract keyword search (Chen and Roco 2009). The increase is rapid and uneven around the world, as suggested by Fig. 1. About 4.5% of SCI papers published in 2008 in all areas included nanoscale science and engineering aspects.
3. *Inventions reflected by the number of patent applications filed* in the top 50 depositories was about 13,000 in 2008 (of which 3,729 were filed at the US Patent and Trade Office, USPTO), as compared to about 1,200 in 2000 (of which 405 were filed at USPTO) (Huang et al. 2004, 2005), with an annual growth rate of about 35%, as shown in Fig. 2. The patent applications in over 50 national or international patent depositories were searched by using the title–abstract keyword search. About 0.9% of patent applications published worldwide, and about 1.1% at USPTO in 2008 in all areas, included nanoscale science and engineering aspects.
4. *The value of products incorporating nanotechnology as the key component* reached about $200 billion in value worldwide in 2008, of which about $80 billion was in the US (these products relied on relatively simple nanostructures). The estimation made in 2000 (Roco and Bainbridge 2001) for a product value of $1 trillion by 2015, of which $800 billion would be in the US, still appears to hold (see Fig. 3). The market is doubling every 3 years as a result of successive introduction of new products. The Lux Research estimate for the 2009 market worldwide was about $254 billion (Chapter 13, Sect. 13.8.11 in Roco et al. 2010), about on the 2000 estimated curve,

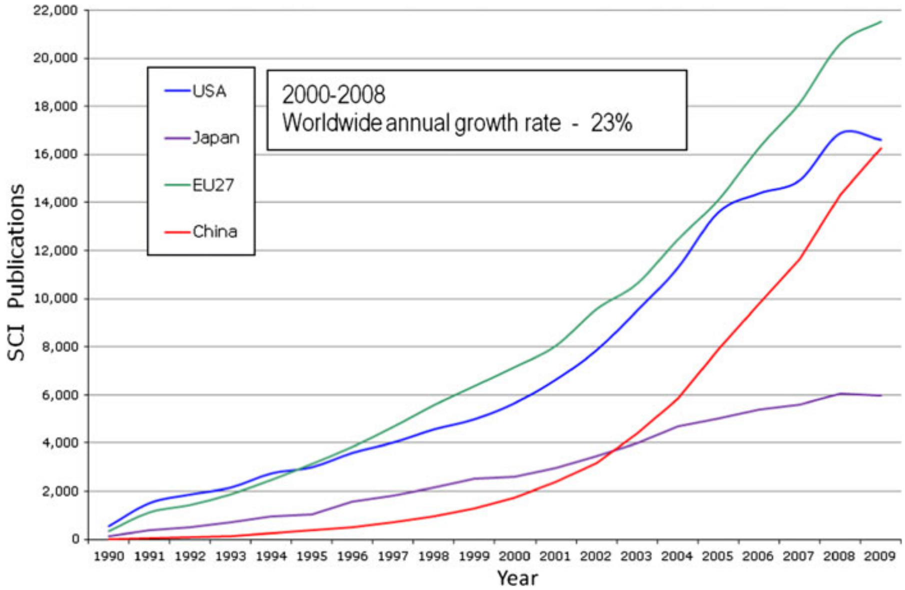

Fig. 1 Nanotechnology publications in the SCI 1990–2009. Data was generated from an online search in the Web of Science using a "title–abstract" search in SCI database for nanotechnology by keywords (courtesy of H. Chen, Y. Dang, and M. Roco)

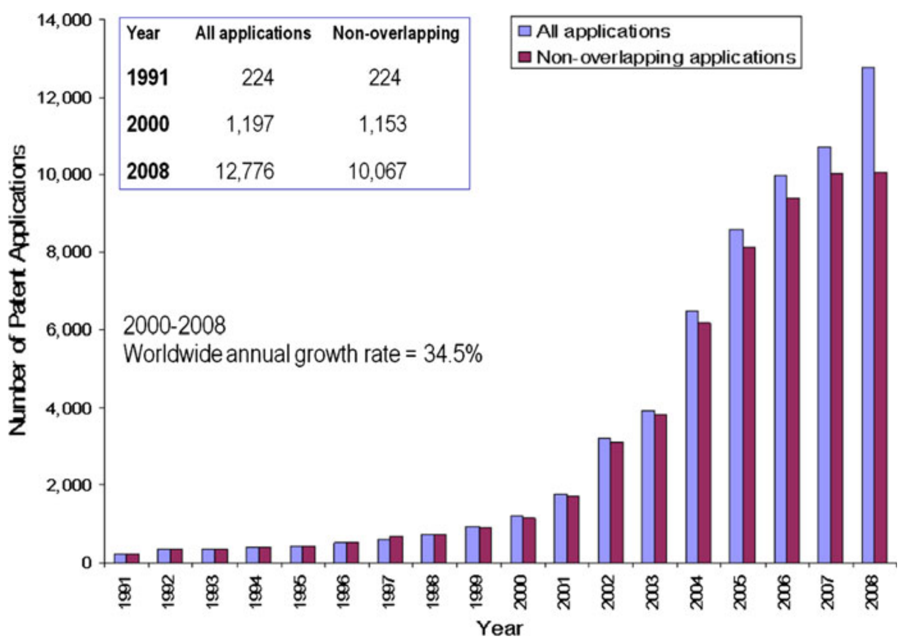

Fig. 2 Total number of nanotechnology patent applications in 15 leading patent depositories in the world from 1991 to 2008. Two sets of data are reported based on the number of all nanotechnology patent applications and the number of non-overlapping nanotechnology patent applications (by considering one patent application per family of similar patents submitted at more than one depository) (Dang et al. 2010)

although the Lux estimate for the value of US nanotechnology products in 2009 of about $91 billion was about 10% under the 2000 estimated growth curve.

5. *Global nanotechnology R&D annual investment from* private and public sources reached about $15 billion in 2008, of which about $3.7 billion was in the US, including the Federal Government contribution of about $1.55 billion.
6. *Global venture capital investment in nanotechnology* reached about $1.4 billion in 2008, of which about $1.17 billion was in the US (courtesy Lux Research 2010). Venture capital funds decreased about 40% during the 2009 financial

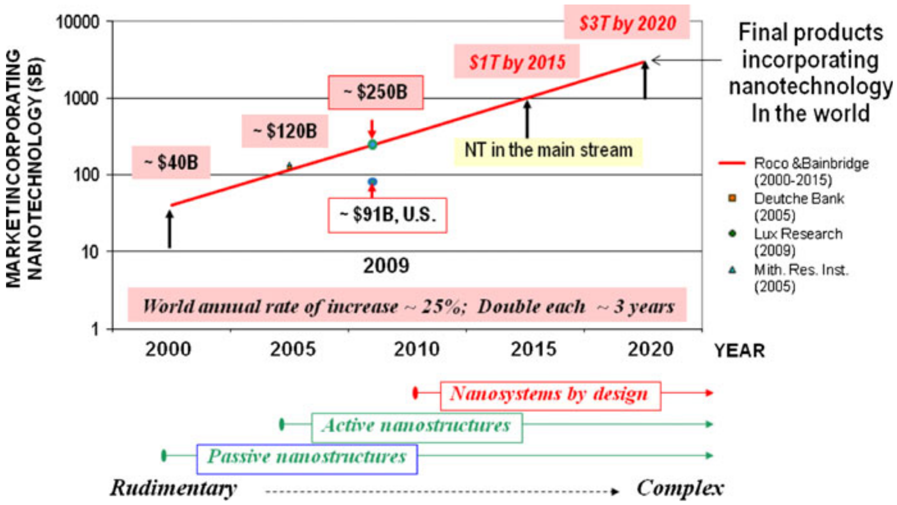

Fig. 3 Market timeline: projection for the worldwide market of finite products that incorporate nanotechnology (estimation made in 2000 at NSF; Roco and Bainbridge 2001). These estimations were based on direct contacts with leading experts in large companies with related R&D programs in the US, Japan, and Europe, as part of the international study completed between 1997 and 1999 (Siegel et al. 1999)

Table 2 Examples of penetration of nanotechnology in several industrial sectors

US	2000	2010	Est. in 2020 (%)
Semiconductor industry	0 (with features < 100 nm)	60% (~$90 B)	100
	0 (new nanoscale behavior)	30% (~$45 B)	100
New nanostructured catalysts	0	~35% (~35B impact)	~50
Pharmaceutics (therapeutics and diagnostics)	0	~15% (~$70 B)	~50
Wood	0	0	~20

The market percentage and its absolute value affected by nanotechnology are shown for 2010

crisis (see Chapter 13, Sect. 13.8.11 in Roco et al. 2010).

Because of the technological and economic promise, nanotechnology has penetrated the emerging and classical industries especially after 2002–2003. The increase in nanocomponent complexity and the proportion of nanotechnology penetration is faster in emerging areas such as nanoelectronics and slower in more classical industry sectors such as wood and paper industry as illustrated in Table 2. Penetration of nanotechnology in key industries is related to the percentage industry spends on R&D. Penetration of nanotechnology in two biomedical eras is exemplified in Chapter 13 (Sect. 13.8.10 in Roco et al. 2010).

Figure 4 shows the balance of Federal nanotechnology investments and return on investments (outputs) in the US in 2009. Other specific indicators of the national investment in nanotechnology have increased significantly in the US since 2000.

- The specific annual Federal R&D nanotechnology expenditure per capita has grown from about $1 in fiscal year (FY) 2000 to about $5.7 in 2010.
- The fraction of the Federal R&D nanotechnology investment as compared to all actual Federal R&D expenditures grew from 0.39% to about 1.5% in 2008.

Qualitative changes also are important to evaluating the impact of the NNI, even if there is no single indicator to characterize them. These include (1) the creation of a vibrant multidisciplinary, cross-sector, international community of professionals and organizations engaged in various dimensions of the nanotechnology enterprise; (2) changes in the scientific research culture that are coming about through energizing interdisciplinary academic research collaborations with industry and the medical field; and (3) increasingly unified concepts for engineering complex nanostructures "from the bottom up" for new materials, biology and healthcare technologies,

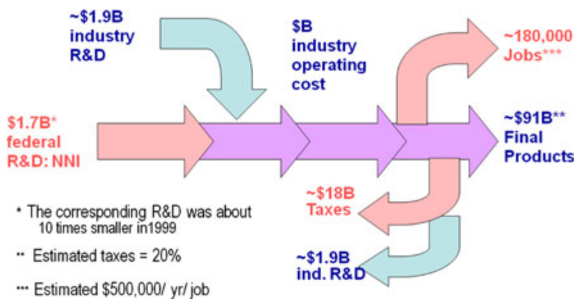

Fig. 4 Estimation of the outcomes of US federal investment in nanotechnology R&D in 2009. The figure shows an annual balance between investments and outputs. *The corresponding R&D was about ten times smaller in 1999 when the fundamental research for 2009 products may have started. **The estimated market of products where nanoscale components are essential; taxes are estimated based on Council of Chemical Research average estimation for chemical industry. ***Estimated number of nanotechnology-related jobs, assuming about $500,000/year/job

digital information technologies, assistive cognition technologies, and multicomponent systems.

Two foundational steps in nanotechnology development

In 2000, it was estimated that nanotechnology would grow in two foundational phases from passive nanostructures to complex nanosystems by design (illustrated in Figs. 5, 6):

The first foundational phase (2001–2010), which was focused as anticipated on inter-disciplinary research at the nanoscale, took place in the first decade after defining the long-term vision. Its main results are discovery of new phenomena, properties, and functions at the nanoscale; synthesis of a library of components as building blocks for potential future applications; tool advancement; and improvement of existing products by incorporating relatively simple nanoscale components. This phase, dominated by a science-centric ecosystem, might be called "Nano 1."

The second foundational phase (2011–2020), will be focused on nanoscale science and engineering integration, is projected to transition toward direct measurements with good time resolution, science-based design of fundamentally new products, and general-purpose and mass use of nanotechnology. The focus of R&D and applications is expected to shift toward more complex nanosystems, new areas of relevance, and fundamentally new products. This phase is expected to be dominated by an R&D ecosystem driven by socio-economic considerations; it might be called "Nano 2."

The transition from the Nano 1 phase to the Nano 2 phase is focused on achieving direct measurements at the nanoscale, science-based design of

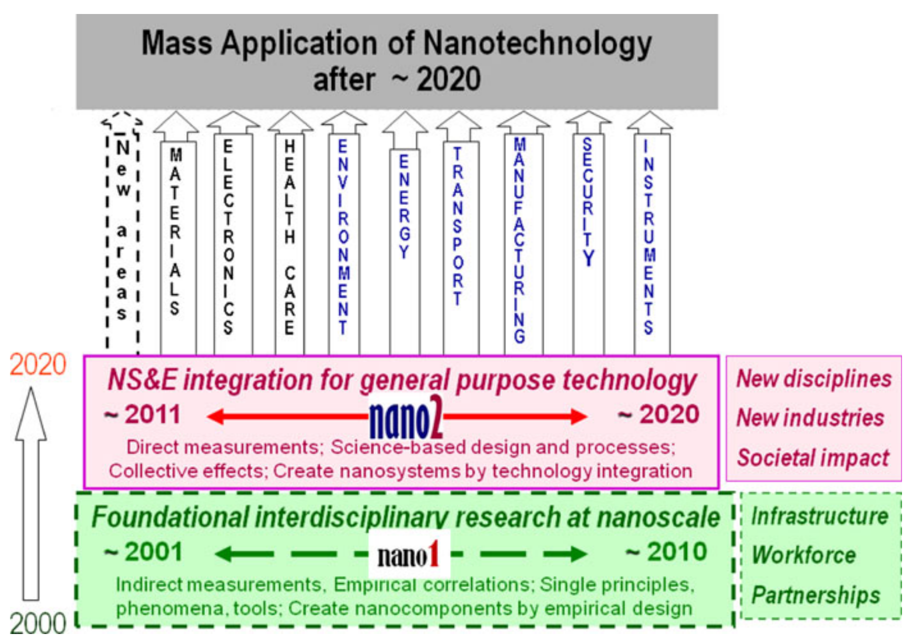

Fig. 5 Creating a new field and community in two foundational phases ("NS&E" is nanoscale science and engineering)

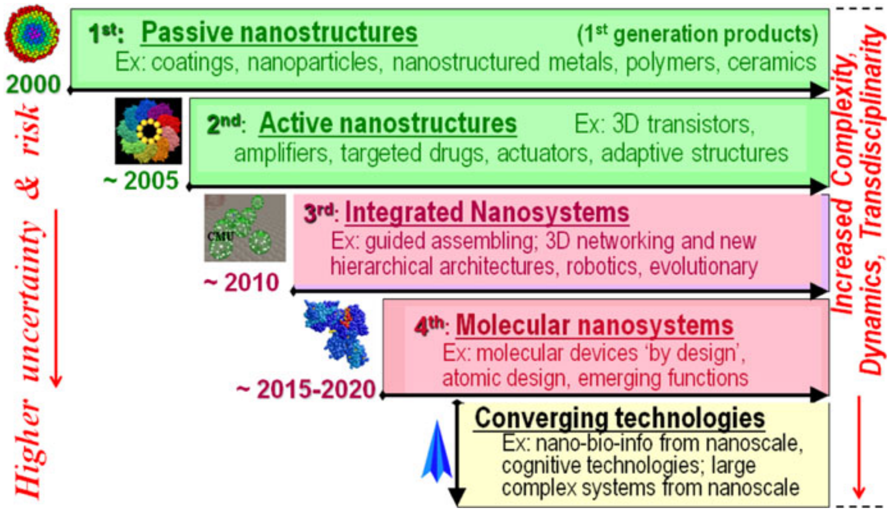

Fig. 6 Timeline for the beginning of industrial prototyping and nanotechnology commercialization: introduction of new generations of products and productive processes in 2000–2020 (Roco 2004, 2006)

Table 3 Transition between the two predominant phases in nanotechnology development, 2000–2020

Interval	2001–2010 ("Nano 1")	2011–2020 ("Nano 2")
Measurements	Indirect, using time and volume averaging approaches	Direct, with atomic precision in the biological or engineering domains, and femtosecond resolution
Phenomena	Discovery of individual phenomena and nanostructures	Complex simultaneous phenomena; nanoscale integration
New R&D paradigms	Multidisciplinary discovery from the nanoscale	Focus on new performance; new domains of application; an increased focus on innovation
Synthesis and manufacturing processes	Empirical/semi-empirical; dominant: top-down miniaturization; nanoscale components; polymers and hard materials	Science-based design; increasing molecular bottom-up assembly; nanoscale systems; increasingly bio-based processes
Products	Improved existing products by using nanocomponents	Revolutionary new products enabled by creation of new systems; increasing bio-medical focus
Technology	From fragmented domains to cross-sector clusters	Toward emerging and converging technologies
Nanoscience and engineering penetration into new technologies	Advanced materials, electronics, chemicals, and pharmaceuticals	Increasing to: nanobiotechnology, energy resources, water resources, food and agriculture, forestry, simulation-based design methods; cognitive technologies
Education	From micro- to nanoscale based	Reversing the pyramid of learning by earlier learning of general nanotechnology concepts (Roco 2003b)
Societal impact	Ethical and EHS issues	Mass application; expanding sustainability, productivity, and health; socio-economic effects
Governance	Establish new methods; science-centric ecosystem	User-centric ecosystem; increasingly participatory; techno-socio-economic approach
International	Form al S&T community; establish nomenclature, patent, and standards organizations	Global implications for economy, balance of forces, environment, sustainability

nanomaterials and nanosystems, and general-purpose technology integration (Table 3). Several R&D targets for achievement by 2020 are presented in this chapter and detailed in this volume.

After 2020, nanotechnology R&D is projected to develop closely with other emerging and converging technologies, creating new science and engineering domains and manufacturing paradigms (Roco 2002;

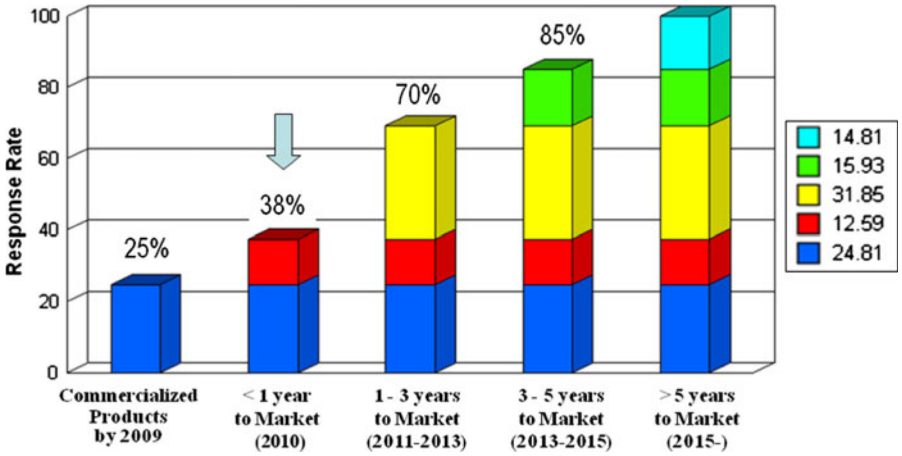

Fig. 7 A shift to more new commercial products is estimated after 2011 (after Fig. 4–31, NCMS 2010)

Roco and Bainbridge 2003). In 1999/2000, a convergence was reached in defining the nanoscale world because typical phenomena in material nanostructures were better measured and understood with a new set of tools, and new nanostructures had been identified at the foundations of biological systems, nanomanufacturing, and communications. The new challenge for the next decade is building systems from the nanoscale that will require the combined use of nanoscale laws, biological principles, information technology, and system integration. After 2020, one may expect divergent trends as a function of system architectures. Several possible divergent trends are system architectures based on guided molecular and macromolecular assembling, robotics, biomimetics, and evolutionary approaches.

A shift in research toward "active nanostructures" that change their composition or state during use has been noted in the rapid increase of related publications since 2005 (Subramanian et al. 2009). The percent of papers on active nanostructures more than doubled to 11% of total nanotechnology papers in 2006. An observed transition to introduction of nanosystems appears to be correlated to commercial interests (Fig. 7, NCMS 2010); more than 50% of 270 surveyed manufacturing companies expressed interest in production or design using nanoscale science and engineering by about 2011.

Genesis and structure of the National Nanotechnology Initiative

As the then Chair of the NSTC's Interagency Working Group on Nanoscale Science, Engineering, and Technology (IWGN),[2] the author had the opportunity to propose the NNI with an annual budget of about 1/2 billion dollars on March 11, 1999, at a meeting of the White House Economic Council (EC) and the Office of Science and Technology Policy (OSTP) as part of a competition for a national research priority to be funded in FY 2001. The approval process moved to the Office of Management and Budget (OMB) in November 1999, the Presidential Council of Advisors in Science and Technology (PCAST) in December 1999, and the Executive Office of the President in January 2000. Hearings were held in the House and Senate of the United States Congress in the Spring of 2000. In November 1999, the OMB recommended nanotechnology as the only new R&D initiative for FY 2001. On December 14, 1999, PCAST highly recommended that the President fund nanotechnology R&D. Thereafter, it was a quiet month: the Executive Office of the President advised the working group to restrain from speaking to the media because a White House announcement would be made.

President Clinton announced the NNI at a speech at the California Institute of Technology (Caltech) in January 2000, asking listeners to imagine the new world that nanotechnology could make possible. After his speech, the IWGN moved firmly to prepare

[2] The IWGN was superseded in August 2000 by the Nanoscale Science, Engineering and Technology (NSET) Subcommittee of the NSTC Committee on Technology. In 1999 Neil Lane was the Director of OSTP, and Tom Kalil was Deputy Director of the White House National Economic Council and the White House co-chair of the IWGN. Jim Murday was the secretary of IWGN.

the Federal plan for R&D investment in nanotechnology and to identify key opportunities and potential participation of various agencies in the proposed initiative. House and Senate hearings brought the needed recognition and feedback from Congress. Representing the working group, the author spoke to major professional societies (the American Chemical Society, the Institute for Electric and Electronics Engineering, the American Society of Mechanical Engineering, and the American Institute of Chemical Engineering), and attended national meetings in about 20 countries to introduce the new US nanotechnology initiative. The NNI has been implemented since FY 2001, with unbroken support from the Clinton, Bush, and Obama Administrations.

A challenge in the early years of the initiative, with so many new developments, was maintaining consistency, coherence, and original thinking. The definition of nanotechnology, the initiative's name, and the name of the National Nanotechnology Coordination Office (NNCO) were decided in 1999–2000. The NNI's name was proposed on March 11, 1999, but it was held under "further consideration" until the Presidential announcement, due to concerns from several professional societies and committees that it did not explicitly include the word "science." The simple name "NNI" was selected to better show its relevance to society.

The NNI is a long-term R&D program that began in FY 2001 with participation from 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. As of 2010, the NNI coordinates the nanotechnology-related activities of 25 Federal departments and independent agencies. Table 4 lists the full membership in 2010. The NSTC coordinates the initiative through the efforts of the agency members of the Nanoscale Science and Engineering (NSET) Subcommittee of the NSTC Committee on Technology. Assisting the NSET Subcommittee is the NNCO, which provides technical and administrative support. The NSET Subcommittee has chartered four working groups: the Global Issues in Nanotechnology (GIN) Working Group; the Nanomanufacturing, Industry Liaison, and Innovation (NILI) Working Group; the Nanotechnology Environmental and Health Implications Working Group (NEHI); and the Nanotechnology Public Engagement and Communications Working Group (NPEC).

Table 4 NNI Members (25 Federal Departments and Agencies) in September 2010

Federal agencies with budgets dedicated to Nanotechnology Research and Development
Consumer Product Safety Commission (CPSC)
Department of Defense (DOD)
Department of Energy (DOE)
Department of Homeland Security (DHS)
Department of Justice (DOJ)
Department of Transportation (DOT, including the Federal Highway Administration, FHWA)
Environmental Protection Agency (EPA)
Food and Drug Administration (FDA, Department of Health and Human Services)
Forest Service (FS, Department of Agriculture)
National Aeronautics and Space Administration (NASA)
National Institute for Occupational Safety and Health (NIOSH, Department of Health and Human Services)
National Institute of Food and Agriculture (NIFA, Department of Agriculture)
National Institutes of Health (NIH, Department of Health and Human Services)
National Institute of Standards and Technology (NIST, Department of Commerce)
National Science Foundation (NSF)
Other participating agencies
Bureau of Industry and Security (BIS, Department of Commerce)
Department of Education (DOEd)
Department of Labor (DOL)
Department of State (DOS)
Department of the Treasury (DOTreas)
Intelligence Community (IC)
Nuclear Regulatory Commission (NRC)
US Geological Survey (USGS, Department of the Interior)
US International Trade Commission (USITC, a non-voting member)
US Patent and Trademark Office (USPTO, Department of Commerce)

The NNI organizing principles

The NNI's long-term view of nanotechnology development aims to enable exploration of a new domain of scientific knowledge and incorporation of a transformational general-purpose technology into the national technological infrastructure, with a twenty-year view to reach some degree of systematic control of matter at the nanoscale and mass use (Roco 2007). The vision that "systematic control of matter at the nanoscale will lead to a revolution in technology and economy for societal benefit" is still the guiding principle of the initiative.

During the 10-year time span of FYs 2001–2010, a thriving interdisciplinary nanotechnology community of about 150,000 contributors has emerged in the US, along with a flexible R&D infrastructure consisting of about 100 large nanotechnology-oriented R&D centers, networks, and user facilities, and an expanding industrial base of about 3,000 companies producing nanotechnology-enabled products. Considering the complexity and rapid expansion of the US nanotechnology infrastructure, the participation of a coalition of academic, industry, business, civic, governmental, and nongovernmental organizations in nanotechnology development is becoming essential and complementary to the centralized approach of the NNI. The leadership role of the Federal government through the NNI must continue in support of basic research, restructuring the education pipeline, and guiding responsible development of nanotechnology as a transformative scientific schema, as envisioned in 2000. At the same time, however, the emphasis of government leadership in nanotechnology development is changing toward increasing support of R&D for innovation, nanomanufacturing, and societal benefit, while the private sector's responsibility is growing for funding R&D in nanotechnology applications. Since 2006, private nanotechnology R&D funding in the US has exceeded public funding.

Several means to ensure accountability are built into the 21st Century Nanotechnology Research and Development Act that governs the NNI (P.L. 108–153, 15 USC 7501, of the US Congress, December 3, 2003). With extensive input from NSET Subcommittee agency members, the NNI organizations submit to Congress every February an annual report on the NNI and a combined nanotechnology budget request. OMB manages and evaluates the NNI budget crosscut. Following the *Nanotechnology Research Directions* report published in 2000, NNI leadership prepares a Strategic Plan every 3 years (2004, 2007, and 2010). The NNI is evaluated every 3 years by the National Research Council of the National Academies and periodically by PCAST in its role as the National Nanotechnology Advisory Panel. Ad hoc evaluations by the Government Accountability Office and other organizations help ensure best use of taxpayer funds and respect for the public interest.

The organizing principles of the NNI have undergone two main stages between 2001 and 2010, and a third stage is projected to begin in FY 2011:

a. *Between FY 2001 and 2005*, nanotechnology research under the NNI was focused on five modes of investment: (1) fundamental research, (2) priority research areas, (3) centers of excellence, (4) infrastructure, and (5) societal implications and education. The second mode, collectively known as "grand challenges," focused on nine specific R&D areas directly related to applications of nanotechnology; they also were identified as having the potential to realize significant economic, governmental, and societal impact in about a decade. These priority research grand challenge areas were:

– 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

Focused research programs and major infrastructure initiatives in the first 5 years led to the formation of the US nanoscale community, a strong R&D infrastructure, and new nanotechnology education programs.

b. *Between FY 2006 and 2010*, nanotechnology research under the NNI was focused on four goals and seven or eight investment categories (NSTC/NSET 2004, 2007). The goals are to (1) advance a world-class research and development program; (2) foster the transfer of new technologies into products for commercial and public benefit; (3) develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology; and (4) support responsible development of nanotechnology. The NNI investment categories

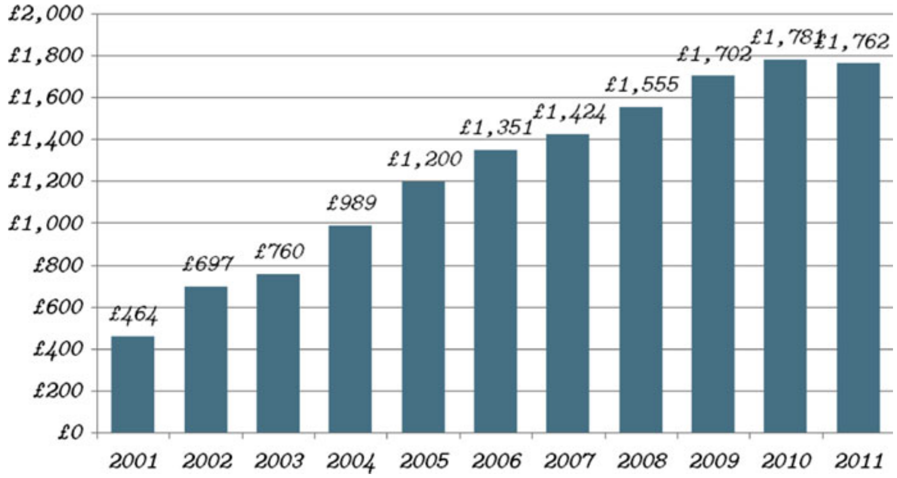

Fig. 8 NNI budgets for FYs 2001–2011 not including the one-time supplemental ARRA funding in 2009 of $511 million

(originally seven, amended in 2007 to eight categories), called program component areas (PCAs), are:

– Fundamental nanoscale phenomena and processes
– Nanomaterials
– Nanoscale devices and systems
– Instrumentation research, metrology, and standards for nanotechnology
– Nanomanufacturing
– Major research facilities and instrumentation acquisition
– Environment, health, and safety
– Education and societal dimensions

c. *Beginning in FY 2011*, the NNI will introduce three research and development "signature initiatives" for important long- and short-term application opportunities[3]: (1) Nanotechnology Applications for Solar Energy, (2) Sustainable Nanomanufacturing, and (3) Nanoelectronics for 2020 and beyond. Other research "signature initiatives," and plans to enhance the innovation ecology and societal outcomes of nanotechnology, are under consideration (NSTC/NSET 2010).

NNI investment in nanotechnology R&D

The NNI's total R&D investment for nanotechnology has increased about 6.6-fold in the past decade, from $270 million in FY 2000 to about $1.8 billion in FY 2010, as shown in Fig. 8. All numbers shown in the figure are actual spending, except for FY 2010, which shows estimated spending for the current year, and FY 2011, which shows the requested budget for next year. The FY 2009 spending shown does not include $511 million in additional funding under the American Recovery and Reinvestment Act (ARRA). The 2011 budget request shown here does not include Department of Defense (DOD) earmarks included in previous years ($117 million in 2009).

Table 5 estimates various individual government budgets and the European Union (EU) budgets for nanotechnology globally using the NNI definition and direct contacts with program managers in other countries. The 2009 government investments around the word totaled about $7.8 billion, of which $1.7 billion was in the US (through the NNI), without including the one-time ARRA funding in 2009 of $511 million. Although the figures in Table 5 for other countries' nanotechnology investments are just a general gauge of activity, it appears in very broad terms that whereas US nanotechnology investment is rising, it is rising slower than the investment of other nations.

The government nanotechnology R&D investments are plotted in Fig. 9 for EU, Japan, US and "Other" countries as defined in Table 5. One notes the change of the global investment rate about 2000 after the announcement of NNI and about 2005–2006 corresponding to the introduction of the second generation of nanotechnology products with the first industry prototypes based on active nanostructures. In 2006, industry nanotechnology R&D investment

[3] Details are available at http://www.nano.gov/html/research/signature_initiatives.html.

Table 5 Estimated government nanotechnology R&D expenditures, 2000–2010 ($ millions/year)

Regions	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
EU+	200	~225	~400	~650	~950	~1,050	~1,150	~1450	1,700	1,900	
Japan	245	~465	~720	~800	~900	~950	950	~950	~950	~950	
USA[a]	270	464	697	862	989	1,200	1,351	1,425	1,554	1,702 + 511[a]	~1,762
Others	110	~380	~550	~800	~900	~1,100	~1,200	~2,300	~2,700	~2,700	
Total	825	1,534	2,367	3,112	3,739	4,200	4,651	6,125	6,904	7,252; 7,763[b]	
Est. US% of EU	*135*	*206*	*174*	*133*	*104*	*114*	*117*	*98*	*91*	*90*; *116*[b]	
Est. US% of total	*33*	*30*	*29*	*28*	*26*	*29*	*29*	*24*	*23*	*22*; *28*[b]	

For the EU+ figures, both national and EU funding is included; EU+ includes EU member countries and Switzerland as a function of year. The category "Others" includes Australia, Canada, China, Russia, Israel, Korea, Singapore, Taiwan, and other countries with nanotechnology R&D. Budget estimates use the nanotechnology definition as defined by the NNI (this definition does not include MEMS, microelectronics, or general research on materials) (see Roco et al. 1999; Roco 2005; and http://nano.gov). A FY begins in the US on October 1 and in most other countries 6 months later, around April 1

[a] One-time supplemental ARRA nanotechnology-related funding

[b] The higher figure includes the one-time supplemental ARRA funding

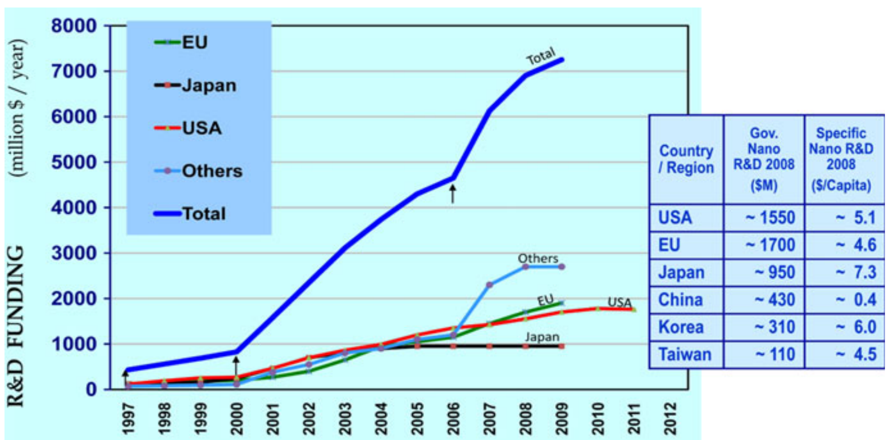

Fig. 9 2000–2009 Federal/national government R&D funding (Budget estimates use the nanotechnology definition as defined by the NNI). Specific nanotechnology R&D per capita is using the national nanotechnology expenditures and effective expenditure for all other R&D programs

exceeded respective public investment in the US and worldwide.

Governance of nanotechnology

Governing any emerging technology requires specific approaches (Roco 2008), and for nanotechnology in particular, consideration of its potential to fundamentally transform science, industry, and commerce, and of its broad societal implications. It should be stressed that the technology governance approach needs to be focused on many facets, not only on risk governance (Roco and Renn 2008). Properly taking into account the roles and views of the various stakeholders in the society—including their perceptions of science and technology, human behavior factors, and the varying social impacts of the technology—is an increasingly important factor in the development of any emerging, breakthrough technology. Optimizing societal interactions, R&D policies, and risk governance for nanotechnology development can enhance economic competitiveness and democratization, but all stakeholders must be equally invested. Chapter 13 (Roco et al. 2010) on innovative and responsible governance discusses four basic functions of the governance and four basic structural levels. Below are illustrated the application of the four basic functions or characteristics of effective governance of nanotechnology, that it should be (1) transformative, (2) responsible, (3) inclusive, and (4) visionary.

Transformative and responsible development of nanotechnology

The goal of achieving transformative and responsible development of nanotechnology has guided many NNI decisions, with a recognition that investments must have a good return, the benefit-to-risk ratio must be justifiable, and societal concerns must be addressed. The goal of being transformative is being addressed not only through fundamental and application-focused R&D and investment policy but also through implementing new modes of advocacy for innovation, resource-sharing, and cross-sector communication. NNI agencies introduced manufacturing at the nanoscale as a grand challenge in 2002, and at about the same time, NSF established the first research program on this topic, "Nanomanufacturing." In the next 4 years, NSF made awards to four Nanoscale Science and Engineering Centers (NSECs) on nanomanufacturing and the National Nanomanufacturing Network (NNN). Since 2006, the NNN has developed partnerships with industry and academic units, programs of the National Institute for Standards and Technology (NIST), National Institutes of Health, Department of Defense (DOD), and Department of Energy (DOE). The NNI agencies also established a new approach for interaction with various industry sectors, to augment previous models: the Consultative Boards for Advancing Nanotechnology (CBAN). DOE, NIST, DOD, and other agencies likewise have established individual programs to support advanced nanotechnology R&D. Several outcomes, such as science and technology platforms inspired or directly supported by the NNI investment have been noted in various areas such as in instrumentation (Sandia National Laboratory), nanoparticles (DuPont), nanocomponents (General Electric) and carbon nanotube cables and sheets [National Reconnaissance Office (NRO), see Fig. 10].

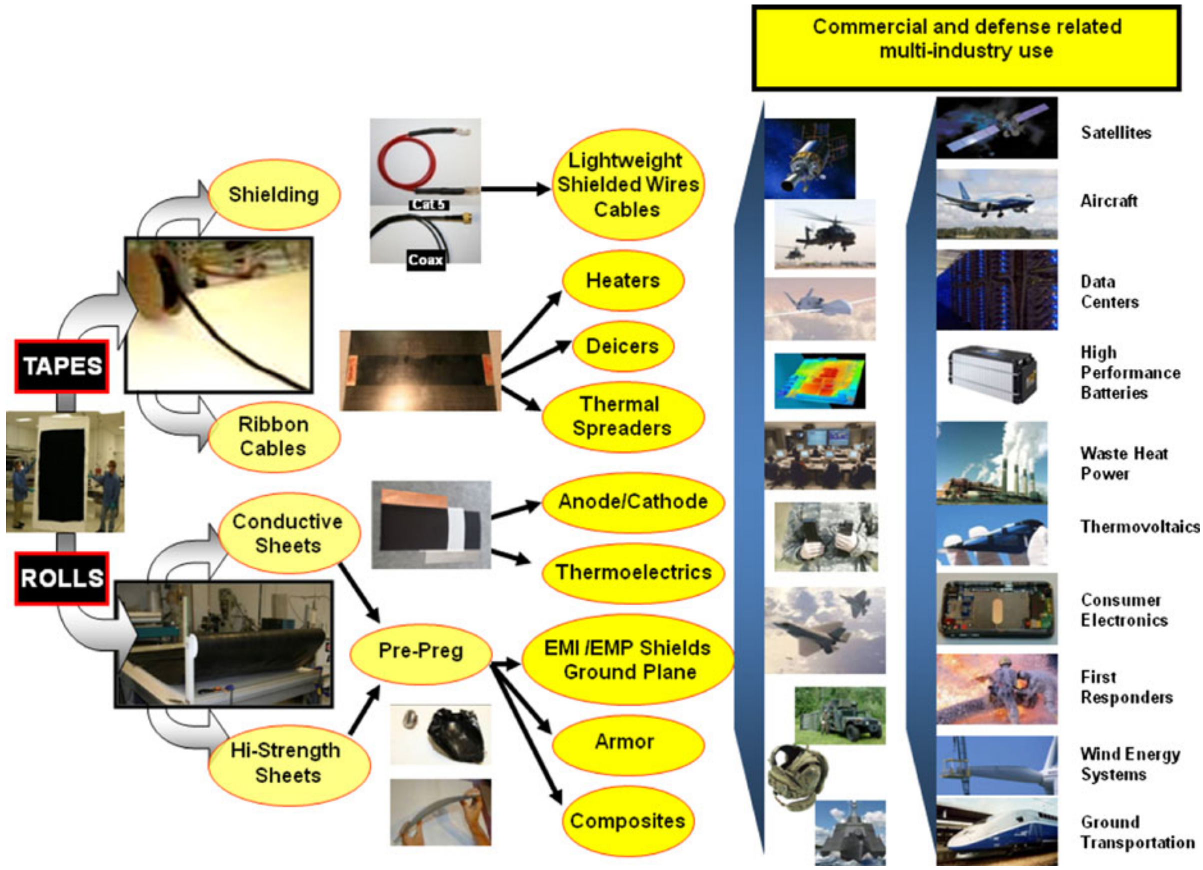

Fig. 10 Platform for carbon nanotube-based cables and sheets in (Courtesy, Peter L. Antoinette, Nanocomp Technologies, Inc., and R. Ridgley, NRO, 2010)

In examples of programs focused on studying and advancing societal aspects of nanotechnology R&D, in 2004-2005, NSF began establishing new kinds of networks with national goals and outreach, focused on high school and undergraduate nanotechnology education (the National Centers for Learning and Teaching in Nanoscale Science and Engineering), nanotechnology in society (the Centers for Nanotechnology in Society), and informal nanotechnology science education (the Nanoscale Informal Science Education Network). Other aspects of pursuing responsible development of nanotechnology include the NNI's considerable and growing focus on nanotechnology environmental, health, and safety (nanotechnology EHS or nanoEHS) research its interagency and international consultations on standards and regulation.

To support the NNI agency focus on the issues of transformative and responsible development of nanotechnology, the NSET Subcommittee established the Nanomanufacturing, Industry Liaison, and Innovation (NILI), Nanotechnology Environmental and Health Issues (NEHI), and Global Issues in Nanotechnology (GIN) Working Groups. The transformative function for nanotechnology development is addressed in Roco et al. (2010) in Chapters 1 and 2 for tools, Chapter 3 for manufacturing, Chapters 7–11 for applications, and Chapter 13 for innovation. The responsible function for nanotechnology development is discussed in Chapter 4 for nanotechnology environmental, health, and safety, in Chapters 5 and 6 for sustainable development, and in Chapter 13 for nanotechnology ethical, legal, and social issues (ELSI).

Inclusiveness in the development and governance of nanotechnology

Addressing the goal of being inclusive in the development and governance of nanotechnology may be illustrated by (1) the inclusion of diverse stakeholders in the planning process (such as industry input, requesting public comments for planning documents, and holding workshops and dialogs with multiple partners in the process of producing the nanotechnology research directions reports of 1999 and 2010) and in preparation of various reports on societal implications (beginning with Roco and Bainbridge 2001); (2) partnering of all interested Federal agencies through the NSET Subcommittee (Table 4); (3) opening NNI strategy development process to the public in meetings and online (e.g., see http://strategy.nano.gov/); (4) R&D programs requiring all relevant disciplines and sectors of activity to work together; (5) supporting a network of 34 regional, state, and local nanotechnology alliances in the US (http://nano.gov/html/meetings/nanoregional-update/ and Fig. 11); and (6) supporting international dialogs on nanotechnology (the first in 2004 with 25 nations and the EU, the third in 2008 with 49 nations and the EU), and the US also participates actively and regularly in a number of other international fora for nanotechnology (ISO, OECD, International Risk Governance Council, etc.) that are focused on development of appropriate international standards, terminology, regulations, etc. To help advance the progress toward responsibility and inclusiveness in nanotechnology development, NSF has established two centers for nanotechnology in society.

Regarding international aspects of nanotechnology governance, a multidisciplinary, international forum is needed to better address the nanotechnology scientific, technological, and infrastructure development challenges. Optimizing societal interactions, R&D policies, and risk governance for the converging new technologies can enhance economical competitiveness and democratization. The International Risk Governance Council (IRGC 2006) has provided an independent international perspective for a framework for identification, assessment, and mitigation of risk.

Vision in the development of nanotechnology

The goal of being visionary in the development of nanotechnology is discussed at length in Chapter 13 (Roco et al. 2010). Support for this function can be illustrated by the long-term view adopted since the beginning of NNI (see Table 6); the integration of nanotechnology with other long-term emerging technologies such as R&D programs at the intersection of nanotechnology, biology, and information technology; development of long-term government partnerships with academia and industry, such as the Nanoelectronics Research Initiative; inclusion of the concept of anticipatory governance from the beginning as part of the 10-year vision; NSF support for the

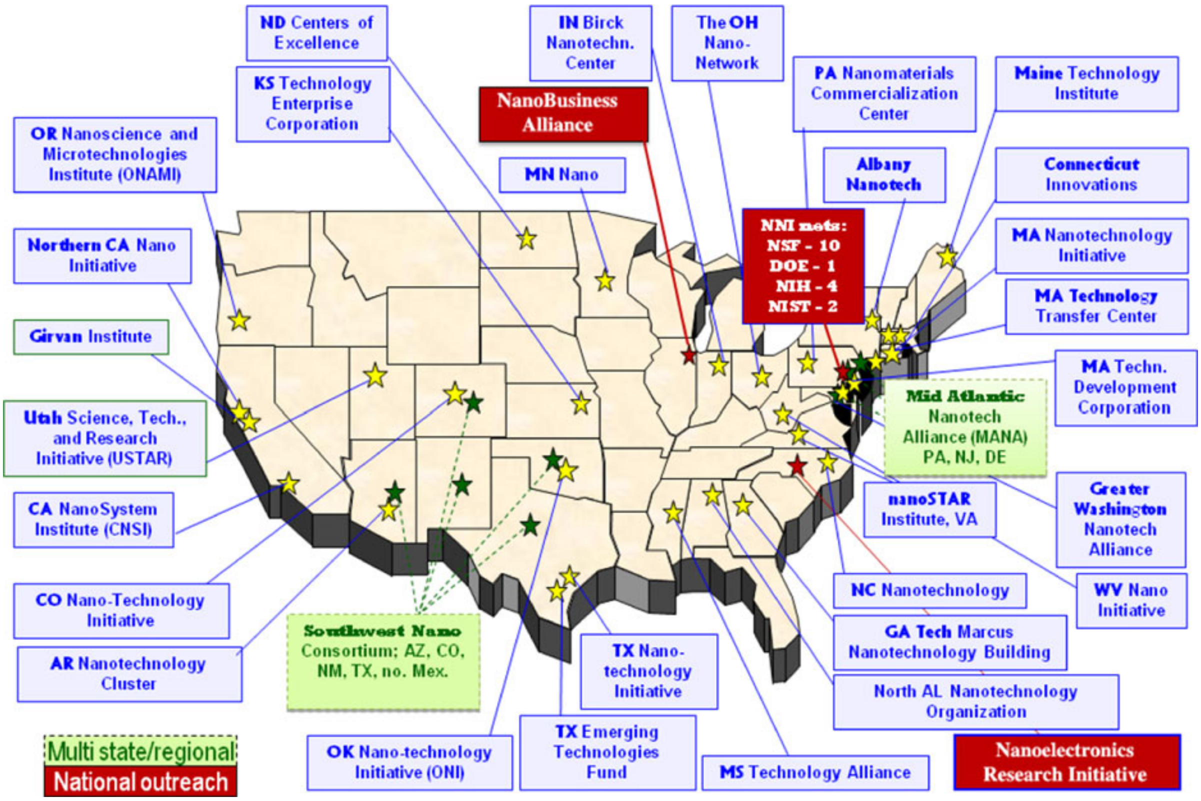

Fig. 11 As of 2009, 34 nanotechnology regional, state, and local initiatives existed in the US (including one in Hawaii)

Centers for Nanotechnology in Society since 2004 to provide a foundation in this regard; and setting grand challenges (2001–2005) and signature initiatives in 2010 to identify and focus development on key R&D issues for future years.

Several observers' comments on the NNI governance approach illustrate their recognition of the value and uniqueness of the model:

- National Research Council (NRC 2002): "…[T]he committee was impressed with the leadership and level of multiagency involvement in the NNI."
- The Presidential Council of Advisors in Science and Technology (PCAST 2005) endorsed the governing approach adopted by NNI: "(The Council) supports the NNI's high-level vision and goals and the investment strategy by which those are to be achieved."
- "NNI is a new way to run a national priority," Charles Vest, president of the National Academy of Engineering, at the March 23, 2005, PCAST meeting reviewing the NNI for Congress.
- PCAST (2010): "NNI… has had "catalytic and substantial impact" on the growth of the US nanotechnology industry"; "…[I]n large part as a result of the NNI the US is today, by a wide range of measures, the global leader in this exciting and economically promising field."
- "The NNI story could provide an useful case study for newer research efforts into fields such as synthetic biology, renewable energy, or adaptation to climate change. These are the kind of areas in which science, applications, governance, and public perception will have to be coordinated across several agencies…[F]or emerging areas like this, the concept of NNI is a good one," David Rejeski, director of the S&T Innovation program at the Woodrow Wilson International Center for Scholars in a Nature interview on September 2, 2010 (Lok 2010).
- "Nanotechnology has become a model and an intellectual focus in addressing societal implications and governance methods of emerging new technologies," David Guston (2010)

Table 6 A long-term view (2000–2020) drives the NNI

The NNI was designed as a science project after extensive planning, 1997–2000
Long-term view (*Nanotechnology Research Directions* 1999)
Definitions and international benchmarking (Nanostructure Science &Technology, Siegel et al. 1999)
Science and Engineering Priorities and Grand Challenges (NSTC/NSET 2000)
Societal implications (NSF 2001)
Plans for government agencies (National plans and budgets 2001)
Public engagement brochure ("Nanotechnology: shaping the word atom by atom," NSTC/IWGN 1999)
Combined four time scales in planning ("grand-challenge" approach 2001–2005; "program component area" approach 2006–2010; "signature initiatives" approach after 2011)
Four time scales
Vision: 10–20 years (Nano 1 in 2000 and Nano 2 in 2010 studies)
Strategic plans: 3 years (2000, 2004, 2007, and 2010)
Annual budget: 1 year (2000, 2003, 2005, and 2006)
Management decisions: 1 month (meetings of the NSET Subcommittee)
Four management levels
Agency research programs
Agencies' principals
National executive (NSTC/OSTP)
Legislative (US Congress)

Lessons learned

Objectives that have not been fully realized after 10 years

- General methods for achieving nanoscale "materials by design" and composite materials: the delay is because the direct theory, modeling, and simulation tools and measurement techniques with sufficient resolution were not ready.
- Sustainable development projects: nanotechnology for energy solutions received momentum only after 5 years, nanotechnology for water filtration and desalination and climate research still has only limited funding; it is not clear if the delay in funding nanotechnology R&D for these topics is because of insufficient pull and collaboration from respective stakeholders that are less organized than in other sectors.
- Widespread public awareness of nanotechnology; the awareness figure remains low, at about 30%; this is a challenge for increasing public participation in governance.

On target in 2010, even if doubted in 2000

- A steep growth rate in scientific papers and inventions: the rate for nanotechnology has been quasi-exponential (23–35% annually), at rates at least two times higher than the average for all scientific fields.
- Significant advancement in interdisciplinary research and education: nanotechnology R&D has led to creation of many multidisciplinary projects, organizations, and communities.
- Estimation that US nanotechnology R&D investment will grow by about 30% annual growth rate (government and private sector, in-depth vertical development and new areas of horizontal development): the rate (see earlier in this paper) held at 25–30% from 2000 to 2008.

Better than expected after 10 years

- Major industry involvement after 2002–2003: as examples, more than 5,400 U.S. companies had papers, patents, and/or products in 2008 (see Chapter 13); and Moore's law has continued for the past ten years, despite serious doubts raised in 2000 about the trend being able to continue into the nanoscale regime.
- Unanticipated discoveries and advances in several science and engineering fields, including plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, and quantum information systems.
- The formation and growing strength of the international nanotechnology community, including in nanotechnology EHS and ELSI: these developments have surpassed expectations, and the debut of governance studies was unanticipated.

Main lessons learned after 10 years

- There is a need for continued, focused investment in theory, direct measurement, and simulation at the nanoscale; nanotechnology is still in the formative phase.

- Besides R&D in new nanostructured metals, polymers, and ceramics, excellent opportunities for nanotechnology R&D exist in classical industries, such as textiles, wood and paper, plastics, and agricultural and food systems. Improved mechanisms are needed for public–private partnerships to establish consortia or platforms for targeted development programs.
- There is a need to better connect science and engineering to translational research and creation of jobs.
- There is a need to continue to increase multistakeholder and public participation in nanotechnology governance.

Closing remarks

The vision for the future of nanotechnology research and development to 2020—as a whole and in each domain (tools, manufacturing, applications, infrastructure, governance, etc.)—is presented in Roco et al. 2010. The goal has been to provide a long-term and timely vision for nanotechnology R&D, with input from leading experts in the nanotechnology community.

Overall, it appears that the NNI has been the major driver for nanoscience and nanotechnology developments and applications in the US and in the World for close to a decade, but that many nations besides the US are continuing to rapidly expand their nanotechnology-related R&D programs in recognition of the fundamental scientific, economic, and social value of doing so.

Besides impacting products, tools, and healthcare, it is inevitable that nanotechnology R&D will also impact learning, imagination, infrastructure, inventions, public acceptance, culture, laws, and the architecture of various other socio-economic factors. From 1997 to 2000, the US scientific establishment developed a vision for nanotechnology R&D, and in the first 10 years of the NNI, 2001–2010, that vision has become a reality. The report by Roco et al. (2010) is intended to extend that vision into the next 10 years, to 2020 (and beyond).

A main impetus for the original development of the NNI was the long-term view, based on an intellectual drive toward exploiting new phenomena and processes, developing an unified science and engineering platform from the nanoscale, and using molecular and nanoscale interactions to radically improve the efficiency of manufacturing. Complementary to these goals has been the promise of broad societal benefit from pursuing nanotechnology R&D, including an anticipation of $1 trillion/year by 2015 of products where nanotechnology plays a key role, which would require 2 million workers with nanotechnology-related skills. Because the rate of market increase is expected to follow the trends in papers and patents of about a 25% increase per year in the previous 10 years, one may estimate that by 2020, there will be about $3 trillion in products that incorporate nanotechnology as a key performance component. The nanotechnology markets and related jobs are expected to double each 3 years.

Nanotechnology is evolving toward new scientific and engineering challenges in areas such as assembly of nanosystems, nanobiotechnology and nanobiomedicine, development of advanced tools, environmental preservation and protection, and pursuit of societal implication studies. All trends for papers, patents, and worldwide investments are still expected to have quasi-exponential growth, with potential inflexion points occurring within several years. There is a need for continuing long-term planning, interdisciplinary activities, and anticipatory measures involving interested stakeholders.

In the next 10 years, the challenges of nanotechnology will likely take new directions, because there is a transition occurring within several dominant development trends:

- From a focus on creating single nanoscale components to a focus on creating active, complex nanosystems
- From specialized or prototype research and development to mass use in advanced materials, nanostructured chemicals, electronics, and pharmaceuticals
- From applications in advanced materials, nanoelectronics, and the chemical industry, expanding into new areas of relevance such as energy, food and agriculture, nanomedicine, and engineering simulations from the nanoscale where competitive solutions are expected

- From starting at rudimentary first-principles understanding of the nanoscale to accelerating development of knowledge, where the rate of discovery remains high and significant changes continually occur in application areas
- From almost no specialized infrastructure to well-institutionalized programs and facilities for nanotechnology research, education, processes, manufacturing, tools, and standards

While expectations from nanotechnology may have been overestimated in the short term, the long-term implications for the impact of nanotechnology on healthcare, productivity, and environmental protection appear now to be underestimated, provided that proper consideration is given in coming years to educational and social issues.

It will be imperative over the next decade to focus on four distinct aspects of nanotechnology development that are discussed in this volume: (1) better comprehension of nature, leading to knowledge progress; (2) economic and societal solutions, leading to material progress; (3) international collaboration on sustainable development, leading to global progress; and (4) people working together for equitable governance, leading to moral progress.

Acknowledgments This paper is based on the author's experience in the nanotechnology field, as founding chair of the NSET subcommittee coordinating the NNI and as a result of interactions in international nanotechnology policy arenas. The opinions expressed here are those of the author and do not necessarily reflect the position of NSTC/NSET or NSF

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