

National Nanotechnology Initiative - Past, Present, Future

Dr. M.C. Roco

National Science Foundation
and National Nanotechnology Initiative

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Abstract

This paper presents the genesis of the National Nanotechnology Initiative, its long-term view (2000-2020), its current status, and its likely evolution.

Introduction

Nanoscale science and engineering activities are flourishing in the United States. The National Nanotechnology Initiative (NNI) is a long-term research and development (R&D) program that began in fiscal year 2001, and today coordinates 25 departments and independent agencies, including the National Science Foundation, the Department of Defense, the Department of Energy, the National Institutes of Health, the National Institute of Standards and Technology, and the National Aeronautical and Space Administration. The total R&D investment in fiscal years 2001-2005 was over \$4 billion, increasing from the annual budget of \$270 million in 2000 to \$1.2 billion including Congressionally directed projects in fiscal year 2005. An important outcome is the formation of an interdisciplinary nanotechnology community with about 50,000 contributors. A flexible R&D infrastructure with over 60 large centers, networks, and user facilities has been established since 2000, as well as an expanding industrial base of more than 1,500 companies with nanotechnology products with a value exceeding \$40 billion at an annual rate of growth estimated at about 25 percent. With such a growth and complexity, participation of a coalition of academic, industry, business, civil organizations, government and NGOs to nanotechnology development becomes essential as an alternative to the centralized approach. The role of government continues in basic research but its emphasis is changing while private sector becomes increasingly dominant in funding nanotechnology applications.

The NNI plan proposed in 1999 has led to a synergistic, accelerated, and interdisciplinary development of the field, and has motivated academic and industry communities at the national and global levels. A key factor that has contributed to establishing NNI in year 2000 was the preparation work for identifying the core nanotechnology concepts and challenges. Secondly, the orchestrated effort to assemble fragmented disciplinary contributions and application-domain contributions has led to broad support from various stakeholders. Thirdly, the long-term view in planning and setting priorities was essential in the transformative governance of nanotechnology. Nanotechnology holds the promise to increase the efficiency in traditional industries and bring radically new applications through emerging technologies. Several potential R&D targets by 2015-2020 are presented in this paper.

The promise of nanotechnology, however, will not be realized by simply supporting research. A specific governing approach is necessary for emerging technologies and in particular for nanotechnology by considering its fundamental and broad implications. Optimizing societal interactions, R&D policies and risk governance for nanotechnology development can enhance economical competitiveness and democratization.

1. Identifying a megatrend in science and technology

What is nanotechnology?

Nanotechnology operates at the first level of organization of atoms and molecules for both living and anthropogenic systems. This is where the properties and functions of all systems are defined. Such fundamental control promises a broad and revolutionary technology platform for industry, biomedicine, environmental engineering, safety and security, food, water resources, energy conversion, and countless other areas.

The first definition of nanotechnology to achieve some degree of international acceptance was developed after consultation with experts in over 20 countries in 1987-1898 (Siegel et al., Roco, 1999). However, despite its importance, there is no globally recognized definition. Any nanotechnology definition would include three elements:

- The size range of the material structures under consideration -- the intermediate length scale between a single atom or molecule, and about 100 molecular diameters or about 100

nm. This condition alone is not sufficient because all natural and manmade systems have a structure at the nanoscale;

- The ability to measure and transform at the nanoscale; without it we do not have new understanding and a new technology; such ability has been reached only partially so far, but a significant progress was achieved in the last five years.
- Exploiting properties and functions specific for nanoscale as compared to the macro or micro scales; this is a key motivation for researching nanoscale.

According to National Science Foundation and NNI, nanotechnology is the ability to understand, control, and manipulate matter at the level of individual atoms and molecules, as well as at the “supramolecular” level involving clusters of molecules (in the range of about 0.1 to 100 nm), in order to create materials, devices, and systems with fundamentally new properties and functions because of their small structure. The definition implies using the same principles and tools to establish a unifying platform for science and engineering at the nanoscale, and using the atomic and molecular interactions to develop efficient manufacturing methods.

There are at least three reasons for the current interest in nanotechnology. First, the research is helping us fill a major gap in our *fundamental knowledge of matter*. At the small end of the scale -- single atoms and molecules -- we already know quite a bit by using tools developed by conventional physics and chemistry. And at the large end, likewise, conventional chemistry, biology, and engineering have taught us about the bulk behavior of materials and systems. Until now, however, we have known much less about the intermediate nanoscale, which is the natural threshold where all living and man-made systems work. The basic properties and functions of material structures and systems are defined here and, even more importantly, can be changed as a function of the organization of matter via 'weak' molecular interactions (such as hydrogen bonds, electrostatic dipole, van der Waals forces, various surface forces, electro-fluidic forces, etc.). The intellectual drive toward smaller dimensions was accelerated by the discovery of size-dependent novel properties and phenomena. Only since 1981 have we been able to measure the size of a cluster of atoms on a surface (IBM, Zurich), and begun to provide better models for chemistry and biology selforganization and selfassembly. Ten years later, in 1991, we were able to move atoms on surfaces (IBM, Almaden). And after ten more years, in 2002, we assembled molecules by physically positioning the component atoms. Yet, we cannot visualize or model with proper

spatial and temporal accuracy a chosen domain of engineering or biological relevance at the nanoscale. We are still at the beginning of this road.

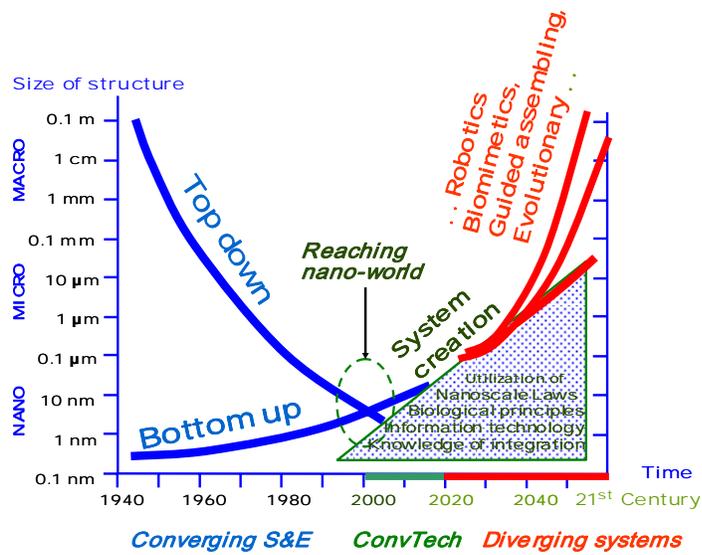
A second reason for the interest in nanotechnology is that nanoscale phenomena hold the promise for *fundamentally new applications*. Possible examples include chemical manufacturing using designed molecular assemblies, processing of information using photons or electron spin, detection of chemicals or bioagents using only a few molecules, detection and treatment of chronic illnesses by sub-cellular interventions, regenerating tissue and nerves, enhancing learning and other cognitive processes by understanding the “society” of neurons, and cleaning contaminated soils with designed nanoparticles. Using input from industry and academic experts in the United States, Asia Pacific countries and Europe between 1997 and 1999, we have projected that \$1 trillion in products incorporating nanotechnology and about 2 million jobs worldwide will be affected by nanotechnology by 2015 (Roco and Bainbridge, 2001). Extrapolating from information technology, where for every worker another 2.5 jobs are created in related areas, nanotechnology has the potential to create 7 million jobs overall by 2015 in the global market. Indeed, the first generation of nanostructured metals, polymers, and ceramics have already entered the commercial marketplace.

Finally, a third reason for the interest is the *beginning of industrial prototyping and commercialization* and that governments around the world are pushing to develop nanotechnology as rapidly as possible. Coherent, sustained R&D programs in the field have been announced by Japan (April 2001), Korea (July 2001), EC (March 2002), Germany (May 2002), China (2002) and Taiwan (September 2002). However, the first and largest such program was the U.S. National Nanotechnology Initiative, announced in January 2000.

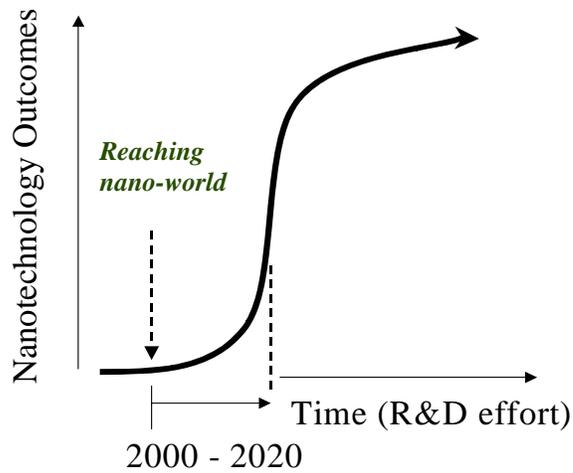
Nanotechnology - A key component of converging technologies

Science and engineering are the primary drivers of global technological competition. Unifying science based on the unifying features of nature at the nanoscale provides a new foundation for knowledge, innovation, and integration of technology. Revolutionary and synergistic advances at the interfaces between previously separated fields of science, engineering and areas of relevance are poised to create nano-bio-info-cogno (NBIC) transforming tools, products and services.

There is a longitudinal process of convergence and divergence in major areas of science and engineering (Roco, 2002; Roco and Bainbridge, 2003). For example, the convergence of sciences at macroscale was proposed during the Renaissance, and it was followed by narrow disciplinary specialization in science and engineering in the 18th - 20th centuries. The convergence at the nanoscale reached its strength in about year 2000, and one may estimate a divergence of the nanosystem architectures in the next decades. Current convergence at the nanoscale is happening because the use of the same elements of analysis (that is, atoms and molecules) and of same principles and tools, as well as the ability to make cause-and-effect connections from simple components to higher-level architectures. In nano realms, the phenomena/processes cannot be separated, and there is no need for discipline specific averaging methods. In 2000, convergence had been reached at the nano-world (Figure 1a) because typical phenomena in material nanostructures could be measured and understood with a new set of tools, and nanostructures have been identified at the foundation of biological systems, nanomanufacturing, and communications. A new challenge is building systems from the nanoscale that will require the combined use of nanoscale laws, biological principles, information technology, and system integration. Then, after 2020, one may expect divergent trends as a function of the system architecture. Several possible divergent trends are system architectures based on: guided molecular and macromolecular assembling; robotics; biomimetics; and evolutionary approaches. While in 2000 we may assume to be at the beginning of the “S” development curve, we also may estimate that in 2020 to be in the fast ascendant section of the curve (Figure 1b).



a.



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Figure 1. a. Reaching at the nanoworld (about 2000) and “converging technologies” approach for system creation from the nanoscale (2000-2020) towards new paradigms for nanosystem architectures in applications (after 2020); **b.** Suggested nanotechnology R&D “S” development curve (schematic).

The transforming effect of NBIC convergence on society is expected to be large, not only because of the high rate of change in each domain and their synergism with global effect on

science and engineering, but also because we are reaching qualitative thresholds in the advancement of each of the four domains. In the United States, we have started two national initiatives on Information Technology Research (ITR, in 1999, about \$2B in FY 2005) and National Nanotechnology Research (NNI, in 2000, reaching about \$1.2B in FY 2005) (Figure 2). **ITR and NNI provide the technological “push” with broad science and engineering platforms. Realizing the human potential, “the pull”, would include the biotechnology and cognitive technologies.** Several topical, agency-specific programs have been initiated in the field of biotechnology, such as NIH Roadmaps (including genome), NSF’s Biocomplexity, and USDA’s roadmap. There was no national initiative on biotechnology and no large scale programs on cognition, except for the core research programs in Social, Behavioral and Economical Sciences and centers for science or learning at NSF. There was a need to balance this situation, and a partial response was, in 2003, the Human and Social Dynamics NSF priority area has been launched. No special interagency program was established on system approach and cognitive sciences.

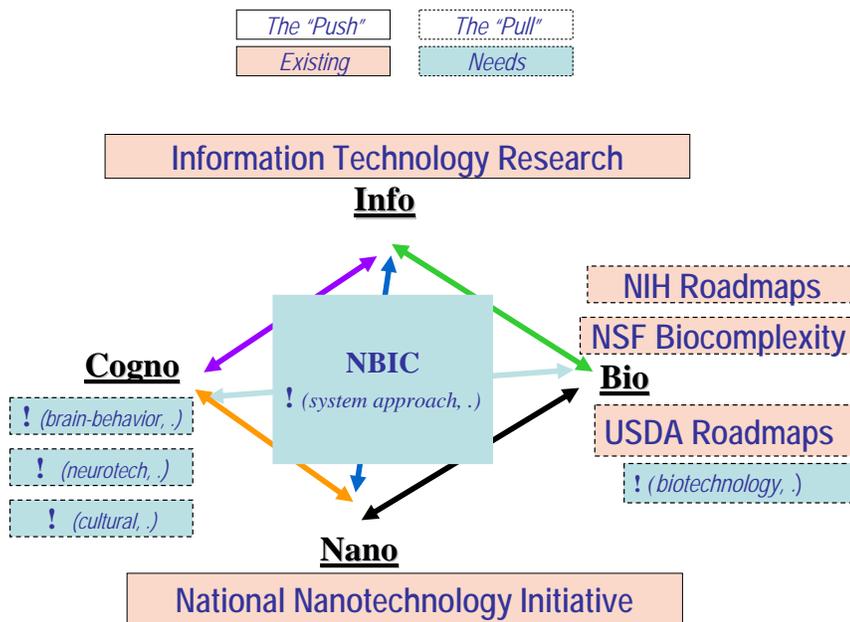


Figure 2. Converging technologies (NBIC) transforming tools: a survey of national R&D programs in 2000.

The convergence is on the broad scale (including anthropology, environment, up to social studies), but the most dynamic component driving an accelerating path of change is the

convergence of nanotechnology, modern biology, and digital revolution (Coherence and Divergence in Megatrends in Science and Engineering, 1999-2000 (Roco, 1999); Converging Technologies for Improving Human Performance (Roco and Bainbridge, 2003).

With proper attention to ethical issues and societal needs, these converging technologies could determine a tremendous improvement in human abilities, societal outcomes, the nation's productivity, and the quality of life of revolutionary products and services.

2. Key factors in establishing NNI (about 2000)

Key factors that have contributed to establishing NNI around the year 2000 and the rapid growth of nanotechnology are:

- The preparatory work for identifying core nanotechnology concepts encompassing all disciplines, including the definition of nanotechnology and what are key research directions;
- The orchestrated effort to assemble fragmented disciplinary contributions and application-domain contributions and get broad and bottom-up support from various contributing communities and other stakeholders; and
- Preparing the initiative as a science project. This included the long-term view (2000-2020) in planning and setting priorities on three time scale (5years, 1 year, 1 month) and three levels (national, agency, and R&D program). The initial R&D focus in the first strategic plan (2001-2005) has been on fundamental research and “horizontal” multidisciplinary R&D with relevance to multiple application areas. A transition to “vertical” industrial development from the basic concepts is a focus for the second plan (2006-2010). A policy of inclusion and partnerships has been promoted, including international collaboration. The R&D projects have been aligned with societal needs and aspirations from the beginning, with a proactive role in the political and international context. The governing approach was data-driven and transformative (Roco, 2005a).

Fundamental changes envisioned through nanotechnology have required a *long-term R&D vision*. A two-decade time scale was planned for transitioning from the focus on passive nanostructures in 2001-2005 to molecular active nanosystems after 2015. To meet the challenges, the NNI was created, and a new approach for its governance was attempted.

The NNI bottom up approach solidified the community of scientists to support the redirection of funds toward the new area of nanotechnology. Done top down might have fractured our community and led to in-fighting. The orchestration of all the government agencies behind this concept was critical in getting the “jump start” that was achieved.

NNI was conceived as an *inclusive process* where various stakeholders would be involved. In 1999 we envisioned “a grand coalition” of academic, industry, government, states, local organizations, and the public that would advance nanotechnology. Twenty-five agencies covered most relevant areas in national interest in NNI in 2006, and industry already is investing more for R&D in the U.S.

Personal observations made during research and interactions with the community in the 1980s helped me posing the right questions. We identified nanotechnology as a “dormant” S&E opportunity, but with an “immense” potential. **Creating a chorus to support nanotechnology, from 1990 to March 1999, was an important preliminary step.**

In 1990, I proposed nanoparticles synthesis and processing at high rates in the Emerging Technologies competition for a new programmatic topic at NSF. It was selected for funding, and become the first program in a federal agency dedicated to nanoscale science and engineering. The awards were for interdisciplinary groups of at least three co-principal investigators in different disciplines. The program supported by four divisions at NSF was largely successful (the results were presented at grantees meetings, in 1994 and 1997).

In the decade before NNI, between 1990 and 2000, a main challenge was the search was for the relevance of nanotechnology. We had to overcome three waves of skepticism. First, a concern was the limited relevance of the field and “pseudoscientific” claims. Then, it was the concern of large and unexpected consequences culminating with the risk so-called “grey-goo” scenarios. The third wave of concerns is on environmental, health and safety (EHS) implications; it arrived only later in 2002-2003 when industrial participation has increased. And yet, the main issues related to long-term societal implications and human development have reached the public and media by 2006.

Participation of multiple agencies is necessary because of the large spectrum of relevance of nanotechnology to the society. In November 1996, I organized a small group of researchers and experts from government, including Stan Williams (Hewlett Packard), Paul Alivisatos (University of California, Berkeley) and Jim Murday (Naval Research Laboratory), and we started to do our homework in setting a vision for nanotechnology. We began with preparing supporting publications, including a report on research directions in ten areas of relevance, despite low expectation of additional funding at that moment. In 1997-1998, we ran a program solicitation “Partnership in Nanotechnology: Functional Nanostructures” at NSF and we received feedback from the academic community. Also, we completed a worldwide study in academe, industry and governments, together with a group of experts including Richard Siegel (Renssalaer Polytechnic Institute, then at Argonne National Laboratory) and Evelyn Hu (University of California, Santa Barbara). By the end of 1998, we had the understanding what are the possibilities at the international level. The visits performed in that time interval were essential in developing an international acceptance of nanotechnology, and defining its place among existing disciplines.

NNI was prepared with the same rigor as a science project between 1997 and 2000; we developed a long term vision for research and development (Roco et al., 2000) and we completed an international benchmarking of nanotechnology in academe, government and industry (Siegel et al., 1999). Other milestones included a plan for the US government investment (NSTC, 2000), a brochure explaining nanotechnology for the public (NSTC, 1999), and a report on the societal implication of nanoscience and nanotechnology (Roco and Bainbridge, 2001). More than 150 experts, almost equally distributed between academe, industry and government, contributed in setting the nanotechnology research directions bringing into the dialogue experts like Richard Smalley (Rice University), Herb Goronkin (Motorola) and Meyya Mayyapan (NASA Ames). The brochure for the public was distributed to 30,000 organizations, proactively prepare a report for societal implications of nanoscience and nanotechnology, and test the interest and capacity of the scientific community. This was the time to rally the interest of science and engineering communities, international support, as well as key industrial sectors.

3. The beginning of NNI

On behalf of the interagency group, on March 11, 1999, in the historic Indian Hall at the White House's Office of Science and Technology Policy (OSTP), I proposed the NNI with a budget of half billion dollars for fiscal year 2001. I was given 10 minutes to make the case. While two other topics were on the agenda of that meeting, nanotechnology captured the imagination of those present and discussions reverberated for about two hours. It was the first time that a forum at this level with representatives from the major federal R&D departments reached a decision to consider exploration of nanotechnology as a national priority. In parallel, over two dozen of other competing topics were under consideration by OSTP for priority funding in fiscal year 2001. We had the attention of Neal Lane, then the Presidential Science Advisor, and Tom Kalil, then economic assistant to the President. However, few experts gave even a small chance to nanotechnology to become a national priority program. However, after a long series of evaluations, NNI was approved and had a budget of \$489 million in FY 2001 (\$464 million proposed by six agencies and \$25 million Congressionally directed, see Table 1).

After that presentation, our focus changed. Because nanotechnology was not known to Congress or the Administration, establishing a clear definition of nanotechnology and communicating the vision to large communities and organizations took the center stage. Indeed, the period from March 1999 through the end of the year was a time of very intense activity. Few experts gave even a small chance to nanotechnology for special funding by the White House. Nevertheless, with this proposal and the "homework" of studies completed, we focused our attention on the six major federal department and agencies -- the National Science Foundation (NSF), Department of Defense (DOD), Department of Energy (DOE), NASA, National Institutes of Health (NIH) and the National Institute of Standards and Technology (NIST) -- that would place nanotechnology as a top priority during the summer of 1999.

We provided detailed technical input for two hearings in the Congress, in both the Subcommittee on Basic Science, Committee on Science, U.S. House of Representatives (June 22, 1999) and the Senate, and support was received from both parties. The preparatory materials included a full 200-page benchmarking report, ten-page research directions and one-page summary on immediate goals. After the Hearing in the House, Nick Smith, the Chair of the first public hearing in preparation of NNI, told "Now we have sufficient information to aggressively pursue nanotechnology funding." Rick Smalley came and testified despite his illness.

Then, the approval process moved to Office of Management and Budget (OMB) (November 1999), Presidential Council of Advisors in Science and Technology (PCAST) (December 1999) and the Executive Office of the President (EOP, White House) (January 2000), and had supporting hearings in the House and Senate of the US Congress (Spring 2000). In November 1999, the OMB recommended nanotechnology as the only new R&D initiative for fiscal year 2001. On December 14, 1999, the PCAST highly recommended that the President fund nanotechnology R&D. Thereafter, it was a quiet month – we had been advised by the Executive Office of the President to restrain from speaking to the media about the topic because a White House announcement would be made. We prepared a draft statement. A video was being produced for the planned multimedia presentation, but we did not have time to complete it.

President Clinton announced the NNI at Caltech in January 2000 beginning with words such as “Imagine what could be done...” He used only slides. After that speech, we moved firmly in preparing the Federal plan for R&D investment, to identify the key opportunities and convincing potential contributors to be proactive. House and Senate hearings brought the needed recognition and feedback from Congress.

The selection of NNI at OMB, OSTP, and PCAST was in competition with other science and technology priorities for fiscal year 2001, and only one topic – nanotechnology - was selected in the process.

I spoke to major professional societies (initially the American Chemical Society, then the Institute for Electric and Electronics Engineering, American Society of Mechanical Engineering and American Institute of Chemical Engineering, and attended national meetings for introduction of nanotechnology in about 20 countries.

A challenge in the first years of the initiative with so many new developments was maintaining consistency, coherence and original thinking.

Three names (nanotechnology definition, the name of the initiative - NNI, and of the National Nanotechnology Coordinating Office) were decided in the same time interval 1999-2000. The name NNI was proposed on March 11, 1999, but it was under “further consideration” until the

Presidential announcement because concerns from several professional societies and committees that the title does not include explicitly “science.” We explained that we selected a simple name showing the relevance to society.

The “Interagency Working Group on Nanoscale Science, Engineering and Technology” (IWGN) was established in 1998 (October 1998-July 2000) as a cross-cut working group in the National Science and Technology Council (NSTC), White House. In 1997, I was contacted by T. Khalil who saw my publications on nanotechnology. Through NSF, I proposed interagency working group working across various topical committees. This was an important victory because the initial proposal in March 1998 was to have working group under the NSTC’s Materials activities. Also, until March 11, 1999, we were advised to be cautious about interacting with media on nanotechnology risks. President Clinton announced the NNI at Caltech in January 2000. In July 2000, the White House elevated the IWGN to the level of “Nanoscale Science, Engineering and Technology” (NSET) Subcommittee of the NSTC’s Committee on Technology with the role “to implement NNI” and I was appointed chairman. The National Nanotechnology Coordination Office (NNCO) name was decided in August 2000, and the Memorandum of Understanding to fund NNCO was signed by the last participating agency on January 17, 2001 in the last day of the Clinton Administration.

In the first year, the six agencies of the NNI invested about \$490 million (including Congressionally - directed funding), only few percentage points less than the tentative budget proposed on March 11, 1999. In fiscal years 2002 and 2003, NNI has increased significantly, from six to 16 departments and agencies. The Presidential announcement of NNI with its vision and program partially motivated or stimulated the international community. About other 60 countries have announced priority nanotechnology programs since the NNI announcement. It was as if nanotechnology had gone through a phase transition. What had once been perceived as blue sky research of limited interest (or in the view of several groups, science fiction, or even pseudoscience), was now being seen as a key technology of the 21st century. The Bush Administration has increased the support for NNI with higher Presidential annual “budget requests” each year. The average annual rate of increase of the NNI budgets was over 35 percent (including Congressionally - directed funding) in the first five years. The structure of NNI programs in the first (fiscal years 2001-2005) and second (fiscal years 2006-2010) strategic plans

is given in Appendix A. The list of NNI participating agencies in January 2006 is provided in Appendix B.

In 2000, we estimated a \$1 trillion nanotechnology related market of nanoproducts incorporating nanotechnology (Figure 3), and the demand for 2 million workers worldwide by 2015 -- using input from industry and experts around the world. We also saw the increasing convergence of nanotechnology with modern biology, the digital revolution, and cognitive sciences in the first half of the 21st century.

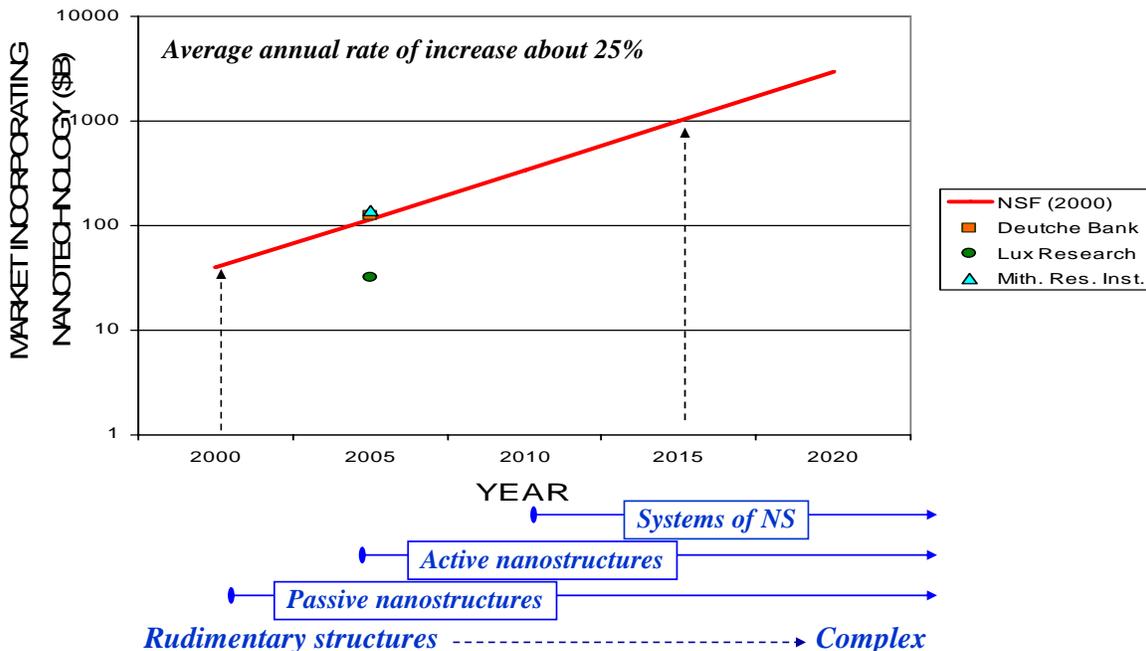


Figure 3. Estimation of the worldwide market incorporating nanotechnology (Estimation made in 2000, at NSF; Roco and Bainbridge, 2001). These estimations have been based on direct contacts with leading experts in large companies with related R&D programs in US, Japan and Europe, and the international study completed between 1997 and 1999 (Siegel et al., 1999).

After initially passing the House with a vote of 405-19 (H.R. 766), and then the Senate with unanimous support (S. 189) in November 2003, the “21st Century Nanotechnology R&D Act” was signed by the President on December 3, 2003. The bi-partisan support is strong because the nanotechnology progress is seen as “a higher purpose” beyond party affiliation. The Bush

administration provided support and has increased the level of investment in NNI to about \$1.2 billion in 2006.

4. NNI at five years (2001-2005)

There are major outcomes after five year (fiscal years 2001-2005) of the NNI. The R&D landscape for nanotechnology research and education has changed, advancing it from fragmented fields and questions such as “what is nanotechnology?” and “could it ever be developed?” to a highly competitive domain where the main question is “how industry and medicine can we take advantage of it faster?” In only five years, nanoscience and nanotechnology have opened an era of integration of fundamental research and engineering from the atomic and molecular levels, increased technological innovation for economic manufacturing of products, and an enabling base for improving human health and cognitive abilities in long term. For this reason, government investments worldwide for nanotechnology R&D have increased five-fold in five years reaching about \$4.1 billion in 2005 from about \$825 million in 2000, and all Fortune 500 companies in materials, electronics and pharmaceutical have made investments in nanotechnology after 2002. Of 30 Dow Jones companies, 19 have initiatives on application of nanotechnology in 2005. The National Nanotechnology Initiative (NNI) fuels these developments. By creating a “power house” of discoveries and innovations, the NNI has been the major driver for nanoscience and nanotechnology developments and applications in the United States and in the World. In 2005, NNI supported over 4,000 projects and 60 new centers, networks and user facilities in the United States. Over \$8 billions are invested worldwide now by governments and industry for nanotechnology R&D. The vision of a decade ago has taken place.

Figure 4 shows the increase of the relative number of NSF awards in nanoscale science and engineering of the total NSF awards, which reached about 11% in 2005. On the same graph one may see the increase with some delay of the relative number of nanotechnology-related papers in the top twenty cited journals (according to ISO), number of nanotechnology related papers in three leading journals (Science, Nature, and Proceedings of the National Academy of Science), and number of nanotechnology patents at the United States Patent Office (USPTO). All documents were searched using the same method (searching for keywords in the title, abstract and claims).

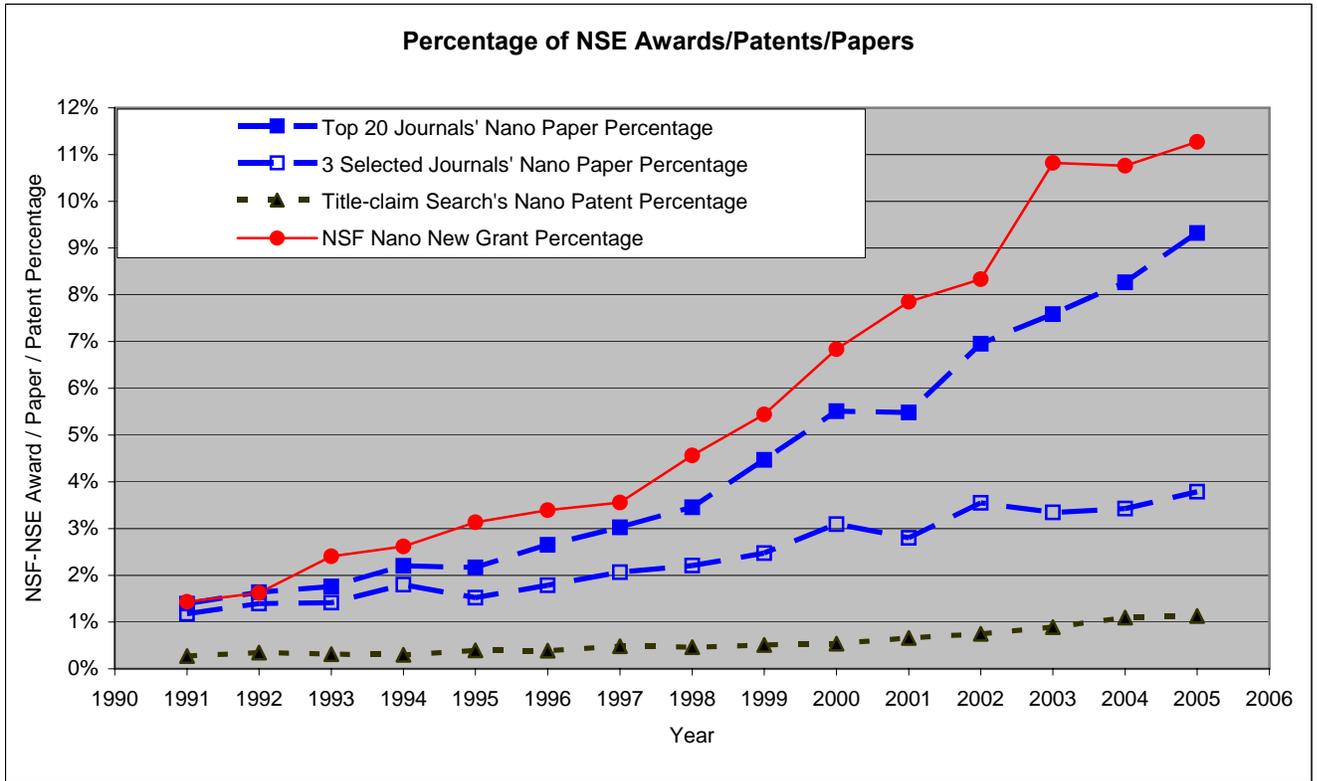


Figure 4. Time line for the number of NSF awards, number of journal articles (ISO), and number of patents (USPTO) on nanoscale science and engineering published between 1991 and 2005. All documents were searched by the same keywords (as described in Huang et al, 2004) in the title and abstract, as well as in the “claims” for patents.

The NNI R&D program has a total investment of about \$1.2 billion in fiscal year 2005 (Table 1). Comparative budgets and investments per capita are given in Figure 5 and Tables 2-4. About 65 percent of funds were dedicated to academic R&D institutions, 25 percent to government laboratories and 10 percent to industry of which 7% for SBIR/STTR awards. The first five years (fiscal years 2001-2005) of NNI have led to significant science and engineering advances, have increased the confidence that nanotechnology development is one of the key technologies at the beginning of the 21st century, and has raised the challenges of responsible development including environmental, health and safety (EHS) (Roco, 2003). Major achievements of NNI in the first five years are listed below.

Federal Department or Agency	FY 2000 Actual (\$M)	FY 2001 Actual (\$M)	FY 2002 Actual (\$M)	FY 2003 Actual (\$M)	FY 2004 Actual (\$M)	FY 2005 Actual (\$M)	FY 2006 Actual (\$M)	FY 2007 Estimate (\$M)	FY 2008 Request (\$M)
National Science Foundation (NSF)	97	150	204	221	256	335	360	373	390
Department of Defense (DOD) (without Congressionally-directed)	70	125	224	322	291	252	324	317	375
Department of Energy (DOE)	58	88	89	134	202	208	231	293	331
National Institutes of Health (NIH)	32	40	59	78	106	165	192	170	203
National Institute of Standards and technology (NIST)	8	33	77	64	77	79	78	89	97
National Aeronautics and Space Administration (NASA)	5	22	35	36	47	45	50	25	24
National Institute for Occupational Safety and Health (NIOSH)	-	-	-	-	-	3	4	5	5
Environmental Protection Agency (EPA)	-	5	6	5	5	7	5	9	10
Homeland Security (TSA)	-	-	2	1	1	1	2	2	1
Department of Agriculture (USDA: CSREES)	-	1.5	0	1	2	3	4	4	3
Department of Agriculture (USDA: Forest Service)							2	3	5
Department of Justice (DOJ)	-	1.4	1	1	2	2	1	1	1
Department of Transportation (DOT: FHVA)							1	1	1
TOTAL without Congr.-directed (% of FY 2000 budget)	270 (100%)	464 (172%)	697 (258%)	862 (319%)	989 (366%)	1,100 (407%)	1,241 (%)	1,292 (%)	1,445 (%)
Congressionally-directed	-	25 (DOD)	40 (DOD)	80 (DOD)	103 (DOD)	~100 (DOD)	100 (DOD) 10 (NASA)	100 (DOD)	
TOTAL with Congr.-directed (% of FY 2000 budget)	270 (100%)	489 (181%)	737 (273%)	942 (349%)	1092 (404%)	1,200 (444%)	1,351 (481%)	1,392 (515%)	1,445 (535%)

Table 1. Contribution of key federal departments and agencies to NNI investment (Each fiscal Year (FY) begins October 1 of the previous year and ends September 30 of the respective year).

Index	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008
GDP (Trillion)	9.8	10.1	10.5	11.0	11.7	12.5			
Specific NNI R&D (\$/Capita) (Assume 293 million of 2004)	0.9	1.7	2.5	3.2	3.7	4.1	4.6	4.8	4.9
Specific NNI R&D (\$/\$M GDP)	27.6	48.4	70.2	85.6	93.3	98.2			

Table 2. Specific NNI R&D expenditure per capita and per GDP between 2000 and 2005 (the NNI budgets include Congressionally-directed supplements)

Region	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007 Est.	2008 Req.
EU +	126	151	179	200	~ 225	~ 400	~ 650	~ 950	~1,050	1,150		
Japan	120	135	157	245	~ 465	~ 720	~ 800	~ 900	~ 950	980		
USA*	116	190	255	270	464	697	862	989	1,200	1,351	1,397	1,445
Others	70	83	96	110	~ 380	~ 550	~ 800	~ 900	~1,000	1,200		
Total	432	559	687	825	1,534	2,367	3,112	3,739	4,200	4,681		
(% of 1997)	(100%)	(129%)	(159%)	(191%)	(355%)	(547%)	(720%)	(866%)	(972%)	(1083%)		

Table 3. Estimated Government Nanotechnology R&D Expenditures, 1997-2005 (\$ Millions/Year). Explanatory notes: National and EU funding is included. The EU+ includes countries in EU (15)/EU(25) and Switzerland (CH): the rate of exchange \$1 = 1.1 Euro until 2002, = 0.9 Euro in 2003, and = 0.8 Euro in 2004-2005; Japan rate of exchange \$1 = 120 yen until 2002, = 110 yen in 2003, = 105 yen in 2004-2005; “Others” includes Australia, Canada, China, Eastern Europe, FSU, Israel, Korea, Singapore, Taiwan, and other countries with nanotechnology R&D; Estimates use the nanotechnology definition as defined in the NNI (this definition does not include MEMS, microelectronics, or general research on materials) (see Roco, Williams and Alivisatos, 2000, Springer, former Kluwer, also on <http://nano.gov>), and include the publicly reported government of allocations spent in the respective financial years; * A fiscal year (FY) begins in the USA on October 1, and in most other countries six month later around April 1; Denotes the actual budget recorded at the end of the respective fiscal year except for “Estimate” and “Request”, without including Congressionally-directed budget.

Country / Region	Gov. Nanotech R&D, 2004 (\$M)	Specific Nanotech R&D, 2004 (\$/Capita)	Specific Nanotech R&D, 2004 (\$/\$M GDP)
USA	1100	3.7	93
EU-25	~1050	2.3	86
Japan	~ 950	7.4	250
China	~ 250	0.2	31
Korea	~ 300	6.2	350
Taiwan	~ 110	4.7	208

Table 4. Specific NNI R&D expenditure per capita and per GDP between 2000 and 2005 (the NNI budgets include Congressionally-directed supplements) (after Roco, 2005b).

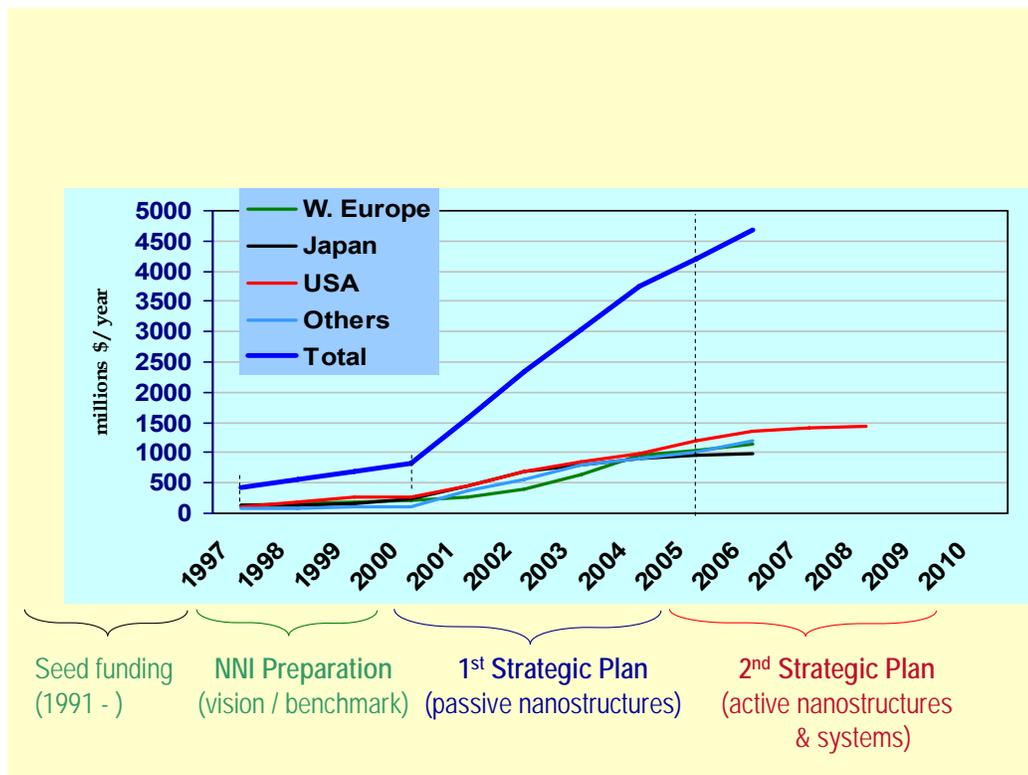


Figure 5. National government investments in nanotechnology R&D in the world and the United States in the past ten years (1997-2006) (see Table 3).

a. First, NNI **developed foundational knowledge in nanotechnology** with about 4,000 projects funded in 2001-2005 in over 500 institutions (about 300 academic and over 200 small businesses and government laboratories) in all 50 states. Research is advancing toward systematic control of matter at the nanoscale faster than envisioned in 2000, when NNI was introduced with words like “Imagine what could be done in 20-30 years from now.” In 2005, about four hundred projects addressed molecular assembling and nanoscale devices and systems, tailoring molecules and manipulating individual atoms. Such R&D projects were not feasible just five years ago. For example, Sam Stupp of Northwestern University has designed molecules for hierarchical self-assembling in desired materials. Alex Zettl of University of California at Berkeley has built the smallest nano-motor with an ax of few nanometers, and Jim Heath at Caltech has analyzed and sense cells as complex nanosystems. The time for reaching commercial prototypes has been reduced by at least of factor of two for key application areas such as detection of cancer, molecular electronics, and nanostructure reinforced composites.

b. NNI has been recognized for **creating an interdisciplinary nanotechnology community in the United States**. According to an external review committee at NSF (NSF COV, 2004), “Two significant and enduring results have emerged from this investment: They are the creation of a nanoscale science and engineering community, and the fostering of a strong culture of interdisciplinary research.”

c. **Nanotechnology education and outreach** is impacted over 10,000 graduate students and teachers in 2005. Systemic changes are in preparation for education, by earlier introduction of nanoscience and reversing the “pyramid of science” with understanding of the unity of nature at the nanoscale from the beginning (Roco, 2003). Nanotechnology education has been expanded systematically to earlier education, including undergraduate (Nanotechnology Undergraduate Education program with over 80 awards since 2002), high schools (since 2003), as well as informal education, science museums and the public. All major science and engineering colleges in United States have introduced courses related to nanoscale science and engineering in the last five years. NSF has established recently three other networks with national outreach addressing education and societal dimensions: (a) The Nanoscale Center for Learning and Teaching aims to reach one million students in all 50 states in the next five years; (b) The Nanoscale Informal Science Education network will develop, among others, about 100 nanoscale science and

technology museum sites in the next five years; (c) The Network on Nanotechnology in Society was established in September 2005 with four nodes at the Arizona State University, University of California at Santa Barbara, University of South Carolina, and Harvard University. The Network will address both short-term and long-term societal implications of nanotechnology, as well as public engagement. All 15 Nanoscale Science and Engineering Centers sponsored by NSF have strong education and outreach activities. The exhibitions organized by the Cornell Nanobiotechnology Center are good illustrations for outreach efforts. The 3,000-square-foot exhibition, "It's a Nano World", first opened at Ithaca, N.Y., in 2003, has reached 3 million people by the end of 2005. It traveled at Epcot in Florida, and science museums in Ohio, South Carolina, Louisiana, Michigan, Virginia and Texas. The exhibition is aimed at 5- to 8-year-olds and their parents. In 2006, a new 5,000-square-foot traveling exhibition, "Too Small to See," aims at middle school students to explain how nanotechnologists create and use devices on a molecular scale.

d. **R&D and innovation results:** With about 25 percent of global government investments (\$1 billion of \$4 billions), the United States accounts for about 50 percent of highly cited papers (Zucker and Darby, 2005), ~ 60 percent of USPTO patents (Huang et al, 2004; Figure 2), and about 70 percent of startups companies (NanoBusiness, 2004) in nanotechnology worldwide. Industry investment in United States has exceeded the NNI in R&D, and almost all major companies in the traditional and emerging fields have nanotechnology groups at least to survey the competition. *Small Times* reported 1,455 U.S. nanotechnology companies in March 2005 with roughly half being small businesses, and 23,000 new jobs were created in small startup 'nano' companies. The NNI SBIR investment was about \$80 million in fiscal year 2005. More than 200 small businesses with a total budget of approximately \$60 million have received support from NSF alone since 2001. Many of these are among the 600 'pure play' nanotechnology companies formed in the United States since 2001 identified in a survey by *Small Times*. All Fortune 500 companies in emerging materials, electronics and pharmaceuticals have nanotechnology activities since 2003.

In 2000, only a handful of companies have corporate interest on nanotechnology (under 1 percent of the companies). A survey performed by the National Center for Manufacturing Sciences (NCMS, 2006) at the end of 2005 shows that 18 percent of surveyed companies are already marketing nanoproducts. Also, a broad spectrum of new applications in advanced

nanoparticles and nanocoatings, as well as durable goods, consumer electronics and medical products are in the pipeline: 80 percent of the companies are expected to have nanoproducts by 2010 (within five years) and 98 percent in longer term (Figure 6). Even if the survey is limited, it shows a strong vote of confidence from a variety of industrial sectors.

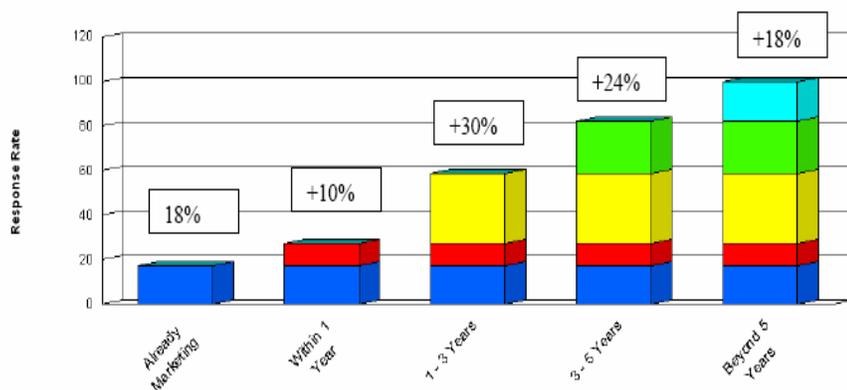


Figure 6. Commercialization time lines indicate many new nanoproducts introductions in 2007-2011, and the high level of expectation in long-term (after NCMS, 2006).

Figure 7 shows the number of USPTO patents searched by keywords in the “title-claims” (Huang et al., 2004). While the United States has a commanding lead of about 61 percent that is similar in the range of 10 percent with other major databases from Europe and Japan, but the decrease in 2005 raises questions. In 2005, the overall number of USPTO patents decreased by about the same proportion.

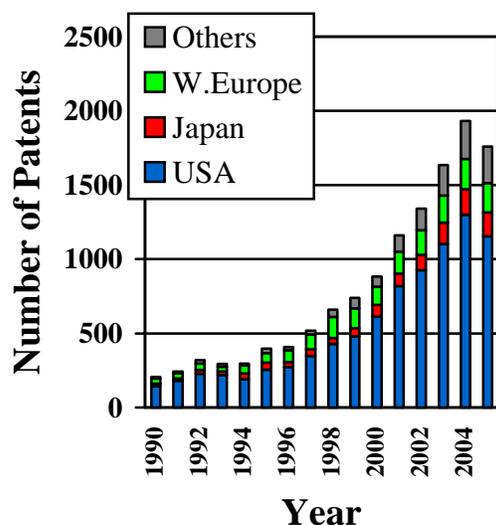


Figure 7. The United States has over 60 percent of world nanotechnology patents in the USPTO database (by searching in “Title-abstract-claims” for nanotechnology keywords with

an intelligent search engine; Huang et al., 2004)

An interesting result is the higher citation of patents authored by NSF grantees (see Figure 7 Huang et al, 2005). Statistical analysis shows that the NSF-funded researchers and their patents have higher impact factors than other private and publicly funded reference groups. This suggests the importance of fundamental research and engineering on nanotechnology development. The number of cites per NSF-funded inventor is about ten as compared to two for all inventors of NSE-related patents recorded at USPTO, and the corresponding Authority Score is 20 as compared to one.

e. Significant infrastructure has been established in over 70 universities and 12 government laboratories with nanotechnology user capabilities. About sixty large centers, networks and user facilities have been created by NSF (24), NIH (19), DOE (5), NASA (4), DOD (3), NIST (2), and CDC/NIOSH (2). Two user networks established by NSF, the Network on Computational Nanotechnology (established in 2002) and the National Nanotechnology Infrastructure Network (established in 2003) have attracted over 12,000 academic, industry, and government users in 2005 (see list of NSF centers in Appendix C). The DOE user facilities are located at five National Laboratories taking advantage of the existing large facilities there. NASA has established four academic based centers.

f. The NNI's vision of a **"grand coalition"** of academe, government, industry and professional groups is taking shape. Over 22 regional alliances have been established throughout the United States and develop local partnerships, support commercialization and education. Professional societies have established specialized divisions, organized workshops and continuing education programs, among them the American Association for the Advancement of Science, American Chemical Society, American Physics Society, Materials Research Society, American Society of Mechanical Engineers, American Institute of Chemical Engineers, Institute of Electrical and Electronics Engineers, and the American Vacuum Society. While Federal R&D investment is increasing, the attention is extending to the legislative and even judiciary branches of the Unites States government.

Partnerships have been created between NNI and industry sectors (Consultative Boards for Advancing Nanotechnology (CBAN) including with the electronic industry sector, chemical industry, and Industrial Research Institute). International agreements have been signed with over 25 countries. An example of partnerships is the International Institute for

Nanotechnology (IIN) at Northwestern University in Illinois. With support from NSF, NIH, DOE, and NASA, this institute has developed partnerships with the state of Illinois, the city of Chicago, and private foundations to create a new kind of science-and-technology-driven regional coalition. With \$300 million in funding for nanotechnology research, educational programs, and infrastructure, IIN has established a large pre-competitive nanoscale science and engineering platform for developing applications, demonstrating manufacturability, and training skilled researchers.

g. Societal implications were addressed from the start of the NNI, beginning with the first research and education program on environmental and societal implications, issued by NSF in July 2000. In September 2000, the report on “Societal Implications of Nanoscience and Nanotechnology” was issued. Today, in 2003, the number of projects in the area had grown significantly, funded by NSF, EPA, NIH, NIOSH, DOE and other agencies. Awareness of potential unexpected consequences of nanotechnology has increased, and federal agencies meet periodically to discuss those issues in the NSET Working Group Nanomaterials Environmental and Health Issues (NEHI). In the crosscut of all programs, **societal implications and applications** (addressing environmental, health and safety; educational; ethical, legal and other social implications) may be identified in about 10 percent of all NNI projects. In the first five years of NNI, the NSF investment with relevance to fundamental research supporting environmental, health, and safety aspects of nanotechnology is about \$82 million, or about 7 percent of the NSF nanoscale science and engineering investment. Research has addressed the sources of nanoparticles and nanostructured materials in the environment (in air, water, soil, biosystems, and work environment), as well as the non-clinical biological implications. The safety of manufacturing nanomaterials is investigated in four NSF centers/networks including at Rice University, Northeastern University, University of Pennsylvania and NNIN (nodes at the University of Minnesota and Arizona State University are focused on nanoparticle measurement).

e. Leadership: As a result of the NNI, the U.S. is recognized as the world leader in this area of science, technology, and economic opportunity. The NNI has catalyzed global activities in nanotechnology and served as a model for other programs. Several recognitions for contributing to NNI are given in Appendix D.

Industry-NNI Collaborative Boards for Advancing Nanotechnology

The NNI has established a new approach for the interaction with industry sectors besides the previous models in supporting academe-industry government collaboration and encouraging technological innovation. Consultative Boards for Advancing Nanotechnology (CBAN) are representing various industry sectors broadly and help coordinate interactions with electronic, chemical, business, medical/pharmaceutical and car manufacturing sectors. The NNI has established a new approach for the interaction with various industry sectors besides the previous models. Joint Consultative Boards for Advancing Nanotechnology (CBAN) have been formed with key industry sectors such as electronic, chemical, biotechnology and business sectors. They provide input to R&D planning for short and long-term, to EHS needs, and contribute to nanotechnology R&D and education. The CBAN with electronic industry was established in October 2003, and five working groups have prepared various reports, and several collaborative activities in long-term R&D planning and funding of research have been completed. The main objectives of CBAN are:

- (a) Joint planning and support of collaborative activities in key R&D areas;
- (b) Disseminate the NNI R&D results to industry and encourage technology transfer and technological innovation and industrial use;
- (c) Identify and promote new R&D for exploratory areas or gaps in current programs, including those with potential in niche markets;
- (d) Expand nanotechnology R&D in industry and long-term topics in academe;
- (e) Periodical joint meetings and joint reports; and
- (f) Exchange information. A formal mechanism via public hearings is planned to provide opportunity to industrial partners to propose R&D topics.

5. Technical challenges in 2005-2020

Nanotechnology has the potential to change our comprehension of nature and life, develop unprecedented manufacturing tools and medical procedures, and even effect societal and international relations. Nanotechnology holds the promise to increase the efficiency in traditional industries and bring radically new applications through emerging technologies. The first set of

nanotechnology grand challenges was established in 1999-2000, and NSET plans to update it in 2004. Let's imagine again what could be done. Ten potential developments by 2015 are:

- ***At least half of the newly designed advanced materials and manufacturing processes are built using control at the nanoscale at least in one of the key components.*** Even if this control may be rudimentary as compared to the long-term potential of nanotechnology, this will mark a milestone towards the new industrial revolution as outlined in 2000. By extending the experience with information technology in the 1990s, I would estimate an overall increase of social productivity by at least 1 percent per year because of these changes. Silicon transistors will reach dimensions smaller than 10 nm and will be integrated with molecular or other kind of nanoscale systems. Alternative technologies for replacing the electronic charge as information carrier with electron spin, phase, polarization, magnetic flux quanta, and/or dipole orientation are under consideration. Technologies will be developed for directed self assembly into non-regular, hierarchically organized, device oriented structures and creation of functional, nanoscale building blocks. Lighter composite nanostructured materials, nanoparticle laden more reactive and less pollutant fuels, and automated systems enabled by nanoelectronics will dominate automotive, aircraft and aerospace industries. Top-down manufacturing is expected to integrate with bottom-up molecular assemblies using modular approaches. Nanoscale designed catalysts will expand the use in “exact” chemical manufacturing to cut and assemble molecular assemblies, with minimal waste. Measurement and imaging of large domains of biological and engineering interest are expected to reach atomic precision and time resolution of chemical reactions. Visualization and numerical simulation of three-dimensional domains with nanometer resolution will be necessary for engineering applications.
- ***Suffering from chronic illnesses is being sharply reduced.*** It is conceivable that by 2015, our knowledge to detect and treat tumors in their first year would be advanced and will have the ability to reduce suffering and death from cancer. In 2000, we aimed for earlier detection of cancer within 20-30 years. Today, based on the results obtained during 2001-2005 in understanding the cell and new instrumentation, we are trying to eliminate cancer as a cause of death if treated in a timely manner. Pharmaceutical synthesis, processing and delivery will be enhanced by nanoscale control, and about half of pharmaceuticals will use nanotechnology in a key component. Modeling the brain based on neuron-to-neuron interactions will be possible by using advances in nanoscale measurement and simulation.

- ***Converging science and engineering from the nanoscale will establish a mainstream pattern for applying and integrating nanotechnology with biology, electronics, medicine, learning and other fields (Roco and Bainbridge, 2003).*** It includes hybrid manufacturing, neuromorphic engineering, artificial organs, expanding life span, enhancing learning and sensorial capacities. Science and engineering of nanobiosystems will become essential to human healthcare and biotechnology. The brain and nervous systems functions are expected to be measure with relevance to cognitive engineering.
- **Life-cycle sustainability and biocompatibility will be pursued in the development of new products.** Knowledge development in nanotechnology will lead to reliable safety rules for limiting unexpected environmental and health consequences of nanostructures. Control of contents of nanoparticles will be performed in air, soils and waters using a national network. International agreements will address the nomenclature, standards and risk governance of nanotechnology.
- ***Knowledge development and education will originate from the nanoscale instead of the microscale.*** A new education paradigm not based on disciplines but on unity of nature and education-research integration will be tested for K-16 (reversing the pyramid of learning (8)). Science and education paradigm changes will be at least as fundamental as those during the “microscale S&E transition” that originated in 1950s where microscale analysis and scientific analysis were stimulated by the space race and digital revolution. The new “nanoscale S&E transition” will change the foundation of analysis and the language of education stimulated by the nanotechnology products. This new “transition” originated at the threshold of the third millennium.
- ***Nanotechnology businesses and organizations will restructure towards integration with other technologies, distributed production, continuing education, and forming consortia of complementary activities.*** Traditional and emerging technologies will be equally affected. An important development will be creation of nanotechnology R&D platforms to serve various areas of applications with the same investigative and productive tools. Two examples are the nanotechnology platform created at a newly build laboratory by General Electric and the discovery instrumentation platform developed at the Sandia National Laboratory.
- The capabilities of nanotechnology for systematic control and manufacture at the nanoscale are envisioned to evolve in four overlapping generations of new nanotechnology products

(Roco, 2004b) (Figure 8). Each generation of products is marked here by creation of first commercial prototypes using systematic control of the respective phenomena and manufacturing processing:

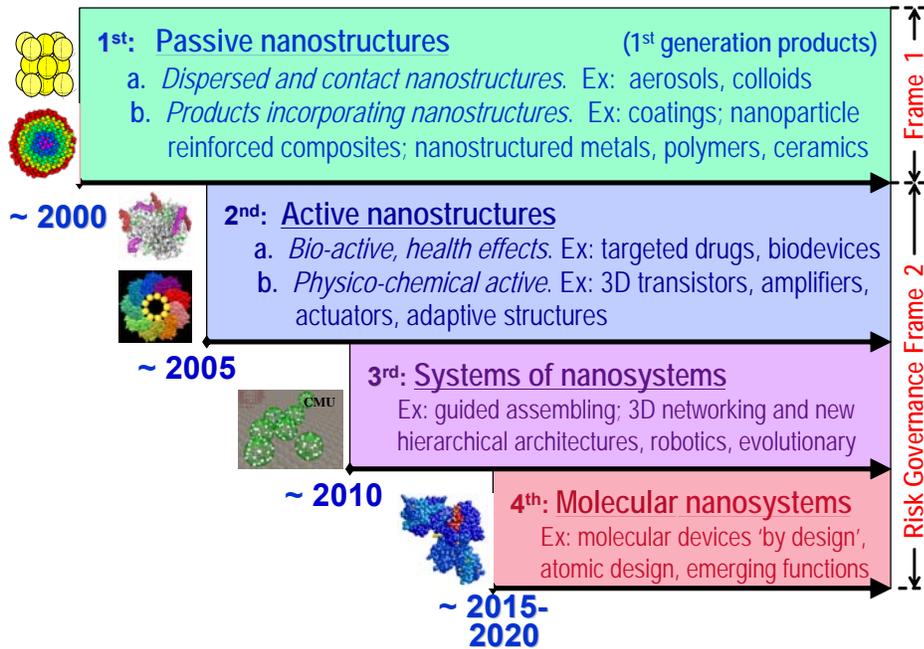


Figure 8. Timeline for beginning of industrial prototyping and nanotechnology commercialization: Four generations of nanoproducts

- a. **First Generation of products (~2001-)** is “**passive nanostructures**” and is typically used to tailor macroscale properties and functions. The specific behavior is stable in time. Illustrations are nanostructured coatings, dispersion of nanoparticles, and bulk materials - nanostructured metals, polymers, and ceramics.
- b. **Second Generation of products (~ 2005 –)** is “**active nanostructures**” for mechanical, electronic, magnetic, photonic, biological, and other effects. It is typically integrated into microscale devices and systems. New transistors, components of nanoelectronics beyond CMOS, amplifiers, targeted drugs and chemicals, actuators, artificial “muscles”, and adaptive structures illustrate this.
- c. **Third Generation (~ 2010 –)** is “**systems of nanosystems with three-dimensional nanosystems**” using various syntheses and assembling techniques such as bio-assembling; robotics with emerging behavior, and evolutionary approaches. A key challenge is networking at the nanoscale and hierarchical architectures. Research focus

will shift towards heterogeneous nanostructures and supramolecular system engineering. This includes directed multiscale selfassembly, artificial tissues and sensorial systems, quantum interactions within nanoscale systems, processing of information using photons or electron spin, assemblies of nanoscale electromechanical systems (NEMS) and converging technologies (nano-bio-info-cogno) platforms integrated from the nanoscale.

- d. **Fourth Generation (~ 2015 -) will bring “heterogeneous molecular nanosystems”**, where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices and from their engineered structures and architectures will emerge fundamentally new functions. Designing new atomic and molecular assemblies is expected to increase in importance, including macromolecules “by design”, nanoscale machines, and directed and multiscale selfassembly, exploiting quantum control, nanosystem biology for healthcare, human-machine interface at the tissue and nervous system level. Research will include topics such as: atomic manipulation for design of molecules and supramolecular systems, controlled interaction between light and matter with relevance to energy conversion among others, exploiting quantum control mechanical-chemical molecular processes, nanosystem biology for healthcare and agricultural systems, and human-machine interface at the tissue and nervous system level.
- **Energy conversion** - is a main objective of nanotechnology development and exploratory projects in areas such as photovoltaic conversion and direct conversion of thermal to electric energy, are expected to be developed
 - **Water filtration and desalinization** - using nanotechnology has a high promise despite that only scarce efforts are underway.
 - **Nano-informatics** – specific databases and methods to use them will be developed for characterization of nanocomponents, on materials and processes integrated at the nanoscale. Such databases will interface with the existing such as bio-informatics, human and plant genome.

6. New science and engineering, new governance approach

The promise of nanotechnology, however, will not be realized by simply supporting research. Just as nanotechnology is changing how we think about unity of matter at the nanoscale and manufacturing, it's also changing how we think about the management of the research enterprise.

This switch can be seen as the specialization of scientific disciplines has migrated to more unifying concepts for scientific research and system integration in engineering and technology. Most of the major U.S. science and technology programs in the 20th century – such as space exploration, energy and environmental programs – have been “pulled” primarily by external factors. The economy, natural resources, national security and international agreements and justifications have initiated top-down R&D funding decisions.

In contrast, nanotechnology development was initially “pushed” by fundamental knowledge (nanoscience and nanoengineering) and the long-term promise of its transformative power. For this reason, we have done the preparation and governance of nanotechnology differently. For nano, research policies have been motivated by long-term vision rather than short-term economical and political decisions.

Transforming and responsible development has guided many NNI decisions. Investments must have return, the benefit-to-risk ratio must be justifiable, and societal concerns must be addressed. We have introduced nanomanufacturing as a grand challenge since 2002, and we have established a research program at NSF with the same name. NSF awarded three nanomanufacturing centers, and NSF, DOD and NIST will create a network in 2006. In another example, in 2004-2005, NSF is establishing a new kind of networks with national goals and outreach. The four networks are in high school and undergraduate nanotechnology education, nanotechnology in society, informal nanotechnology science education, and hierarchical manufacturing. The NEHI (Nanotechnology Environmental and Health Issues) and NILI (Nanotechnology Innovation and Liaison with Industry) working groups were established by NSET (NSTC’s Nanoscale Science, Engineering and Technology Subcommittee that coordinated NNI). The NNI has established a new approach for the interaction with various industry sectors besides the previous models: Consultative Boards for Advancing Nanotechnology (CBAN) as described earlier.

Improving technological innovation has been another strategy. While R&D activities have spread rapidly in the last five years (they now are in over 60 countries), and nanotechnology has been recognized as a key R&D domain, the economical potential and societal benefits of nanotechnology basically remain in the exploratory phase. Rather, they are seen as promising, and the national investment policies do not generally recognize nanotechnology as important as

information technology and biotechnology. This may be explained by the relatively recent developments in nanoscale knowledge and the *limited economical understanding of its implications*. There is an apparent gap between the accelerated accumulation of scientific data, and ways to apply the results safely and economically. The promise for future economical benefits is a key driver for any emerging technology, but it is generally difficult to document it

Proactive actions have been taken for addressing societal implications. Immediate and long-term issues are addressed in parallel. We combined formal and informal approaches of interaction in order to receive better input from stakeholders, and encouraged push-pull dynamics (such as input academic and industry perspectives) in setting research priorities. The speed and scope of nanotechnology R&D exceeds for now the capacity of researchers and regulators to fully assess human and environmental implications. *A specific framework for risk governance* is needed because nanotechnology developments are fundamental in long-term, operating as an open and complex system. One may need to connect the governance at the national and the international levels. Interaction with industry, civil organizations and international community are essential for the responsible development of nanotechnology.

The International Dialog on Responsible Nanotechnology R&D (June 17-18, 2004 in Alexandria, Virginia) was the first meeting of government representatives from over 25 countries and the E.U. dedicated to broad societal issues that cannot be addressed by any single country. This activity may yield a set of principles, structured priorities, and mechanisms of interaction, including sharing data on responsible research and development of nanotechnology.

We need to develop anticipatory, deliberate and proactive measures in order to accelerate the benefits of nanotechnology and its applications. Adaptive and corrective approaches in government organizations are to be established in the complex societal system with the goal of improved long-term risk governance. User- and civic-group involvement is essential for taking better advantage of the technology and developing a complete picture of its societal implications. A multidisciplinary, international forum is needed in order 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) may provide an independent framework for identification, assessment and mitigation of risk.

“NNI is a new way to run a national priority,” told Charles West at the March 23, 2005 PCAST meeting reviewing the NNI for Congress.

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.”

It was clear, however, that nanotechnology couldn’t advance through the guidance of nanotechnologists or public policy administrators alone. The directions in which research was traveling were too complex and required more than a top-down management system.

Rather, it would require the efforts of all interested stakeholders. It would also require visionary, nanotechnology-specific and multi-tier management to develop “higher purpose” goals. Key stakeholders needed to be involved from the beginning for a successful project. Furthermore, introduction of nanotechnology was a global process.

The most recent NNI discussions are with the Department of Labor for an anticipatory approach in training of workers for emerging nanotechnology application areas. We have support on both sides of the aisle in the 21st Century Nanotechnology R&D Act received 100 percent approval from Senate in December 2003 (Congress, 2003), and NSET coordinating NNI passed unchanged from the Democratic to Republican administrations, receiving strong support from the White House. We have justified development of nanotechnology as beyond the interest of a single political party. In January 2000, then President Clinton announced the NNI, and in January 2006, in the State of the Union address, President Bush listed nanotechnology a top technological opportunity for national competitiveness.

7. Closing remarks

The NNI has been the major driver for nanoscience and nanotechnology developments and applications in the United States and in the World.

Besides products, tools and healthcare, nanotechnology also implies learning, imagination, infrastructure, inventions, public acceptance, culture, anticipatory laws and architecture of other factors. In 1997-2000, we developed a vision, and in the first five years, 2001-2005, the vision has become an R&D reality. A main reason for the development of NNI has been the vision based on intellectual drive towards exploiting new phenomena and processes, developing a unified science and engineering platform from the nanoscale, and using the molecular and nanoscale interactions for efficient manufacturing. Another main reason has been the promise of broad societal implications, including \$1 trillion per year by 2015 of products where nanotechnology plays a key role, which would require 2 million workers.

Nanotechnology is entering new S&E challenges (such as active nanostructures, nanosystems, nanobio and nanobiomedicine, advanced tools, environmental and societal implication studies, etc.) in 2006. All trends for papers, patents, and worldwide investments are still with exponential growth, with potential inflexion points in several years. There is a need for continuing long-term planning, interdisciplinary activities and anticipatory measures involving interested stakeholders.

In the next 5-10 years, the challenges of nanotechnology will increase in new directions because there is a transition:

- From investigating single phenomena and creating single nanoscale components to complex systems, active nanostructures and molecular nanosystems
- From scientific discovery to technological innovation in advanced materials, nanostructured chemicals, electronics, and pharmaceuticals
- Expanding to new areas of relevance such energy, food and agriculture, nanomedicine, and engineering simulations from the nanoscale
- Accelerating development, where the rate of discovery remains high and significant changes occur in interval of several years.

While expectations from nanotechnology may be overestimated in short term, the long-term implications on healthcare, productivity and environment appear to be underestimated provided proper consideration is given to educational and social implications.

Acknowledgements

This paper is based on my experience in coordinating the NNI. Opinions expressed here are those of the author and do not necessarily reflect the position of NSTC/NSET or NSF.

Appendix A.

The structure of NNI in the first (2001-2005) and second (2006-2010) strategic plans.

VISION: A future in which the ability to understand and control matter on the nanoscale - 1 to 100 nm - leads to a revolution in technology and industry.

A1. NNI modes of support in fiscal years 2001-2005 (1st NNI Strategic Plan)

- The funding strategy for the National Nanotechnology Initiative was based on five modes of investment. The first mode supports a balanced investment in fundamental research across the entire breadth of science and engineering, and it is lead by the National Science Foundation.

- The second mode, collectively known as the "grand challenges," focuses on nine specific R&D areas that are more 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 challenges 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

- The third mode of investment supports centers of excellence that conduct research within host institutions. These centers pursue projects with broad multidisciplinary research goals that are not supported by more traditionally structured programs. These centers also promote education

of future researchers and innovators, as well as training of a skilled technical workforce for the growing nanotechnology industry.

- The fourth mode funds the development of infrastructure, instrumentation, standards, computational capabilities, and other research tools necessary for nanoscale R&D.
- The fifth mode recognizes and funds research on the societal implications, and addresses educational needs associated with the successful development of nanoscience and nanotechnology. Besides the graduate and postgraduate education activities, NSF supports nanoscale science and engineering programs for earlier nanotechnology education for undergraduates, high schools, and public outreach.

A2. NNI Goals in Fiscal Years 2006-2010 (2nd NNI Strategic Plan) (NSTC, 2004)

This plan describes the goals of the NNI as well as the strategy by which those goals are to be achieved. The goals are as follows:

- Maintain a world-class research and development program aimed at realizing the full potential of nanotechnology
- Facilitate transfer of new technologies into products for economic growth, jobs, and other public benefit
- Develop educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology
- Support responsible development of nanotechnology

The investment strategy includes the major subject categories of investment, or program component areas (PCAs), cutting across the interests and needs of the participating agencies:

1. Fundamental nanoscale phenomena and processes
2. Nanomaterials
3. Nanoscale devices and systems
4. Instrumentation research, metrology, and standards for nanotechnology
5. Nanomanufacturing
6. Major research facilities and instrumentation acquisition
7. Societal dimensions

Appendix B. NNI members

List of Federal Agencies Participating in the NNI (January 2006)
Federal agencies with budgets dedicated to nanotechnology research and development
Department of Agriculture, Cooperative State Research, Education, and Extension Service (USDA/CSREES) Department of Agriculture, Forest Service (USDA/FS) Department of Defense (DOD) Department of Energy (DOE) Department of Homeland Security (DHS) Department of Justice (DOJ) Department of Transportation (DOT) Environmental Protection Agency (EPA) National Aeronautics and Space Administration (NASA) National Institute of Standards and Technology (NIST, Department of Commerce) National Institute for Occupational Safety and Health (NIOSH, Department of Health and Human Services/Centers for Disease Control and Prevention) National Institutes of Health (NIH, Department of Health and Human Services) National Science Foundation (NSF)
Other participating agencies
Bureau of Industry and Security (BIS, Department of Commerce) Consumer Product Safety Commission (CPSC) Department of Education (ED) Department of Labor (DOL) Department of State (DOS) Department of the Treasury (DOTreas) Food and Drug Administration (FDA, Department of Health and Human Services) International Trade Commission (ITC) Intelligence Technology Innovation Center, representing the Intelligence Community (IC) Nuclear Regulatory Commission (NRC) Technology Administration (TA, Department of Commerce) U.S. Patent and Trademark Office (USPTO, Department of Commerce)

Appendix C. List of National Science Foundation Centers and Networks in the field of nanoscale science and engineering established since 2000

University	Name of the center, network or user facility
<i>Nanoscale Science and Engineering Centers (NSECs)</i>	
Columbia University	Center for Electron Transport in Molecular Nanostructures
Cornell University	Center for Nanoscale Systems
Rensselaer Polytechnic Institute	Center for Directed Assembly of Nanostructures
Harvard University	Science for Nanoscale Systems and their Device Applications
Northwestern University	Institute for Nanotechnology
Rice University	Center for Biological and Environmental Nanotechnology
University of California, Los Angeles	Center for Scalable and Integrated Nanomanufacturing
University of Illinois at Urbana-Champaign	Center for Nanoscale Chemical, Electrical, Mechanical, and Manufacturing Systems
University of California at Berkeley	Center for Integrated Nanomechanical Systems
Northeastern University	Center for High Rate Nanomanufacturing
Ohio State University	Center for Affordable Nanoengineering
University of Pennsylvania	Center for Molecular Function at the Nanoscale
Stanford University	Center for Probing the Nanoscale
University of Wisconsin	Center for Templated Synthesis and Assembly at the Nanoscale
Arizona State University University of California, Santa Barbara University of South Carolina Harvard University	Nanotechnology in Society Network
<i>Centers from the Nanoscale Science and Engineering Education Solicitation</i>	
Northwestern University	Nanotechnology Center for Learning and Teaching
Boston Museum of Science	Nanoscale Informal Science Education
<i>NSF Networks and Centers that Complement the NSECs</i>	
Cornell University and 12 other nodes	National Nanotechnology Infrastructure Network
Purdue University and 6 other nodes	Network for Computational Nanotechnology
Oklahoma University, Oklahoma State university	Oklahoma Nano Net
Cornell University	STC: The Nanobiotechnology Center

Appendix D. Recognitions for NNI contribution

The author of this chapter received several recognitions for contributing to NNI partially described in this chapter:

- From the U.S. interagency committees after announcing NNI (2000) and the first strategic plan (2006):
 - Interagency WGN/National Science and Technology Council Plaque,
"To Dr. M. Roco, who with big ideas has created a National Nanotechnology Program focused on things small",
Washington, D.C, February 16, 2000.
 - Nanoscale Science, Engineering and Technology, NSTC Plaque,
"To Mihail C. Roco, Dr Nano, Founding Father of the U.S. National Nanotechnology Initiative; For his vision, dedication and energy in advancing the field of nanotechnology in the U.S. and across the world." Washington, D.C., January 19, 2006. (The picture on the plaque is shown in Figure D1).
- From professional organizations:

Dr. Roco is a Correspondent Member of the Swiss Academy of Engineering Sciences, a Fellow of the American Society of Mechanical Engineers, a Fellow of the Institute of Physics, and a Fellow of the American Institute of Chemical Engineers. The "Engineer of the Year" (two times, in 1999 and 2004) by the U.S. National Society of Professional Engineers and NSF, Distinguished Service Award of the NSF (2001); AIChE Nanoscale Science and Engineering Forum Award for "Leadership and service to the national science and engineering community through initiating and bringing to fruition the National Nanotechnology Initiative", New York, September 2005.
- From national and international surveys:

Small Times Magazine: "Best of Small Tech Awards" ("Leader of the American nanotech revolution", Nov. 2002); **Forbes Nanotechnology:** "First in Nanotechnology's Power Brokers", Forbes, March 2003 ("Leading Architect of NNI"); **Scientific American:** World Technology Leader – Scientific American Top 50 in 2004 (for: "Led nearly \$1-billion-a-year U.S. government effort in nanotechnology"; "building a solid consensus in the scientific and non-technical communities that nanotechnology is important for future scientific and economic development, and he has furthered public acceptance of

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