The Vision and Action Plan of the National Nanotechnology Initiative

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ABSTRACT

The vision of novel phenomena, unity in nature, and promise of the most efficient manufacturing length scale has been essential in establishing the multidisciplinary National Nanotechnology Initiative (NNI). The research opportunities and projections of their societal outcomes have been integrated into a transforming strategy to yield the program announced in January 2000. This paper briefly outlines the motivation of this major investment, its systematic preparation since 1996, current activities in fiscal year 2002 ($604 million), and key challenges for the future. Modeling and simulation at the nanoscale plays a special role because the limited spatial and temporal resolution of measuring devices at the nanoscale. Virtually all industrialized countries have initiated or have in advanced planning stages a national activity on nanoscale science and engineering stimulated by the NNI since 2000. This transforms nanotechnology into a field of broad international interest, increasing collaboration and stimulating competition.

Keywords: Nanoscience, nanotechnology, R&D strategy, international perspective.

1 THE VISION

We know most about single atoms and molecules at one end, and on bulk behavior of materials and systems at the other end. We know less about the intermediate length scale - the nanoscale, which is the natural threshold where all living systems and man-made systems work. This is the scale where the first level of organization of molecules and atoms in nanocrystals, nanotubes, nanobiomotors, etc. is established. Here, the basic properties and functions of material structures and systems are defined, and even more importantly can be changed as a function of organization of matter via 'weak' molecular interactions.

We are beginning not only to see and touch matter at the nanoscale, but also to uncover new phenomena and envision manufacturing processes. Developing a strategy for a research and development (R&D) program of national and international relevance must be treated with at least the same rigor as the investigation of an individual research project. There are two main reasons why nanotechnology has received increased attention in the last few years:

a. The intellectual drive towards smaller dimensions, which was essentially enhanced by the discovery of new phenomena, properties and the manipulation capabilities at the nanoscale.

b. The promise of significant societal implications, which include better understanding of nature, efficient manufacturing techniques for almost every human-made object, a new world of products beyond what has been possible with other technologies, molecular medicine, and sustainable development leading to cleaner environment. It is projected that $1 trillion products worldwide will be affected by nanotechnology in 10-15 years [1].

2 TIMELINE OF NNI

A planning activity at the national level to advance nanoscale science and engineering has been underway in the U.S. since November 1996 through an ad-hoc interagency Nanotechnology Group. Nanotechnology was perceived as a dormant opportunity with immense potential. We felt that there is a tremendous potential for scientific and technological progress, as well as a generality and a unity in concepts among disciplines and areas of relevance that would stimulate intellectual advancement and economic developments. First, we have established a vision that is focused on the novel system behavior and manufacturability at the nanoscale and less on the advantages of smallness itself. This vision is applicable to all disciplines, involves potential contributors from all areas of relevance, and aims for long-term objectives.

Seed research funding limited to specific objectives or areas of relevance has been provided on a continuous basis at NSF starting with the Nanoparticle Synthesis and Processing initiative (focus on chemical processing, 1991-2001, $3-4 million per year) and the National Nanofabrication User Network (with the original focus on miniaturization in microelectronics, 1994-2003, $4-5 million per year). In 1997-1998, NSF sponsored a multidisciplinary program entitled "Partnership in Nanotechnology: Functional Nanostructures" and in 1999-2000 the program on "Modeling and Simulation at the Nanoscale" (see http://www.nsf.gov/nano). The purpose of this program was to develop a knowledge base of the interplay of multiphenomena at multiscales by encouraging synergistic interaction among research groups with different areas of interest in nanoscale modeling and simulation. The goal was to support three to five groups, each focusing on a set of coupled phenomena over a few length scales and a set of methodologies. The intent of the overall initiative has been to support an assemblage of groups that cover a broad range of phenomena and processes in key areas. It has been expected that a synergistic relationship among the funded groups will develop over time.

The activities in U.S. and other countries were fragmented, nanotechnology had various definitions, and a unifying vision was needed. The White House National Science and Technology Council (NSTC) established the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) in October 1998, in order to develop a vision, a strategy and a plan of action for advancing nanotechnology. The first activity was a workshop with a broad spectrum of about 150 leading experts in the field equally distributed among academe, private sector and government experts. The results were summarized in "Nanotechnology Research Directions: Vision for Nanotechnology in the Next Decade" [2].

On behalf of IWGN, I have proposed the National Nanotechnology Initiative (NNI) at the meeting on March 10, 1999 of the White House, Office of Science and Technology Policy, Committee of Technology. The proposed plan would ensure that the fundamental sciences and key technological opportunities of nanotechnology would reach their potential sooner, a flexible and balanced infrastructure and educated workforce would be available for nanotechnology development, and key technological grand challenges would be addressed (see "NNI: The Initiative and the Implementation Plan", NSTC, 2000 [3]). After the NNI planning process was completed, NSTC has established the Subcommittee on Nanoscale Science, Engineering and Technology (NSET) in August 2000. NSET succeeds the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN) as the primary interagency coordination mechanism. Its goal is to work towards NNI implementation, facilitate interagency collaboration for nanoscale R&D, continue to improve the vision for nanotechnology, and provide a framework for establishing U.S. R&D priorities and budget. The NSET will coordinate planning, budgeting, implementing, and reviewing the NNI to ensure a broad and balanced initiative. The Subcommittee is composed of representatives from agencies and White House officials with interest in the NNI.

The FY 2002 Budget request by President Bush is approximately $604 million (see Table 1), a 43% increase. The number of departments and independent agencies in NSET has increased from 6 in 2000 to 15 in June 2001. International developments partially stimulated by NNI have created an even broader impact than envisioned initially.

The nanoscale science, engineering and technology investment of all U.S. Federal agencies of $116 million in fiscal year (FY) 1997 has increased to about $190 million in 1998, $255 million in 1999, and $270 million in 2000 (NSTC, 2000). The report "Nanotechnology Research Directions" called for a national initiative in FY 2001 that would significantly increase the Federal government annual investment to about a half billion dollars. On November 18, 1999, the Presidential Council of Advisers in Science and Technology (PCAST) Nanotechnology Panel met to discuss the IWGN proposal and made a positive recommendation to the Administration. Then President Clinton announced NNI in January 2000 and submitted the NNI plan to Congress in February 2000 [4]. The White House, Office of Management and Budget (OMB) approved the NNI budget at the beginning of November 2000. A White House letter signed jointly by the OSTP and the OMB, which was sent to all agencies in late summer 2000, placed nanotechnology at the top of the list of emerging fields of research and development in the U.S. where agencies should collaborate. In October 2000, the U.S. Congress enacted the Federal nanotechnology investment portfolio of $422 for FY 2001. The FY 2002 Budget under President Bush is approximately $604 million (see Table 1), and the request for FY 2003 is $710 million.

The NSET members are from DOD, DOE, DOJ, DOS, DOTreas, DOT, EPA, NASA, NIH, NIST, NRC, NSF, USDA, and White House offices (National Economic Council, NSTC, OMB, and OSTP). The key societal challenges and opportunities of NNI have been addressed in a series of publication: "Societal Implications of Nanoscience and Nanotechnology" [1], "Nanoscience and Nanotechnology: Shaping Biomedical Research" [5], and "Nanotechnology - Shaping the World Atom by Atom" [6].

Table 1.
Summary of Federal nanotechnology investment in FY 2002 Budget Request (in million of dollars)

Agency	**FY 2000**	**FY 2001**	**FY 2002**
DOD	70	110	180.0
DOE	58	93	91.1
DOJ	-		1.4
DOT/FAA	-	-	2.0
EPA	-	-	5.0
NASA	5	20	46.0
NIH	32	39	40.8
NIST	8	10	17.5
NSF	97	150	199.0
USDA	-	-	1.5
Total*	**270**	**422**	**604.5 (+43%)**

(*) Figures are listed only for eight major agencies.

The key transforming strategy of NNI are:

- *Focus on fundamental research:* This strategy aims to encourage revolutionary discoveries and open a broader net of results as compared to development projects for the same resources.

- *Policy of inclusion and partnerships:* This applies to various disciplines, areas of relevance, research providers and users, technology and societal aspects, and international integration.

- *Recognize the importance of visionary, macroscale management measures:* It includes defining the vision of nanotechnology, establishing the R&D priorities and interagency implementation plan, integrating short-term technological developments into the broader loop of long-term R&D opportunities and societal implications, using peer review for NNI, developing a suitable legal framework, and integrating some international efforts.

- *Prepare the nanotechnology workforce*: A main challenge is to educate and train a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology. The concepts at the nanoscale (atomic, molecular and supramolecular levels) should penetrate the education system in the next decade in a similar manner to how the microscopic approach made inroads in the last forty-fifty years. It is estimated that about 2 million nanotechnology workers will be needed worldwide in 10-15 years [6].

- *Address broad humanity goals:* Nanoscale science and engineering will lead to a better understanding of nature, and improved wealth, health, sustainability, and peace.

3 2002 NNI PLAN OF ACTION

The NNI research and development priorities have been developed in consultation with experts from academe, private sector and government laboratories, as well as through the coordination of the funding agencies. This investment of $568 million is still a small fraction (0.6%) of the federal R&D budget. The main activities are:

- *Long-term fundamental nanoscience and engineering research* - NSF will make the largest investment in fundamental research of $199 million in FY 2001, or about 5% of its research budget. NSF programs embrace topics from chemistry, materials, molecular biology and engineering to revolutionary computing, mathematics, geosciences and social sciences. About 1,000 projects with over 5,000 faculty and students, and about 15 centers, will be supported in FY 2001. DOE, DOD, NIH and NASA also sponsor fundamental aspects of nanotechnology.
- *Grand Challenges* – areas where potential breakthroughs could provide major, broad-based economic benefits, as well as dramatically improve the quality of life. The FY 2002 has identified 11 areas of Grand Challenges (see NNI Implementation Plan, 2000 plus two new areas).
  - Nanostructured materials 'by design'
  - Nanoelectronics, optoelectronics, and magnetics
  - Advanced healthcare, therapeutics, and diagnostics
  - Nanoscale processes for environmental improvement
  - Efficient energy conversion and storage
  - Microcraft space exploration, and industrialization
  - Nanoscale instrumentation/ metrology (new in 2002)
  - Manufacturing processes at the nanoscale (new)
  - Chemical/bio/radiological/explosive detection and protection (modified)
  - Applications to economical and safe transportation
  - Applications to national security.
- *Centers and Networks of Excellence* - will encourage research networking and shared academic users' facilities. These nanotechnology research centers will play an important role in development and utilization of specific tools, and in promoting partnerships in the coming years.
- *Research Infrastructure* - includes funding for metrology (measurement science), instrumentation, modeling and simulation, and user facilities. The goal is to develop a flexible and enabling infrastructure both in support of fundamental research and of U.S. industry's ability to commercialize the new discoveries and innovations rapidly.
- *Ethical, Legal, and Societal Implications, and Workforce Education and Training* - efforts will promote a new generation of skilled workers with the multidisciplinary perspectives necessary for rapid progress in nanotechnology. Nanotechnology's effect on society -- legal, ethical, social, economic, and workforce preparation -- will be studied to help identify potential concerns and ways to address them.

The NNI implementation plan in FY 2002 (October 2001 - September 2002) includes the proposed funding themes and modes of support by the U.S. funding agencies, as well as coordinated activities in order to increase synergism, avoid unnecessary overlapping, and create a balance and flexible infrastructure. Program solicitations for FY 2002 proposals have been issued by NSF, DOD, DOE, NASA, EPA and other agencies as part of the NNI implementation plan (full information is available on http://nano.gov). The NSF Nanoscale Science and Engineering program announcement (NSF 01-157) includes "*Multi-scale, Multi-phenomena Theory, Modeling and Simulation at the Nanoscale" as a major theme. The announcement recognizes that t*he emergence of new behaviors and processes in nanostructures, nanodevices and nanosystems creates an urgent need for theory, modeling, large-scale computer simulation and new design tools in order to understand, control and accelerate development in new nanoscale regimes and systems. Research on theory, mathematical methods, modeling and simulation of physical, chemical and biological systems at the nanoscale will include techniques such as quantum mechanics and quantum chemistry, multi-particle simulation, molecular simulation, grain and continuum-based models, stochastic methods, and nanoscale mechanics. Approaches that make use of more than one such technique and focus on their integration will play an important role in this effort. The interplay of coupled, time-dependent and multiscale phenomena and processes in large atomistic and molecular systems will be encouraged. A critical issue is the ability to make connection between structures, properties and functions.

4 FUTURE CHALLENGES

It is estimated that in 2001 we are at the beginning of the development curve where the rate of discovery is increasing and we need about five years to reach the rising sector of the classical "S" curve. In addition to technical Grand Challenges, other challenges for the advancement of nanotechnology must be considered:

- *Interdisciplinarity and unity in research and education*: Nanoscale science and engineering research is intrinsically interdisciplinary but it is performed in an academic environment that principally rewards individual performance. Creative approaches are envisioned in order to change the focus from single discipline to a system approach. The unity of principles in nanoscience, no matter the discipline and area of relevance is another important challenge. At a larger scale, we look for increased synergism between nano-, bio-, info- technologies and social sciences with a focus on the human dimension.

- *Timely education and training:* The educational foundation in science and engineering will move from the microscopic to the molecular level. Changes in teaching from kindergarten to graduate students, as well as continuing education activities for retraining, are envisioned. An important corollary activity is the retraining of teachers themselves. Interdisciplinary fellowships in graduate schools are necessary. It is estimated that nanotechnology will enter our lives in a significant manner in 10-15 years. The availability of sufficient scientists and industrial experts is in question if we continue on the path adopted in the last years. One may consider changes in the way we structure the information on nanotechnology in order to improve learning and disseminate the results [7]. A five-year goal is to ensure that 50 % of research institutions' faculty and students have access to the full range of nanoscale research facilities, and access to nanoscience and engineering education for students is enabled in at least 25% of research universities.

- *Nanoscale manufacturing*: No research at the nanoscale can be performed without synthesis and processing of nanostructures and fabrication of nanosystems, and no nanotechnology would exist without developing economical approaches to large scale production of the same. Two new Grand Challenge areas that have been identified for FY 2002 are: measurements, instrumentation and standards; and manufacturing at the nanoscale. Rudimentary nanostructures such as thin layers and nanoparticle dispersions have already made inroads in manufacturing. Important challenges are developing systematic methods for economical fabrication of three-dimensional nanostructures, establishing nanoscale manufacturing capabilities and the markets for nanotechnology producers and users. Another important challenge is establishing standardized, reproducible, microfabrication approaches to nanocharacterization, nanomanipulation and nanodevices

- *Societal implications and continuing funding*: Societal implications include the envisioned benefits from nanotechnology as well as the second-order consequences, such as potential risks, disruptive technologies, and ethical aspects. Further long-term developments of the field depend on the way one addresses the 'societal challenges' of nanotechnology. The NSTC interagency subcommittee is actively seeking input from research groups, social and economical experts, professional societies and industry on this issue.

- *International challenges:* Virtually all industrialized countries have in development for nanotechnology or have established a plan at the national level in recent years (see for illustration [8], [9], [10]). There are good opportunities for win-win agreements in the precompetitive research areas. A synopsis of the worldwide developments shows different R&D areas of strength in each geographical zone [11]. The levels of nanotechnology government investments in Europe, Japan, U.S. and other countries have increased by about three times since 1997. Estimated government sponsored R&D in $ millions/year are shown in Table 2. The worldwide nanotechnology research and development (R&D) investment reported by government organizations has increased by a factor of 3.5 between 1997 and 2001, and the highest rate of 90% is in 2001.

	1997	1998	1999	2000	2001	2002
W. Europe	126	151	179	200	est. 225	
Japan	120	135	157	245	410 +140*	
USA	116	190	255	270	422	550
Others (~)	70	83	96	110	est. 380	
Total	*432*	*559*	*687*	*825*	*1,577*	

Table 2. *Estimated government sponsored R&D in $ millions/year (Note: "W. Europe" includes countries in EU and Switzerland; "Others" include Australia, Canada, China, FSU, Korea, Singapore, Taiwan and other countries with nanotechnology R&D. These estimations use the nanotechnology definition as in NNI (see [2]), and include the publicly reported government spending. (*) Japan has supplemented its initial $410 million nanotechnology investment in 2001 with about $140 million for materials including nanostructured metals and polymers.*

5 CLOSING REMARKS

I would like to close this brief overview of NNI with several comments regarding international collaboration in the future. Nanoscale science and engineering R&D is mostly in a precompetitive phase. International collaboration in fundamental research, long-term technical challenges, metrology, education and studies on societal implications will play an important role in the affirmation and growth of the field. The U.S. NNI develops in this context. The vision setting and collaborative model of NNI has received international acceptance, and most industrialized countries are establishing or are planning to establish their own programs. Opportunities for collaboration towards an international nanotechnology effort, particularly in the precompetitive areas, will amplify once those national programs are in place. Also, one may note that large companies rely heavily on R&D results from external company sources (about 80% in 2001), of which a large proportion is from another country (Europe 35%, Japan 33%, U.S. 12%, according to E. Roberts, MIT, at the Sloan School of Management). An increased number of companies act globally with significant flow of ideas, capital, and people. This trend will accelerate and will be the environment in which nanotechnology will develop.

Priority goals may be envisioned for international collaboration in nanoscale research and education: better comprehension of nature, increasing productivity, sustainable development, and development of humanity and civilization. Examples include understanding single molecules and operation of single cells, improving health and human performance, simulation and measuring methods, assembly and fabrication tools for the building blocks of matter, highly efficient solar energy conversion and water desalinization for sustainable development.

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