increasing productivity in manufacturing to extending the quality of life and sustainability limits on Earth.

Table 2.2
Estimated Government Nanotechnology R&D Expenditures, 1997-2004 ($ Millions/Year)

Region	1997	1998	1999	2000	2001	2002	2003	2004	2005
W. Europe	126	151	179	200	~ 225	~ 400	~ 650	~ 950	1,050
Japan	120	135	157	245	~ 465	~ 720	~ 800	~ 900	950
USA*	116**	190**	255**	270**	465**	697**	863**	~ 989	1,081
Others	70	83	96	110	~ 380	~ 550	~ 800	~ 900	1,000
Total	**432**	**559**	**687**	**825**	**1,535**	**2,367**	**3,113**	**3,739**	**4,081**
(% of 1997)	(100%)	(129%)	(159%)	(191%)	(355%)	(547%)	(720%)	(866%)	(945%)

Explanatory notes: Estimates include research in nanotechnology as defined by the NNI (this definition does not include MEMS, microelectronics, or general research on materials), and reflect the publicly reported government spending.
"W. Europe" includes countries in EU (15) and Switzerland. Rates of exchange $1 = 1.1 Euro until 2002, = 0.9 Euro in 2003, and = 0.8 Euro in 2004-2005. National and EU funding are included.
Japanese rate of exchange $1 = 120 yen until 2002, = 110 yen in 2003, = 105 yen in 2004-2005.
"Others" includes Australia, Canada, China, Eastern Europe, former Soviet Union, Israel, Korea, Singapore, Taiwan, and other countries with nanotechnology R&D.
* A fiscal year begins in USA on October 1, six months before most other countries.
** Denotes the actual expenditures recorded at the end of the respective fiscal year.

Results of the NNI Investment

There are major outcomes after the first three years (fiscal years 2001-2003) of the NNI. The NNI has already created a nanoscale science and engineering "powerhouse" of discoveries and inventions in the United States with about 40,000 researchers, students and workers qualified at least in one aspect of nanotechnology. The R&D landscape for nanotechnology research and education has changed, advancing from questions, such as, "What is nanotechnology?" and "Could it ever be developed?" to "How can we take advantage of it faster?" and "Who is the leader?" The FY 2005 NNI investment is about four times the corresponding Federal investment in FY 2000 ($1081 million from $270 million), and the attention is extending to the legislative and even judicial branches of the U.S. Government.

Further evidence of progress includes the following:

- Research is advancing towards systematic control of matter at the nanoscale faster than envisioned in 2000, when NNI was introduced with words like "Imagine what could be done 20 to 30 years from now." After three years, in 2003, the NNI supports about 2,500 active awards in about 300 academic organizations and about 200 small businesses and nonprofit organizations in all 50 states. The time of reaching commercial prototypes has been reduced by at least a factor of two for several key areas such as detection of cancer, molecular electronics, and special nanocomposites. About half of highly cited papers by the Institute for Scientific Information, High-Impact Papers electronic database appear to continue to originate from the United States [7].
- Systemic changes are being implemented for education, by earlier introduction of nanoscience and reversing the "pyramid of science" with the understanding of the unity of nature at the

scale of atoms, molecules, and their assemblies taught in the earliest years of science education. In 2002, NSF announced the nanotechnology undergraduate education program, and in 2003, the nanotechnology high school education program. In the next years, we plan to change the language of science even earlier and involve science museums to "seed" that language in K-12 students. About 7,000 students and teachers have been trained in 2003 with NSF support. All major science and engineering colleges in the United States have introduced courses related to nanoscale science and engineering in the last three years.

- Significant infrastructure has been established in more than 60 universities with nanotechnology user capabilities. Five networks (Network for Computational Nanotechnology, National Nanotechnology Infrastructure Network, Oklahoma Network for Nanotechnology, the DOE large facilities network, and the NASA nanotechnology academic centers) have been established.
- Industry investment has reached about the same level of investment as the NNI in long-term R&D, and almost all major companies in traditional and emerging fields have nanotechnology groups at least to survey the competition. For example, Intel has reported $20 billion revenues from nanotechnology in 2003. About 61 percent of patents (about 1,011 of 1,644) related to nanotechnology (searched by keywords in the title, abstract, and claims) as recorded by the U.S. Patent and Trade Office in 2002 are from the United States, while the NNI funding represents about 25 percent of the world government investment (about $770 million of $3.0 billion). According to a NanoBusiness Alliance estimate of business activity in late 2003, 70 percent of the nanotechnology start-up companies worldwide (approximately 1,100 of 1,500) were located in the United States. Despite the general economic downturn, nanotechnology venture funding in the United States doubled in 2002 as compared to 2001. NSF supported more than 100 small businesses with an investment of $36 million between 2001 and 2003.
- The NNI's vision of a "grand coalition" of academe, government, industry, and professional groups is taking shape. More than 22 regional alliances have been established throughout the United States to develop local partnerships and support commercialization and education. Professional societies have established specialized divisions, organized workshops and continuing education programs. Among the professional societies are 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 American Vacuum Society.
- Societal implications were addressed from the start of the NNI, beginning with the first research and education program on environmental and societal implications, announced in a program solicitation by NSF in July 2000. In September 2000, the report on *Societal Implications of Nanoscience and Nanotechnology* was issued. In 2004, the number of projects in the area grew significantly, funded by NSF, EPA, NIH, DOE, and other agencies. Awareness of potential unexpected consequences of nanotechnology has increased, and Federal agencies meet periodically to discuss those issues.

Where Is the NNI Going from Here?

Nanotechnology has the potential to change our comprehension of nature and life, develop unprecedented manufacturing tools and medical procedures, and even change societal and international relations. The first set of nanotechnology grand challenges was established in 1999-2000. Let's imagine again what could be done. I envision several potential developments by 2015:

- Half of the newly designed advanced materials and manufacturing processes are built using control at the nanoscale. 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 outlined in 2000. By extending the experience with information technology in the 1990s, I would estimate an overall increase in productivity of at least 1 percent per year because of these changes. Ahead are several challenges. Visualization and numerical simulation of three-dimensional domains with nanometer resolution will be necessary for engineering applications. Nanoscale-designed catalysts will expand the use in "exact" chemical manufacturing to cut and link molecular assemblies with minimal waste. Silicon transistors will reach dimensions smaller than 10 nm and will be integrated with molecular or other kind of nanoscale systems (beyond or integrated with Complementary Metal-Oxide Semiconductor technology [CMOS]). Changing our goals and strategies in this area is the experimental proof of concept, completed in 2003, which showed that CMOS can work at 5 nanometer gate lengths (and potentially at a smaller scale). One may recall that in 2000, we contemplated the "brick wall" of physical principles that would limit the advancement of silicon technology by the end of this decade. Now we are looking to advances in CMOS technology over another decade (by 2020) and then to its integration with bottom-up molecular assembling.
- Suffering from chronic illnesses is being sharply reduced. It's conceivable that by 2015, our ability to detect and treat tumors in their first year of occurrence might sharply reduce suffering and death from cancer. In 2000, we aimed for earlier detection of cancer within 20 to 30 years. Today, based on the results obtained during the period 2001 through 2003 with respect to understanding the processes within a cell and new instrumentation to characterize those cellular processes, 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 as a key component. Modeling the brain based on neuron-to-neuron interactions will be possible by using advances in nanoscale measurement and simulation.
- Converging technologies from the nanoscale will establish a mainstream pattern for applying and integrating nanotechnology with biology, electronics, medicine, learning, and other fields. It includes hybrid manufacturing, neuromorphic engineering, artificial organs, expansion of the life span, and enhanced learning and sensorial capacities. New concepts in distributed manufacturing and multi-competency clustering will be developed.
- 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 nanomaterials. Synergism among life cycles of various groups of products will be introduced for overall sustainable development. Control of nanoparticles will be performed in air, soils, and waters using a national network for monitoring and remediation.
- Knowledge development and education will begin with instruction about the nanoscale instead of the microscale. Earlier exposure to nanoscience education could change the role of science and enhance motivation for schoolchildren. A new education paradigm not based on disciplines but on the 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 that occurred during the "microscale S&E transition" that originated in the 1950s, when microscale analysis and scientific analysis were stimulated by the space race and digital revolution. Stimulated by nanotechnology products, the new "nanoscale S&E transition"