

F. Frankel - copyright

The Future of the National Nanotechnology Initiative

Dr. M.C. Roco

Chair, Subcommittee on Nanoscience, Engineering and Technology (NSET),
National Science and Technology Council (NSTC)

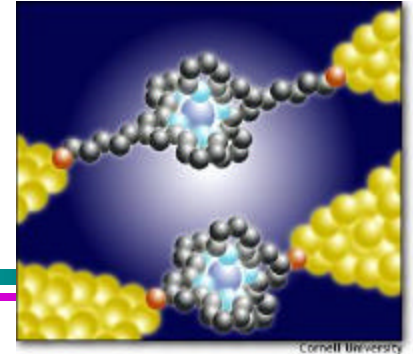
Senior Advisor for Nanotechnology, National Science Foundation

Boston, November 7, 2003



Nanotechnology

Definition on http://nano.gov/omb_nifty50.htm (2000)



- † Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure
- † **NNI definition encourages new contributions that were not possible before.**
 - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain
 - the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions
 - integration along length scales, and fields of application



Broad societal implications

(examples of societal implications;
worldwide estimations made in 2000, NSF)

✍ Knowledge base: better comprehension of nature, life

✍ New technologies and products: ~ \$1 trillion/year by 2015
(With input from industry US, Japan, Europe 1997-2000, access to leading experts)

Materials beyond chemistry: \$340B/y

Pharmaceuticals: \$180 B/y

Aerospace about \$70B/y

Electronics: over \$300B/y

Chemicals (catalysts): \$100B/y

Tools ~ \$22 B/y

Est. in 2000 (NSF) : about \$40B for catalysts, GMR, materials, etc.; + 25%/yr

Est. in 2002 (DB) : about \$116B for materials, pharmaceuticals and chemicals

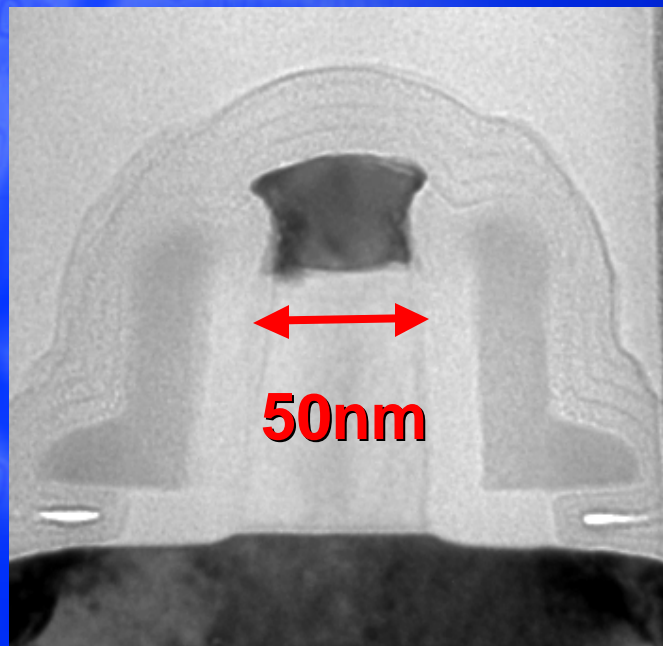
Would require worldwide ~ 2 million nanotech workers

✍ Improved healthcare: extend life-span, its quality, physical capabilities

✍ Sustainability: agriculture, food, water, energy, materials, environment; ex:
lighting energy reduction ~ 10% or \$100B/y

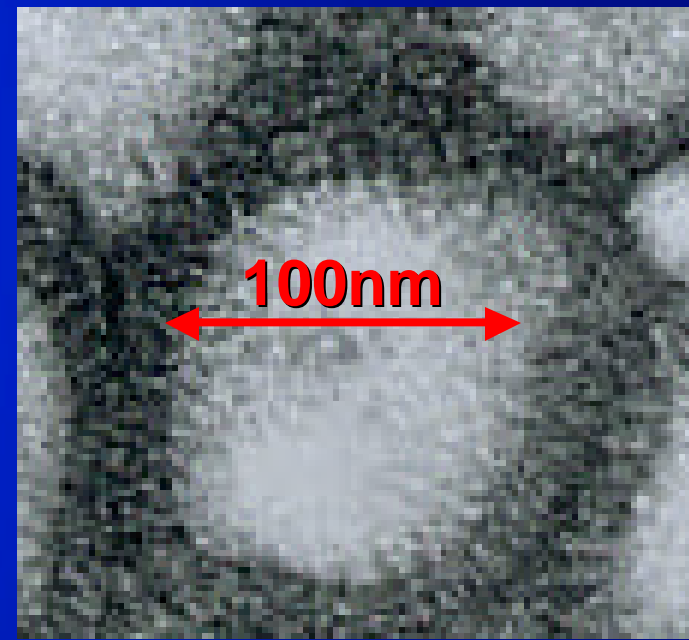
Example of today's technology: 50 nm transistor dimension

Intel's projected revenues 2003 from silicon nanotech products: > \$20 Billion



**Transistor for
90nm-node**

Source: Intel

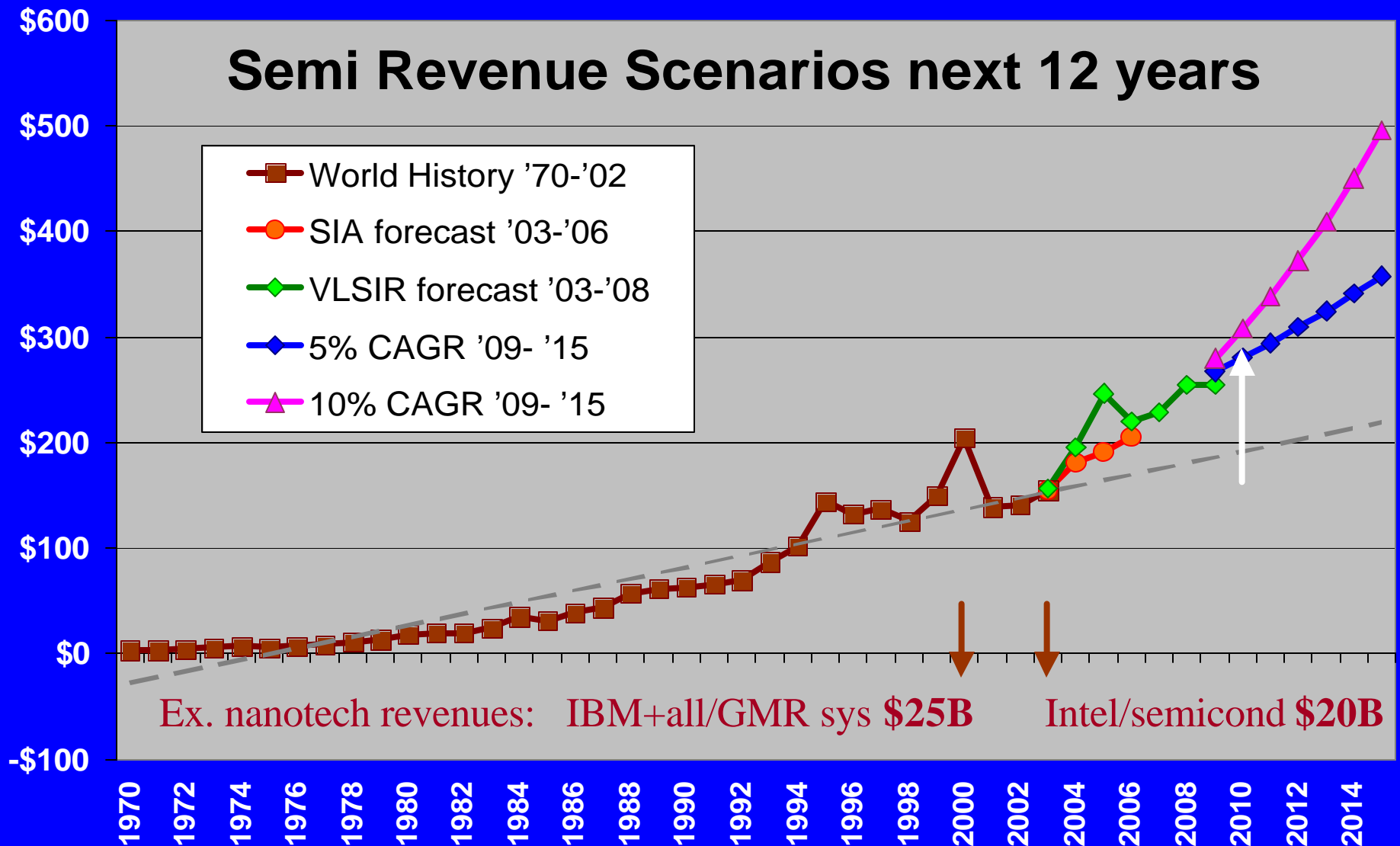


Influenza virus

Source: CDC

Gate dielectric thickness = 1.2 nm

Semiconductors Extrapolated to 2015 (\$B)



Source: Semiconductor Industry Assn. 70-02; VLSI Research 03-08

Note: \$300B nanotech revenues sooner than predicted (2010 instead of 2015)

NNI implementation plan published in July 2000

Major changes in the first 3 years of NNI (Part 1)

- † **Research**: NNI supports about 2,500 active awards in about 300 academic organizations in all 50 states;
Developments faster than expected: Reducing the time of reaching commercial prototypes by at least of factor of two for several key applications
- † **Education**: 7,000 students and teachers trained in 2003;
All science and engineering colleges have introduced courses related to NSE
- † **Significant infrastructure**: in over 60 universities with user capabilities; **Five networks (NCN, NNIN, OKN, DOE, NASA) have been established.**

Scientific Breakthroughs

in the first two years (NNI, 2001-2002)

† **Developments faster than expected**

Reducing the time of reaching commercial prototypes by at least of factor of two for several key applications

† **10 key advancements set up in 2000**

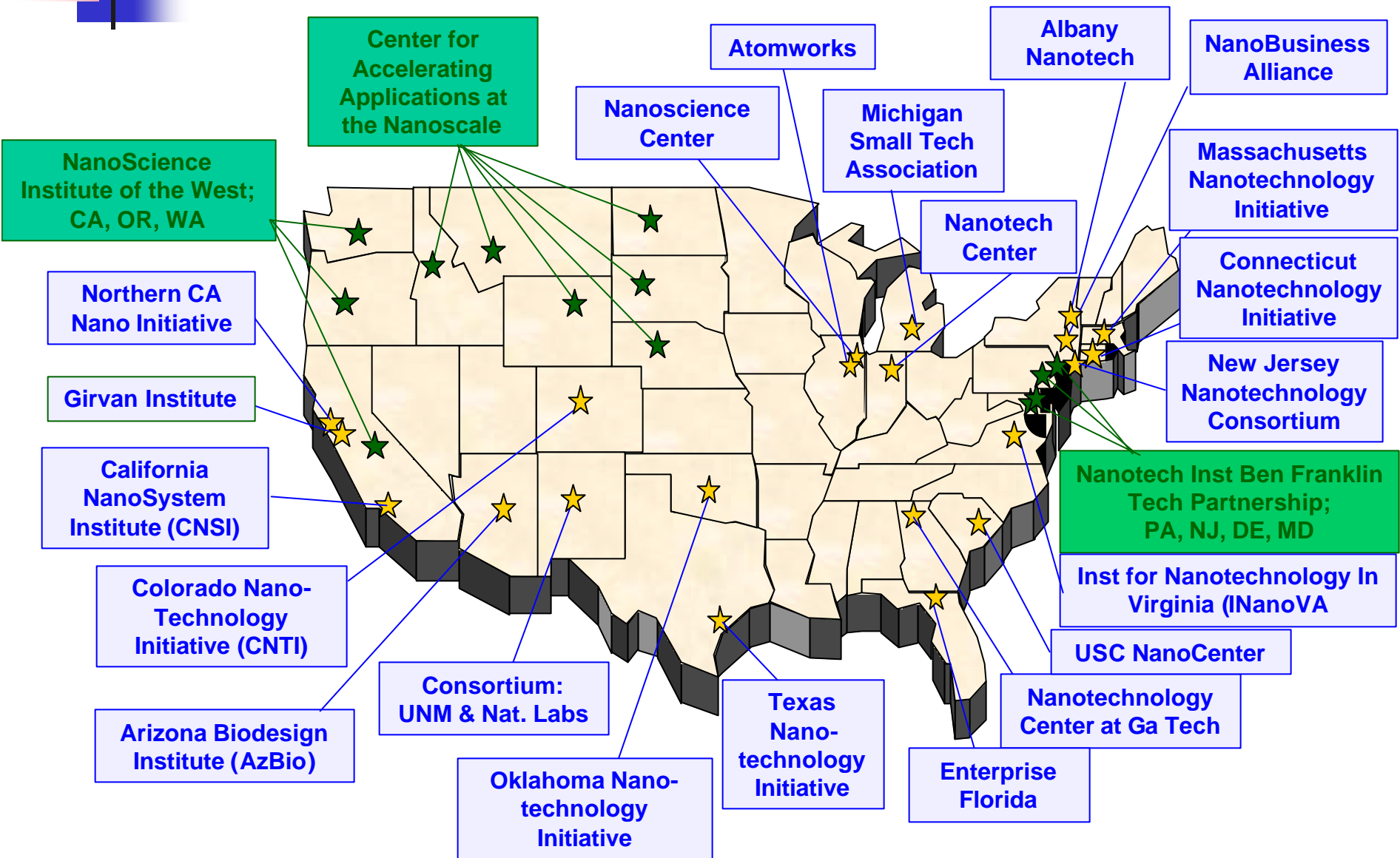
- Engineer materials with atomic precision using biosystems as agents
- Create circuits with the logic element a molecule wide
- Assemble DNA, nanocrystals to build molecular devices and systems
- Detect anthrax, other contaminants with unprecedented speed
- Single molecule behavior and interaction
- Artificial genetic system
- Conducting polymers
- New concepts for large scale production of nanotubes, their use
- Drug delivery systems
- Detection of cancer

NNI implementation plan published in July 2000

Major changes in the first 3 years of NNI (Part 2)

- † **Industry:** about the same level of investment as NNI in medium and long-term research; Investment by large companies; From “if?” to “how?” and “who will lead?”
- † **Innovation and venture funding:**
US has over 6,000 patents in 2002 with USPTO (75% world)
- † **Estimation on revenues from nanotechnology:**
Reaching \$1trillion in 2015 worldwide, and the estimations moving closer because of accelerated development; growth >25% per year
- † **States and regional alliances:** “meltdown” in 2002 -
> 20 states committed funding, > 22 regional alliances

Sampling of Current Regional, State, & Local Initiatives in Nanotechnology



NNI implementation plan published in July 2000

Major changes in the first 3 years of NNI (Part 3)

- † **Professional societies**: Specialized divisions, workshops, education; AAAS, ACS, APS, MRS, ASME, AIChE, IEEE, AVS, other major societies in the race
- † **Government investment**: Worldwide investment has increased 7 times in 6 years reaching \$3B in 2003 (of which US \$0.77B and NSF \$0.22B)
- † **Societal implications from the beginning**: Workshop on Societal Implications of Nanoscience and Nanotechnology in 2000; NSF programs on SI since 2000
- † **Other broader implications**: In Federal Government (NNI), Legislative (5 year Bill), Judiciary branches, cultural

After 3 years of NNI:
New R&D potential targets for 2015 (2)

2004

2015

Nanoscale visualization and simulation of 3D domains

Micro domains with nano space and time resolutions

Transistor beyond/integrated CMOS under 10 nm

New catalysts for chemical manufacturing

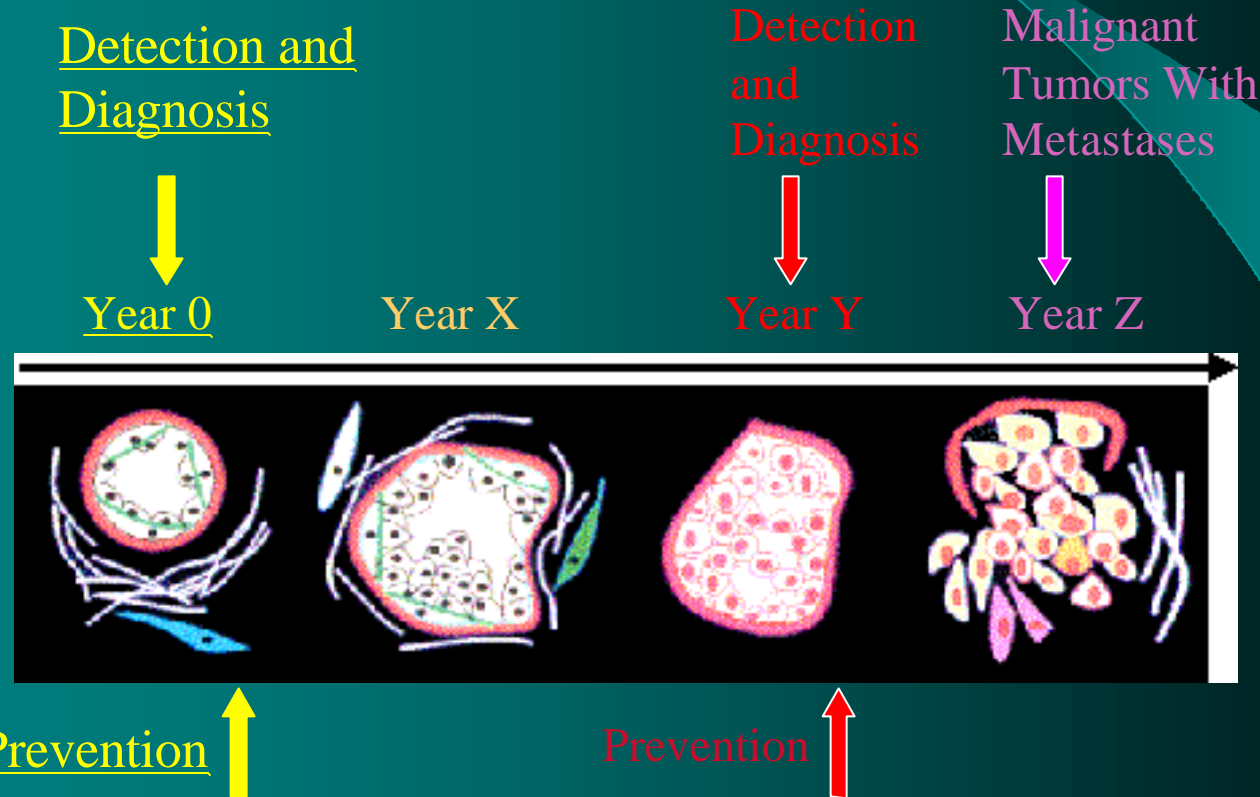
No suffering and death from cancer when treated

Control of nanoparticles in air, soils and waters

Challenge: To Eliminate Suffering and Death Due to Cancer – 2015

“A Vision Not a Dream!” by using nanotechnology, A v. *Eschenbach*, NCI

Where We Want To Be ← Where We Are



Cancer results from accumulation of multiple genetic changes in a cells.
Nanotechnology will allow earlier detection and prevention (Year 0)

**After 3 years of NNI:
New R&D potential targets for 2015**

2004

2015

Advanced materials and manu.: $\frac{1}{2}$ from molecular level

Pharmaceuticals synthesis and delivery: $\frac{1}{2}$ based on nano

Converging technologies from the nanoscale

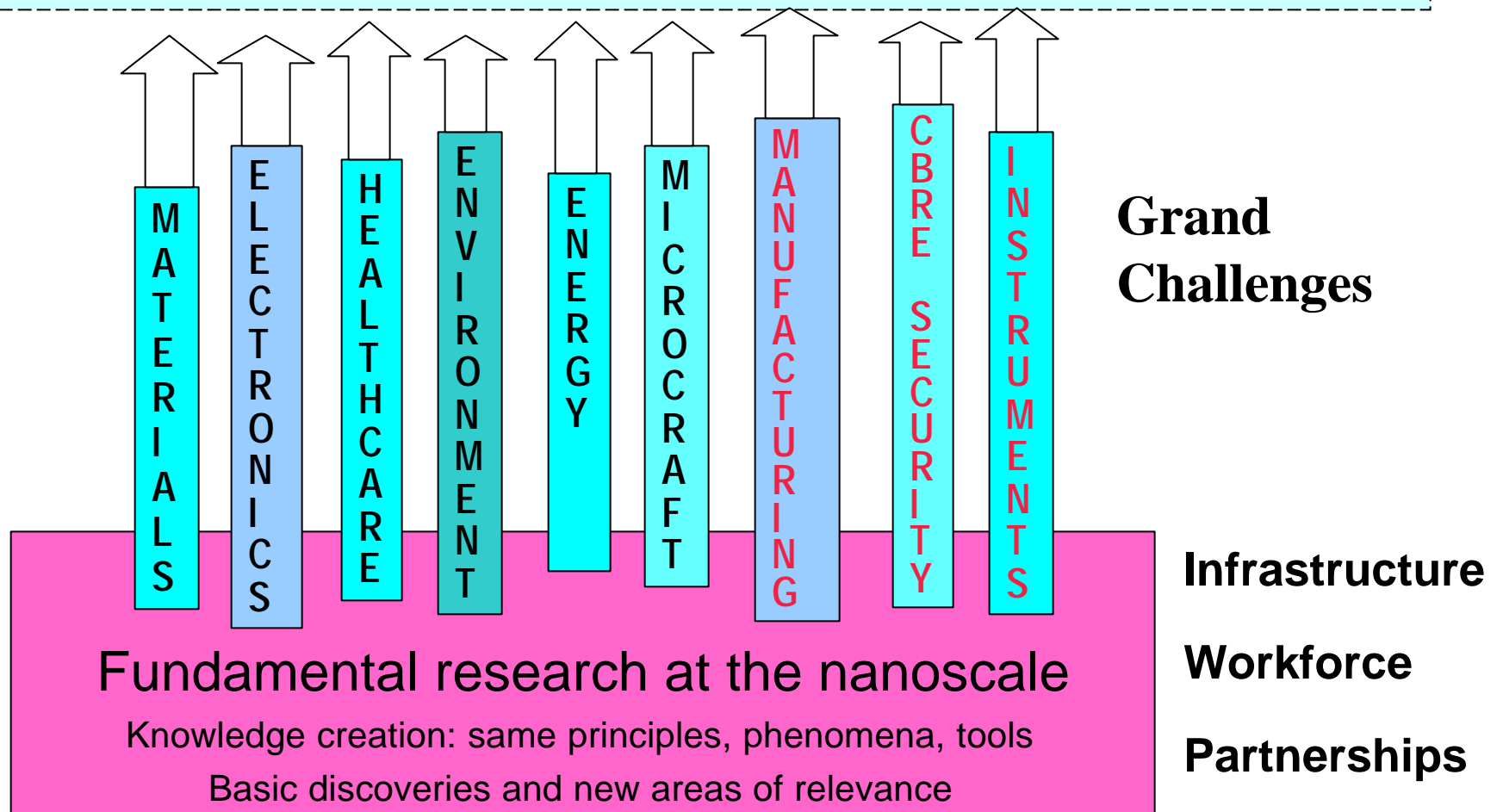
Including: artificial organs, expand life expectancy, increase productivity

Life-cycle biocompatible/sustainable development

Education: nanoscale instead of microscale-based

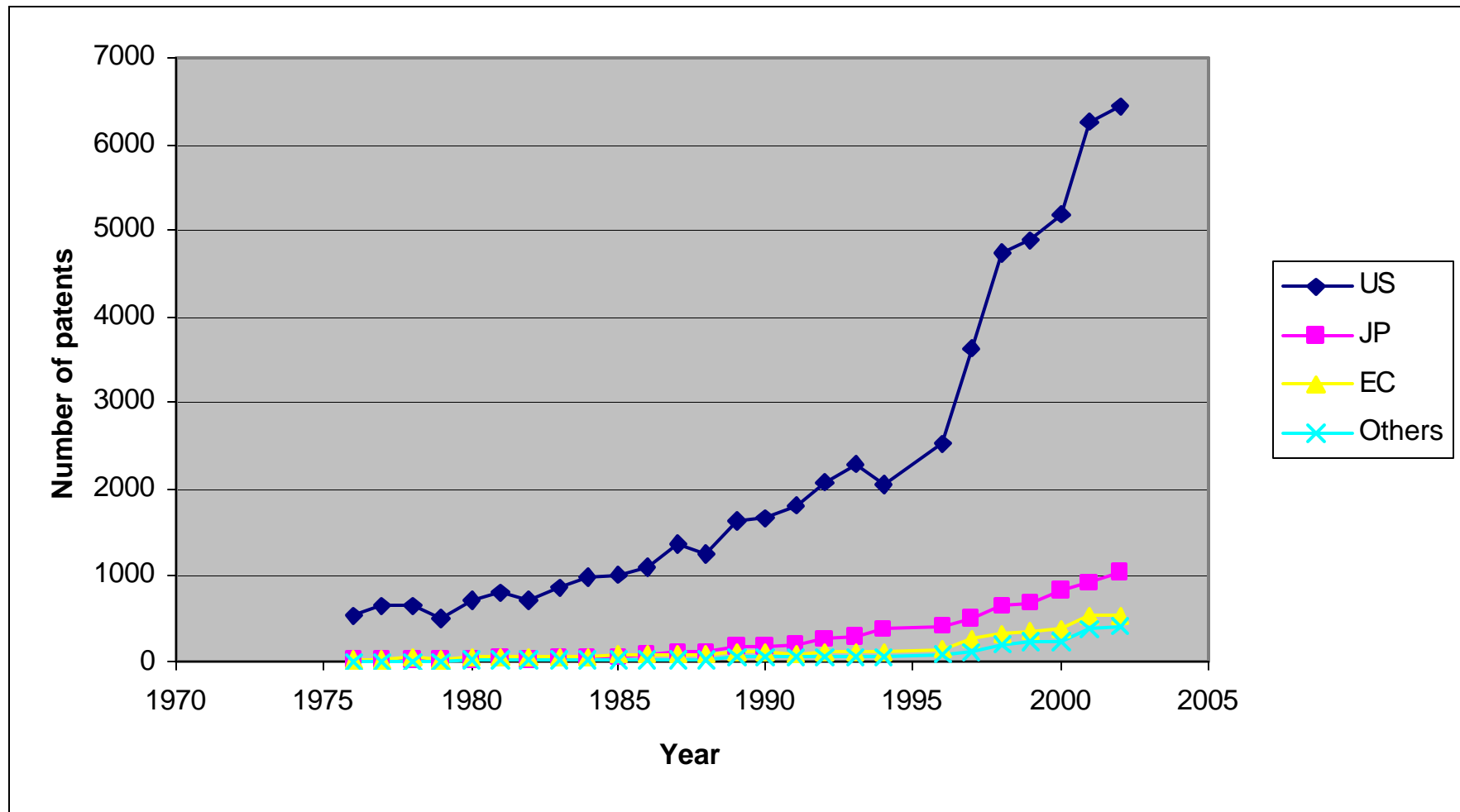
Interdisciplinary “horizontal” knowledge creation vs. “vertical” transition from basic concepts to Grand Challenges

Revolutionary Technologies and Products



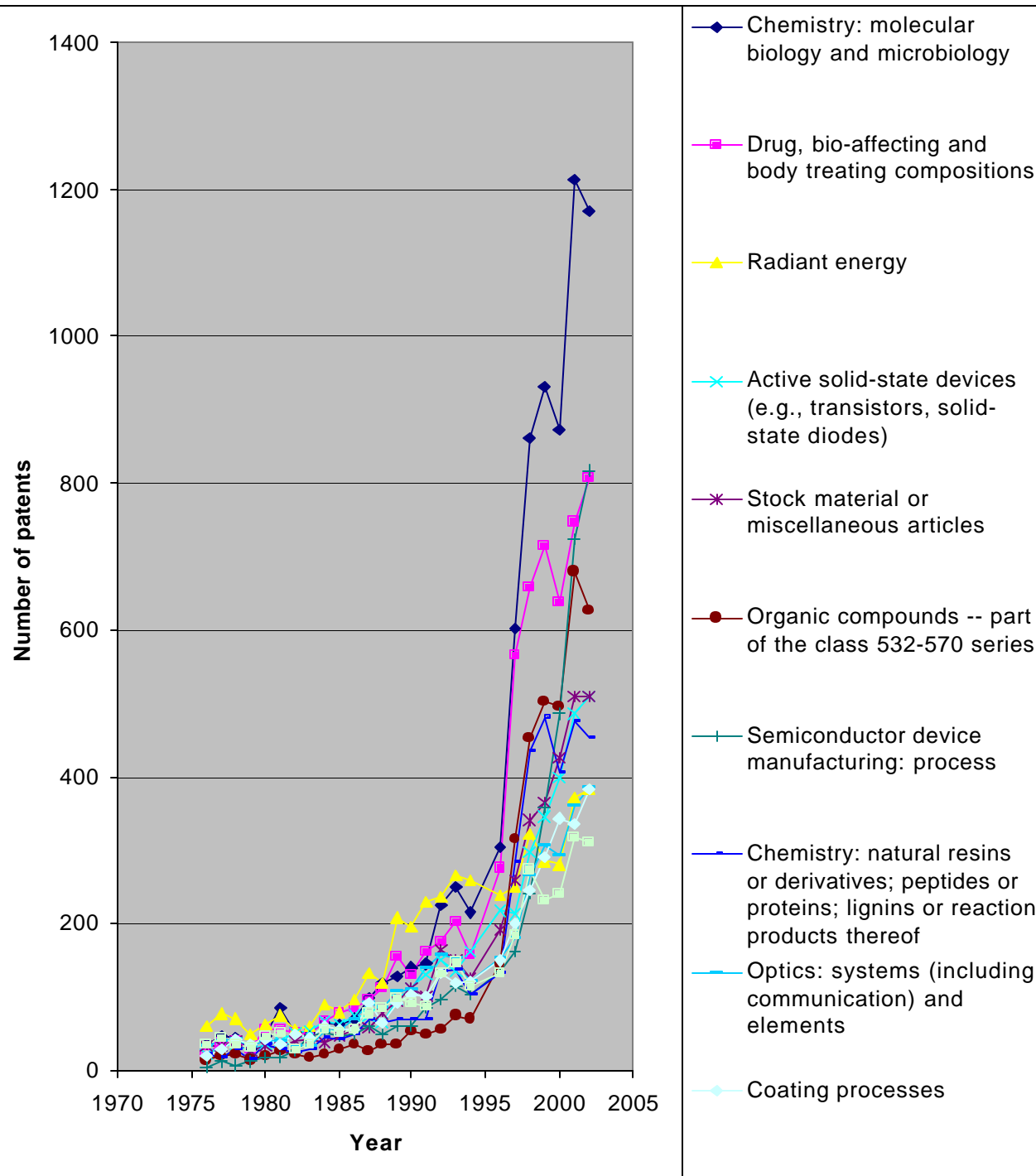
Nanotechnology patents per region (NSF, 2003)

Searched by keywords at USPTO : nano*, atomic force microscop*, atomistic/molecular simulation, biomotor, molecular device, molecular electronics, molecular modeling, molecular motor, molecular sensor, quantum computing, quantum dot*, quantum effect*, scanning tunneling microscop*, selfassembl*



www.nsf.gov/nano (from J. of Nanoparticle Research, 2003)

Technology field analysis by year



www.nsf.gov/nano

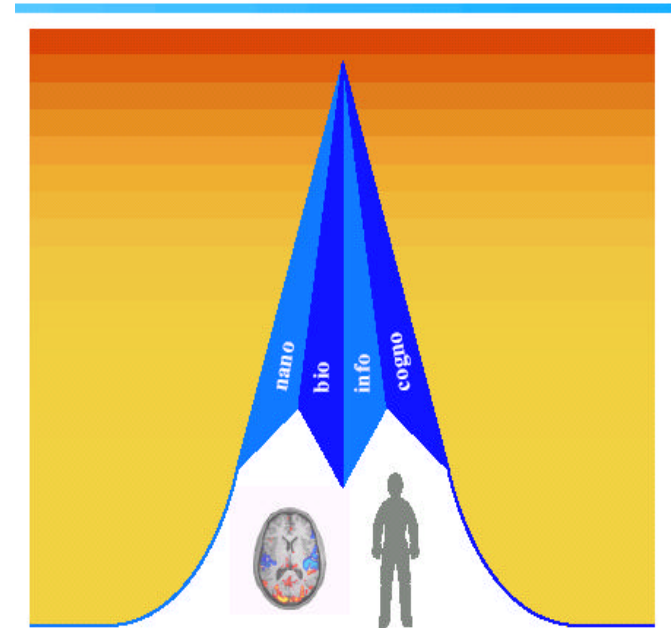
(Longitudinal
Nanotechnology Patent
Analysis,
from J. of Nanoparticle
Research, 2003)

Integrating science and technology from the nanoscale

† Broad and timely opportunity

- ✍ Understanding unity in nature, and technology integration from the nanoscale
- ✍ Powerful transforming tools (NBIC: nano-bio-info-cogno) developing at confluence of disciplines
- ✍ Improvement of individual and group human performance becomes possible
- ✍ Need for anticipation ('learning before doing') and deliberate choices

† NBIC - agents of accelerated, synergistic change



CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

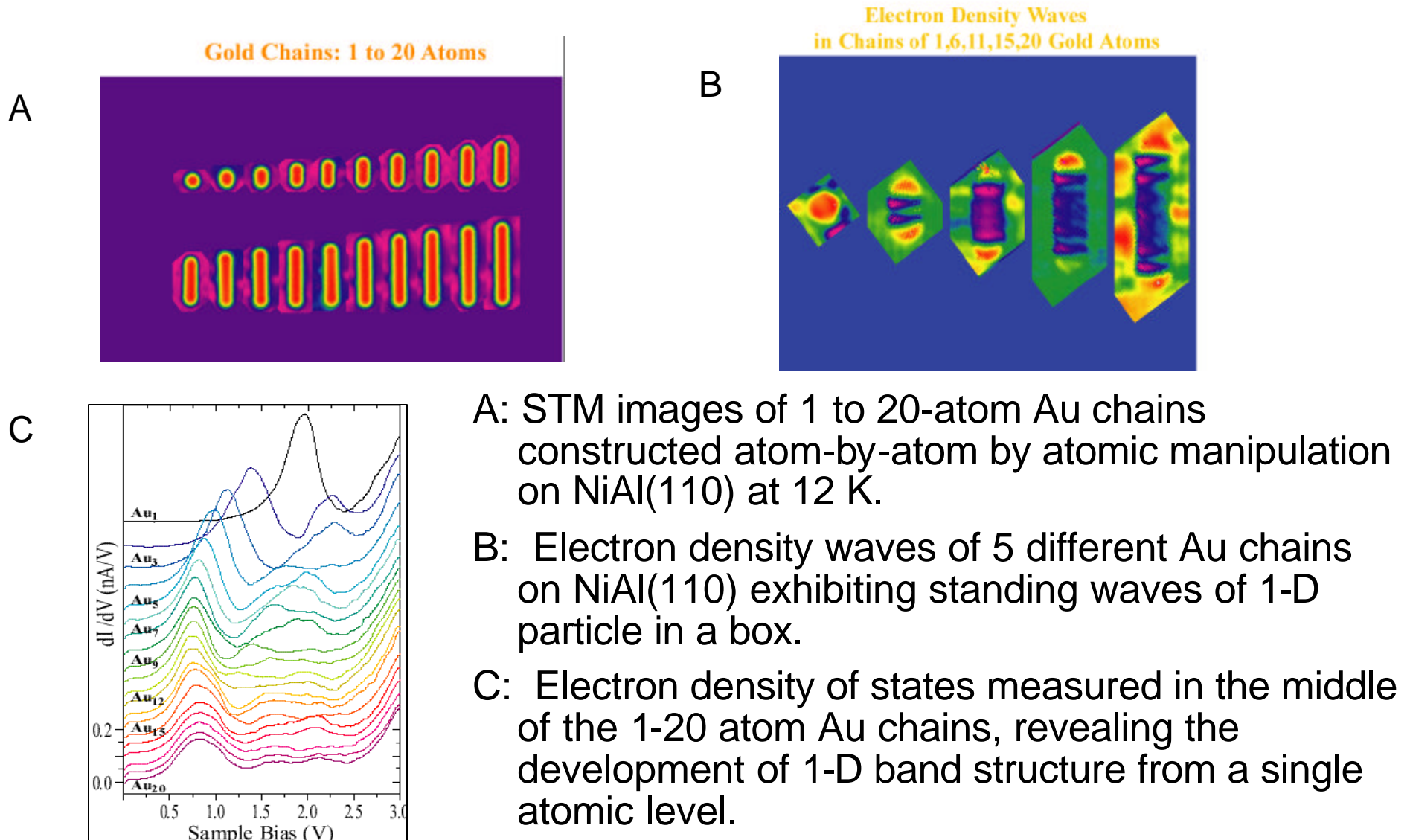


(December 2001)

Online www.nsf.gov/nano,
also Kluwer Academic Publ

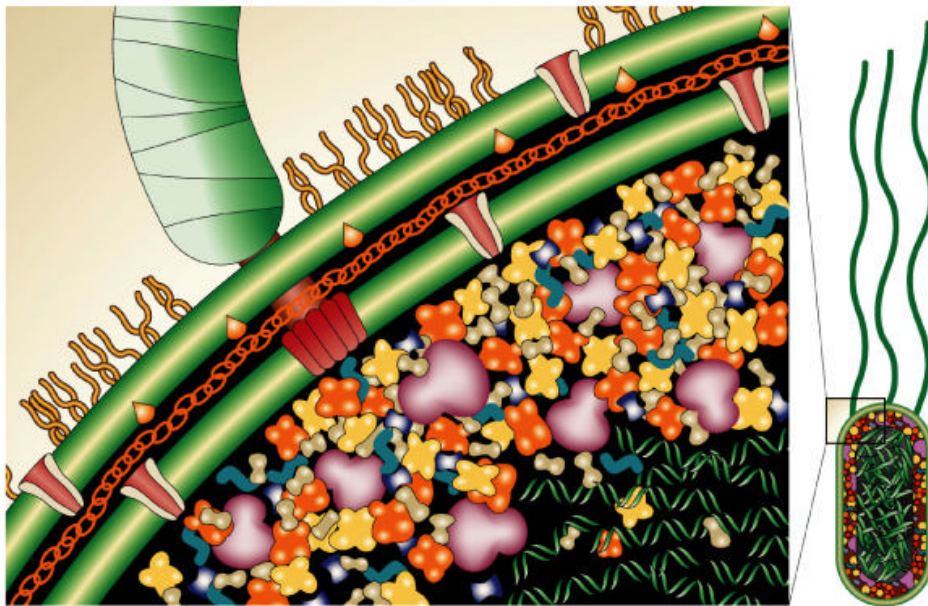
Specify the state of a molecule










EX: Atom-by-Atom Construction of Nanostructures, W. Ho et al.



Specify the state of a cell

E. Coli



 Ribosomes	 mRNA
 Lipopolysaccharide	 Phospholipid
 DNA	 Lipoprotein
 tRNA	 Peptidoglycan
 Protein	

Measure and simulate
the populations
of all the proteins
present

3 dimensional
Highly parallel

...

Functional Nano-Scale Bio-Materials by Controlled Self-Assembly

EX: Matthew Tirrell, UCSB, NSF-0103516

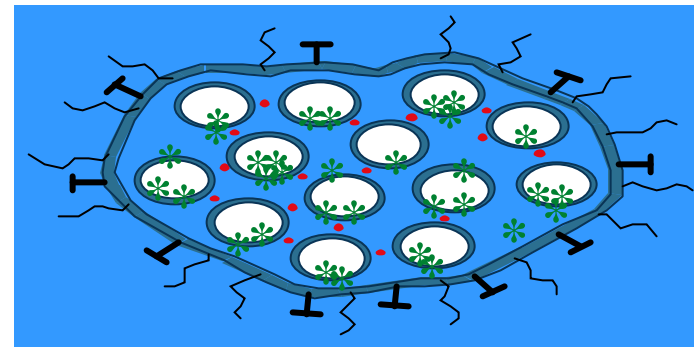
? Self-assembly processing of nanoscale bio-materials and devices
(Creating bio-mimetic nested structures, micromachines components)



Triple
Helix

? Molecules (e.g., a Triple Helix) have been designed to incorporate into bilayer walls of structures to control their interactions both with each other and with their surroundings.

? Controllable secondary structures such as rods, tubules, vesicles, and micelles will lead to structures for functions that may not be naturally occurring or that mimic or supply interesting functionality.

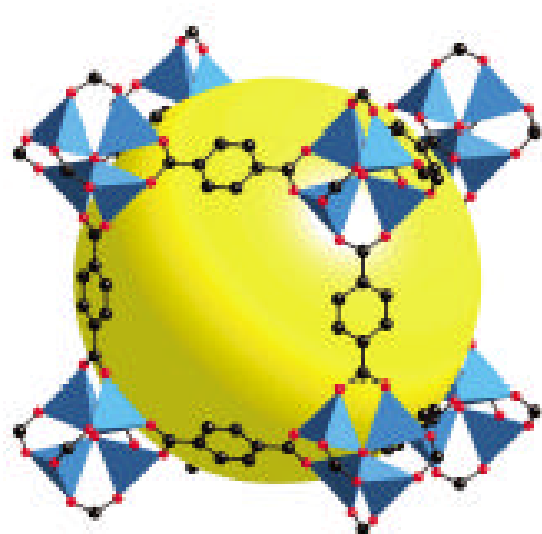


Vesosomes: Vesicle-Encapsulated Vesicles



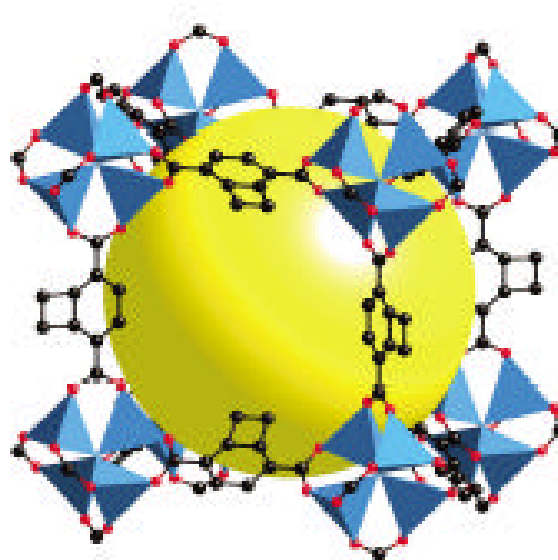
Molecular Fuel Tanks

O.M. Yaghi, U. Michigan, #0242630



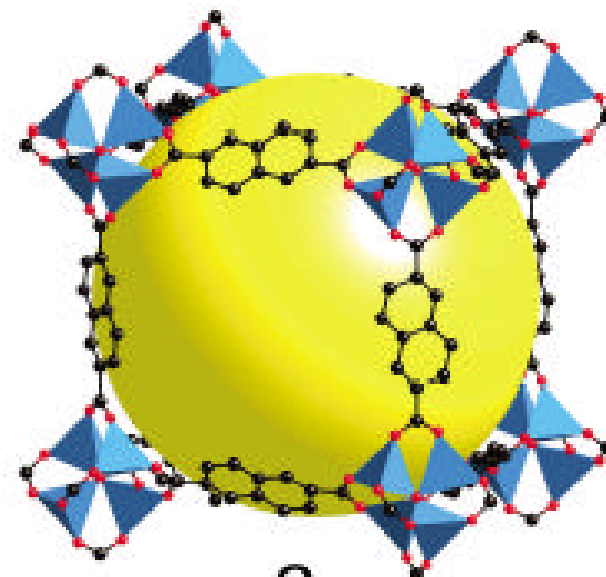
A

0.5 %



B

1.0 %

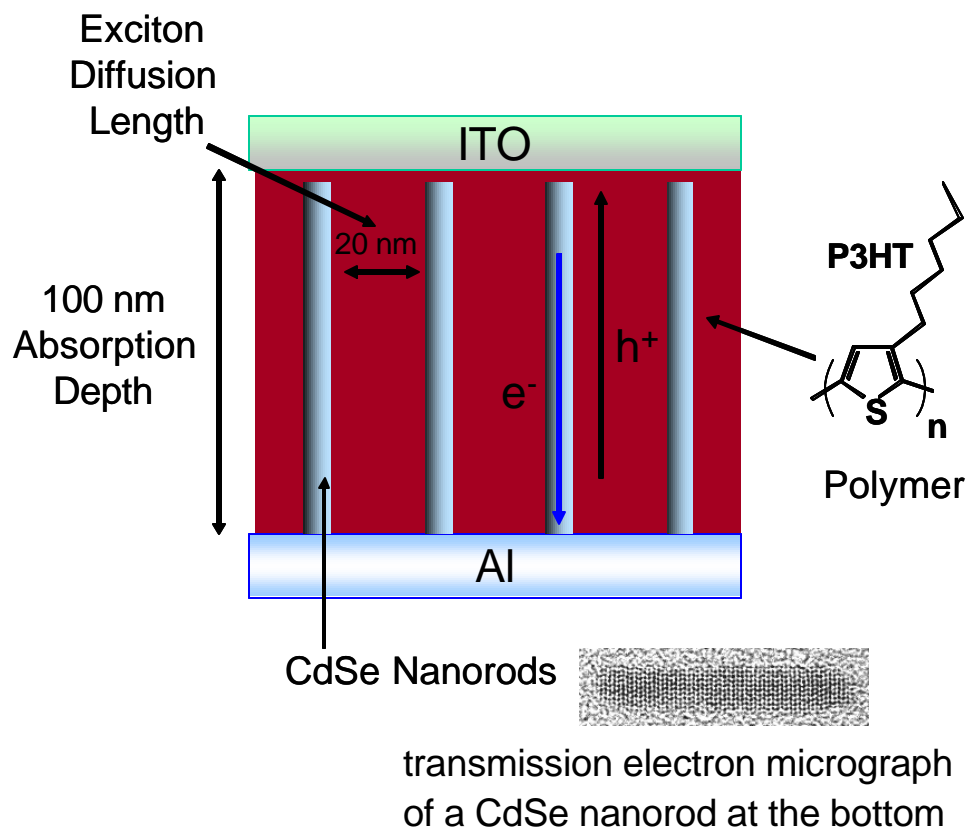


C

2.0 %

Uptake (wt%) of hydrogen storage in Metal-Organic Frameworks at RT and 10 bar

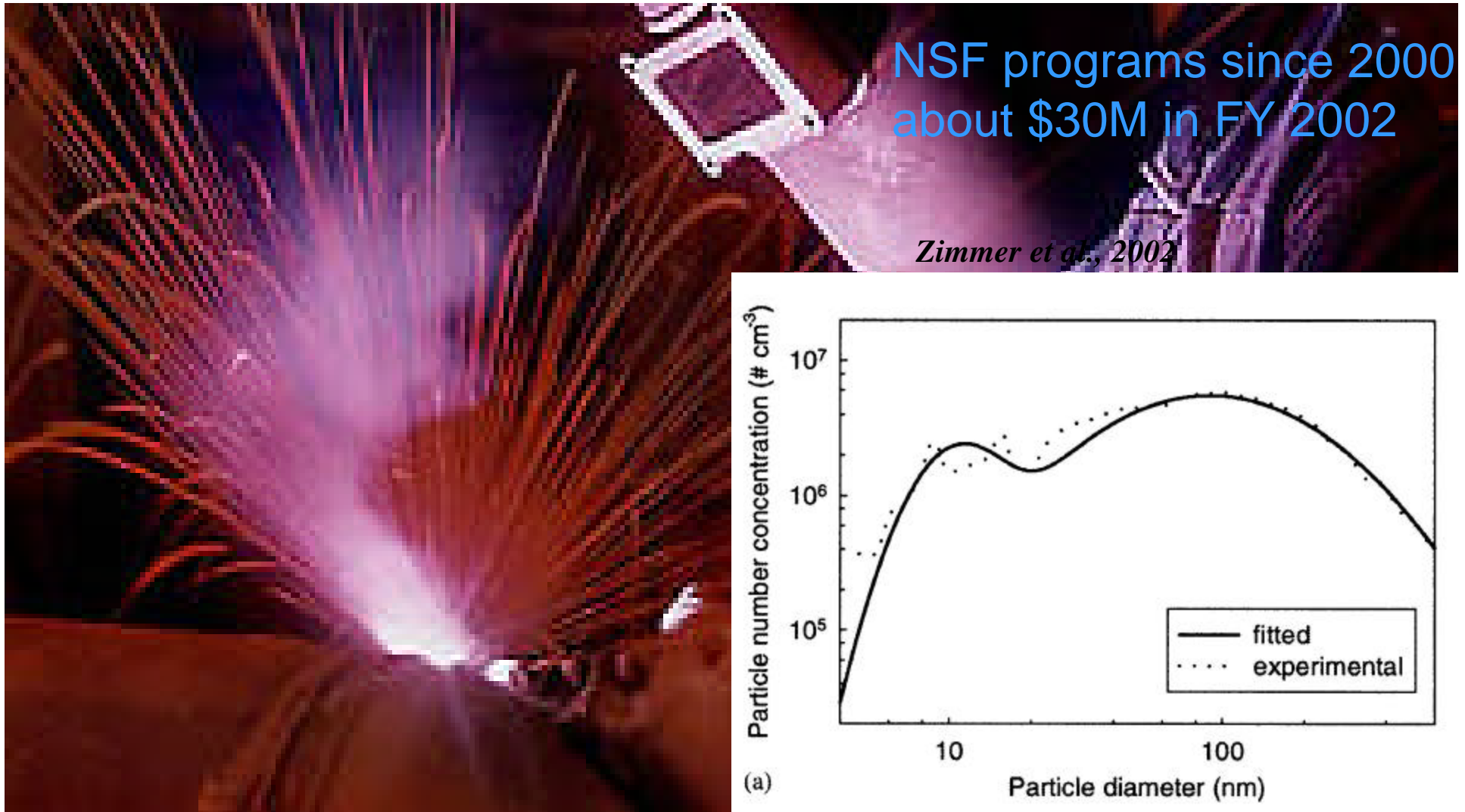
Energy: Schematic design of the nanorod-polymer solar cell



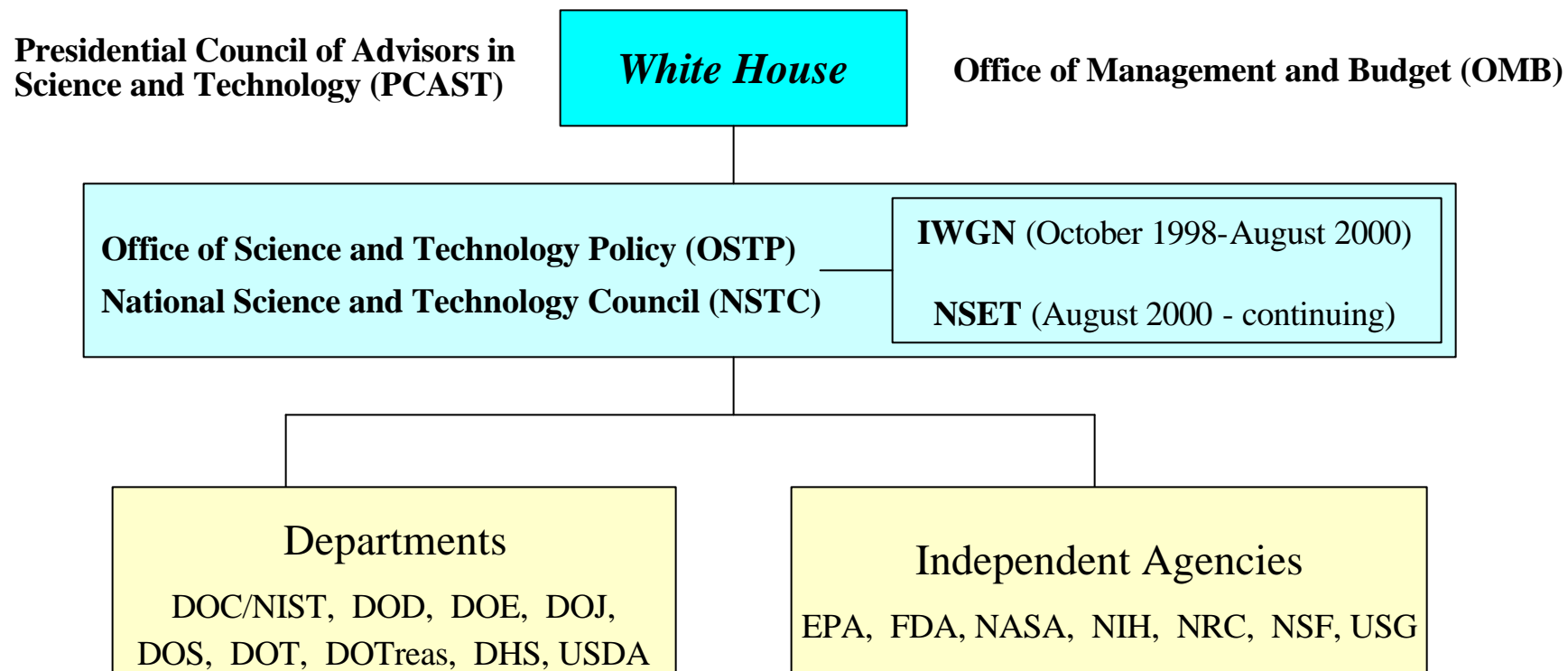
(courtesy P. Alivisatos, Univ. California, Berkeley; and Nanosys, Inc.).

Environmental issues related to nanotechnology include:

- Sustainable development, life-cycle of products, measurement and mitigation, clean-up techniques, global effects
- Combustion, welding, water/air filtration, cell behavior, toxicity



Organizations that have prepared and contribute to the National Nanotechnology Initiative (**NNI**)



Estimation: Federal Government R&D funding NNI (~\$770M in 03)
 Industry (private sectors) ~ NNI funding
 20 state and local (universities, foundations) ~ 1/2 NNI funding

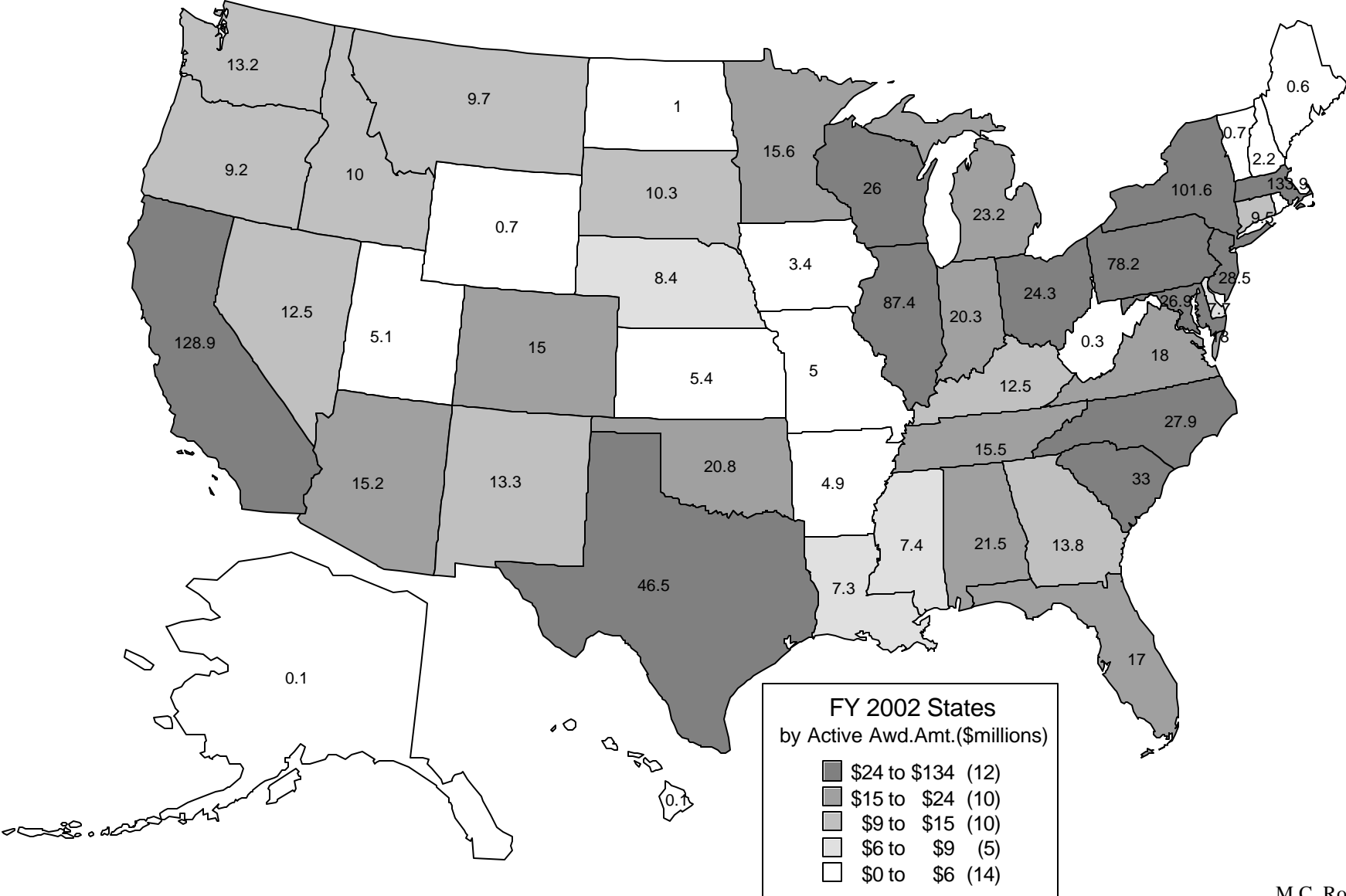
NNI: R&D Funding by Agency

<i>Fiscal year</i> (all in million \$)	2000	2001 Enacted/actual	2002 Enacted/actual	2003	2004 Request
National Science Foundation	97	150 /150	199 /204	221	249
Department of Defense	70	110 /125	180 /224	243	222
Department of Energy	58	93 /88	91.1 /89	133	197
National Institutes of Health	32	39 /39.6	40.8 /59	65	70
NASA	5	20 /22/	35 /35	33	31
NIST	8	10 /33.4	37.6 /77	66	62
Environmental Protection Agency	-	/5.8	5 /6	5	5
Homeland Security (TSA)	-		2 /2	2	2
Department of Agriculture	-	/1.5	1.5 /0	1	10
Department of Justice	-	/1.4	1.4 /1	1.4	1.4
TOTAL	270.0	422.0 /464.7	~ 600 /697	~ 770	~ 849

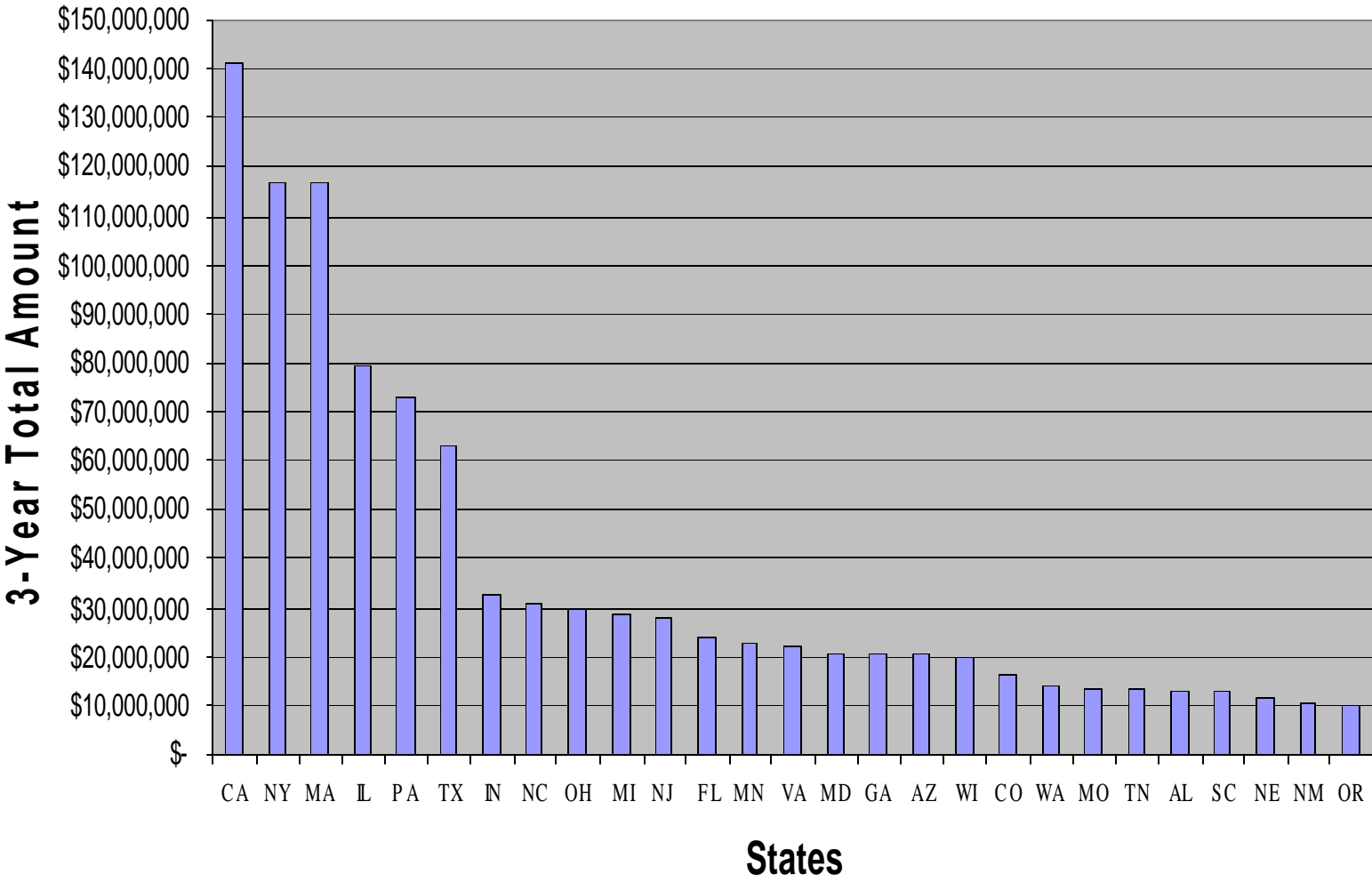
Other NNI (NSET) participants are:

OSTP, NSTC, OMB, DOC, DOS, DOT, DOTreas, FDA, NRC, DHS, IC

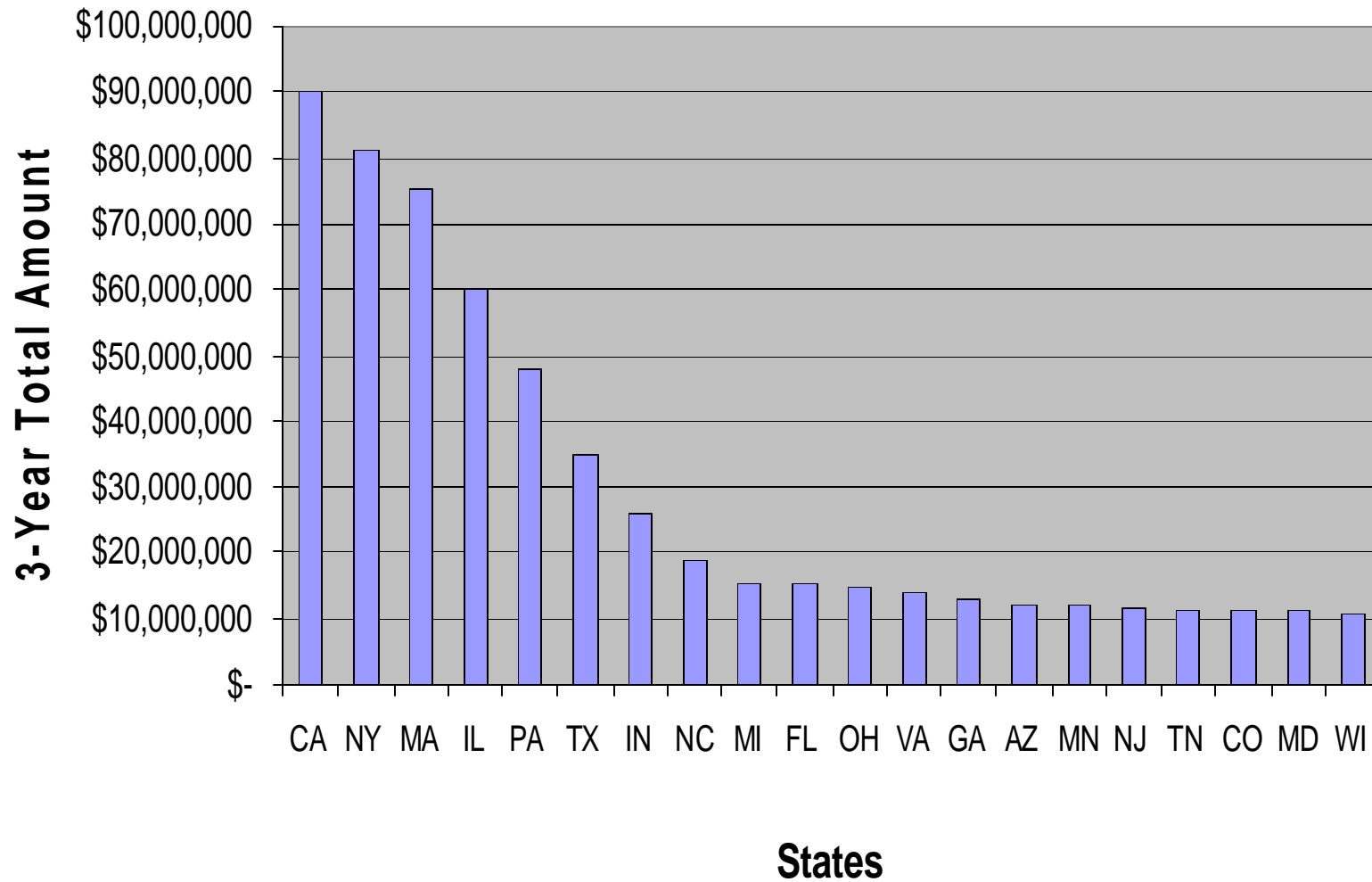
FY 2002 NSE active awards: Geographical distribution



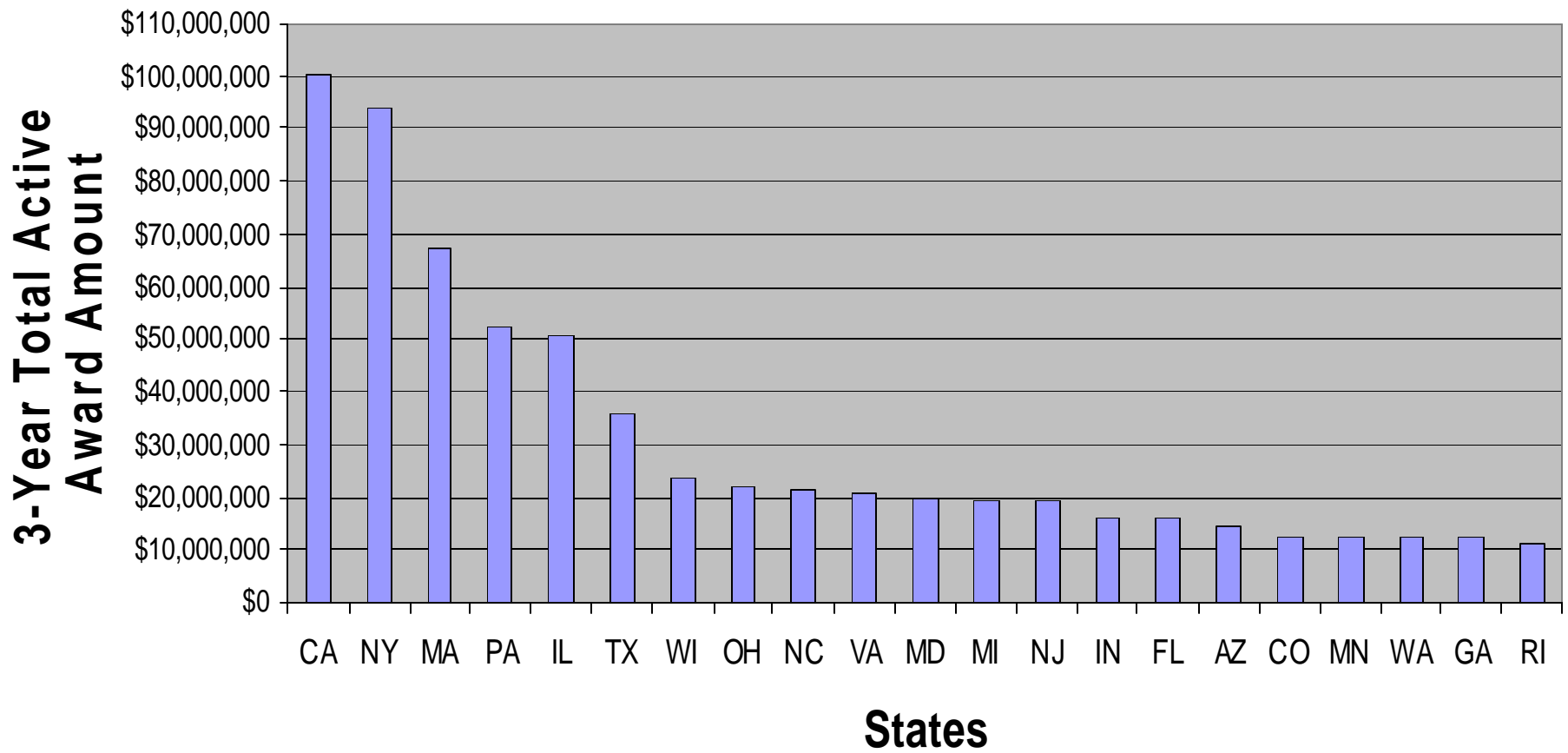
States Awarded \$10 million or More by NSF for NEW NNI Research during FY 2001-2003



States Awarded \$10 million or More by NSF for NEW NNI Research during FY 2001-2003 (through 6/30/03)

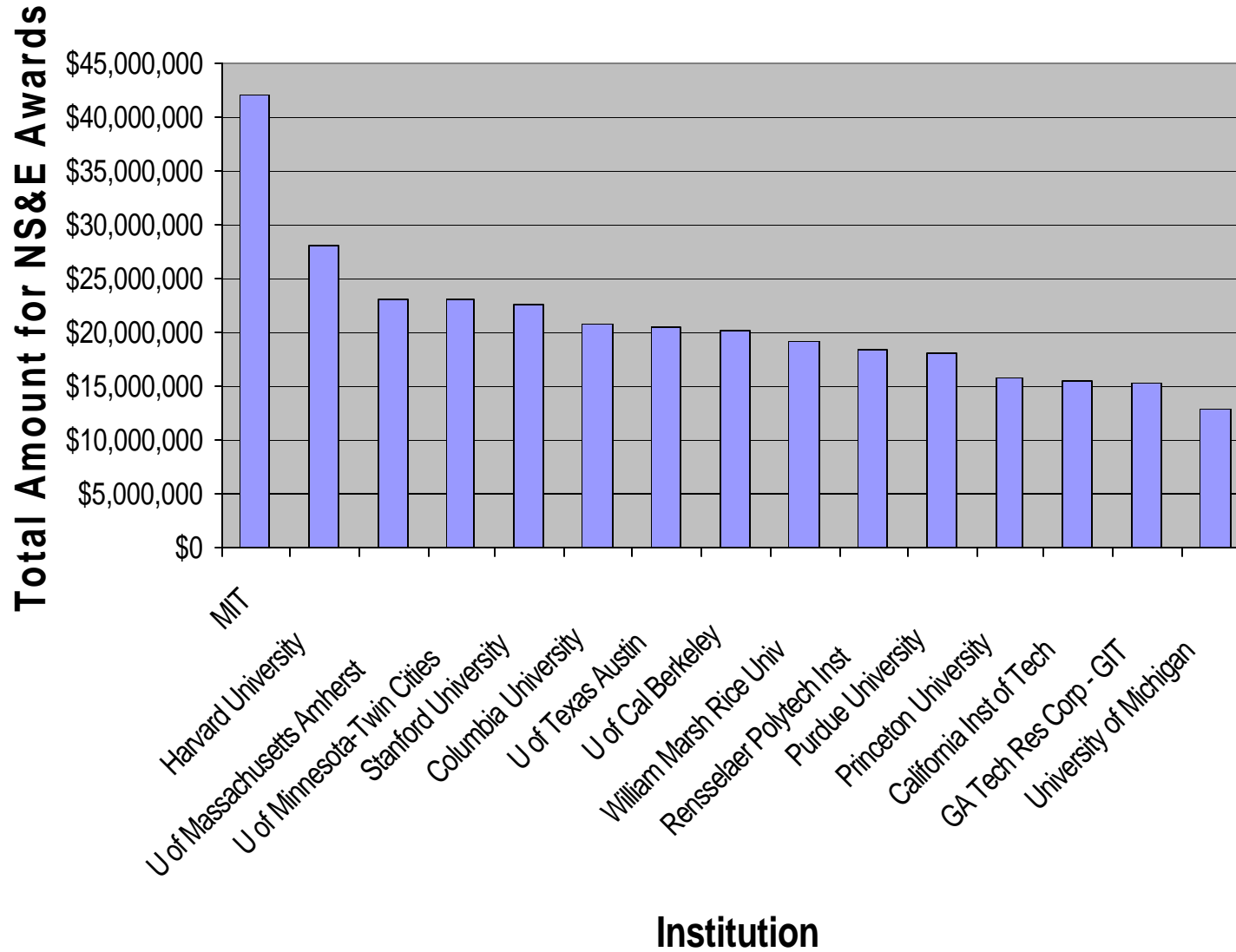


States with ACTIVE NSF-Supported NNI Research Awards Totaling \$10 million or more during FY 2001-2003



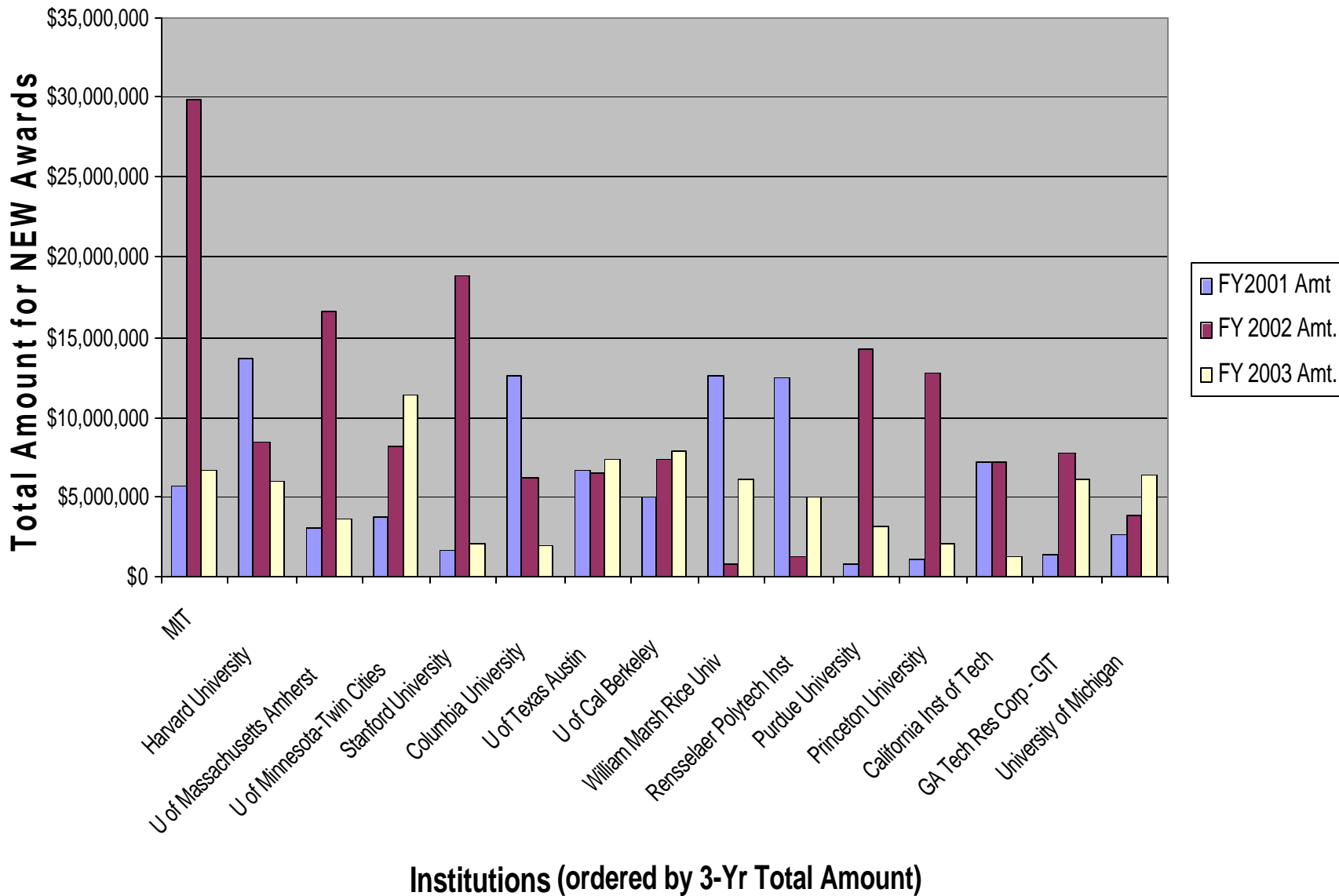
NSF FY 2001-2003

NEW Nanoscale S&E Awards for Top 15 Institutions by Total Amount



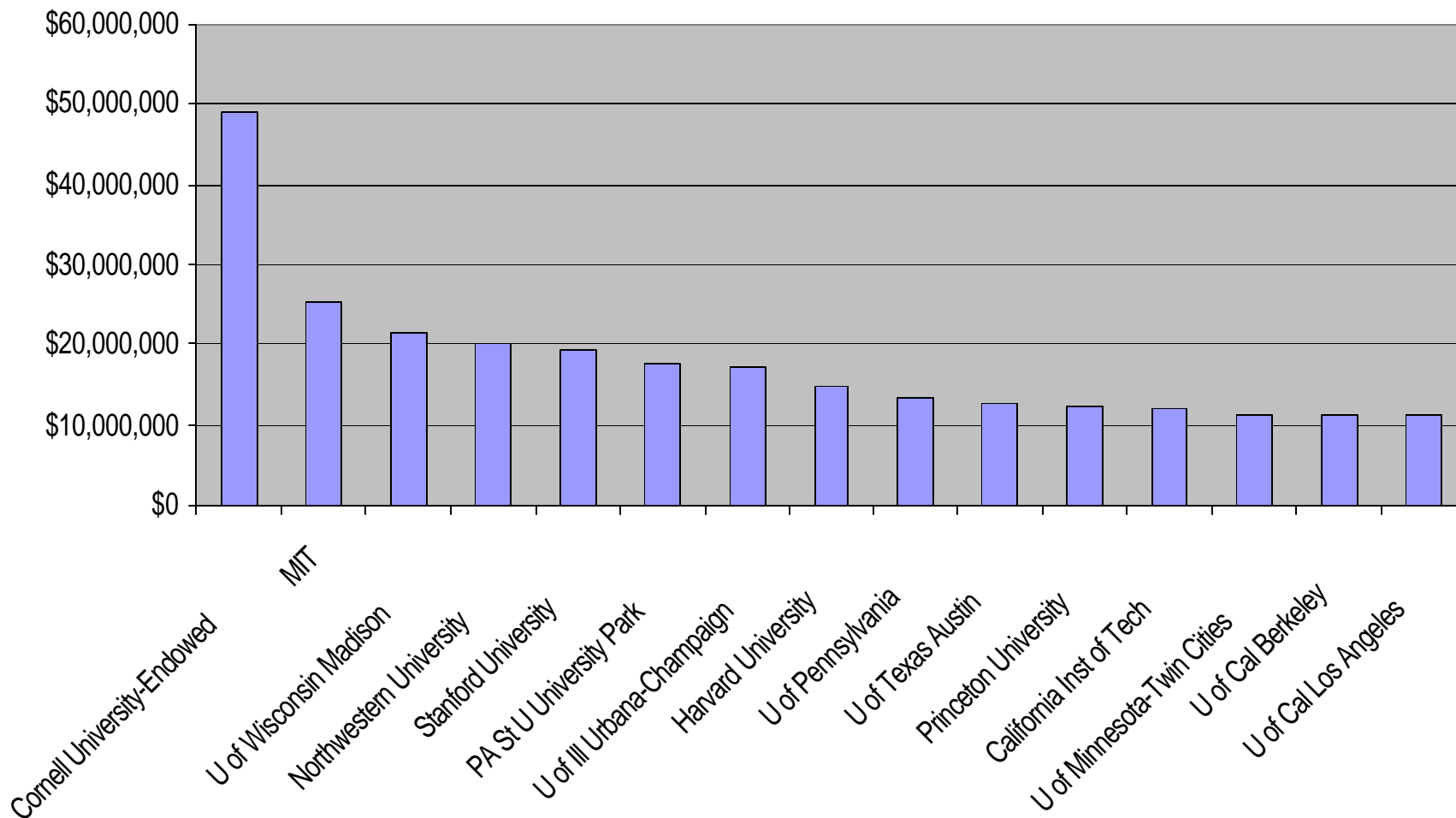
NSF FY 2001-2003

NEW Nanoscale S&E Awards for Top 15 Institutions by Total Amount



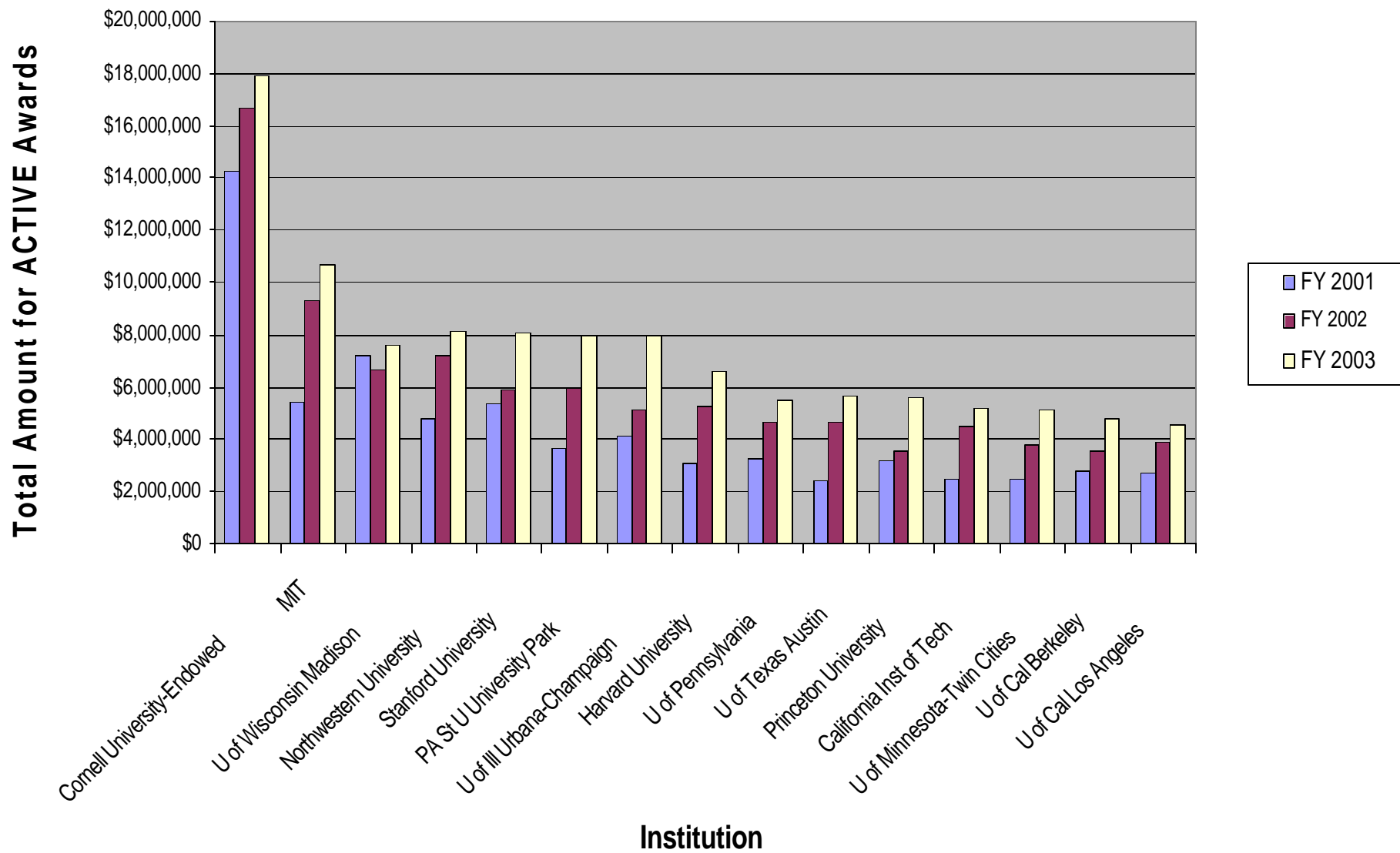
3-Yr Total Amount for ACTIVE Nanoscale S & E Awards (FY 2001-2003)

Estimated Total Expenditures for
Active Awards



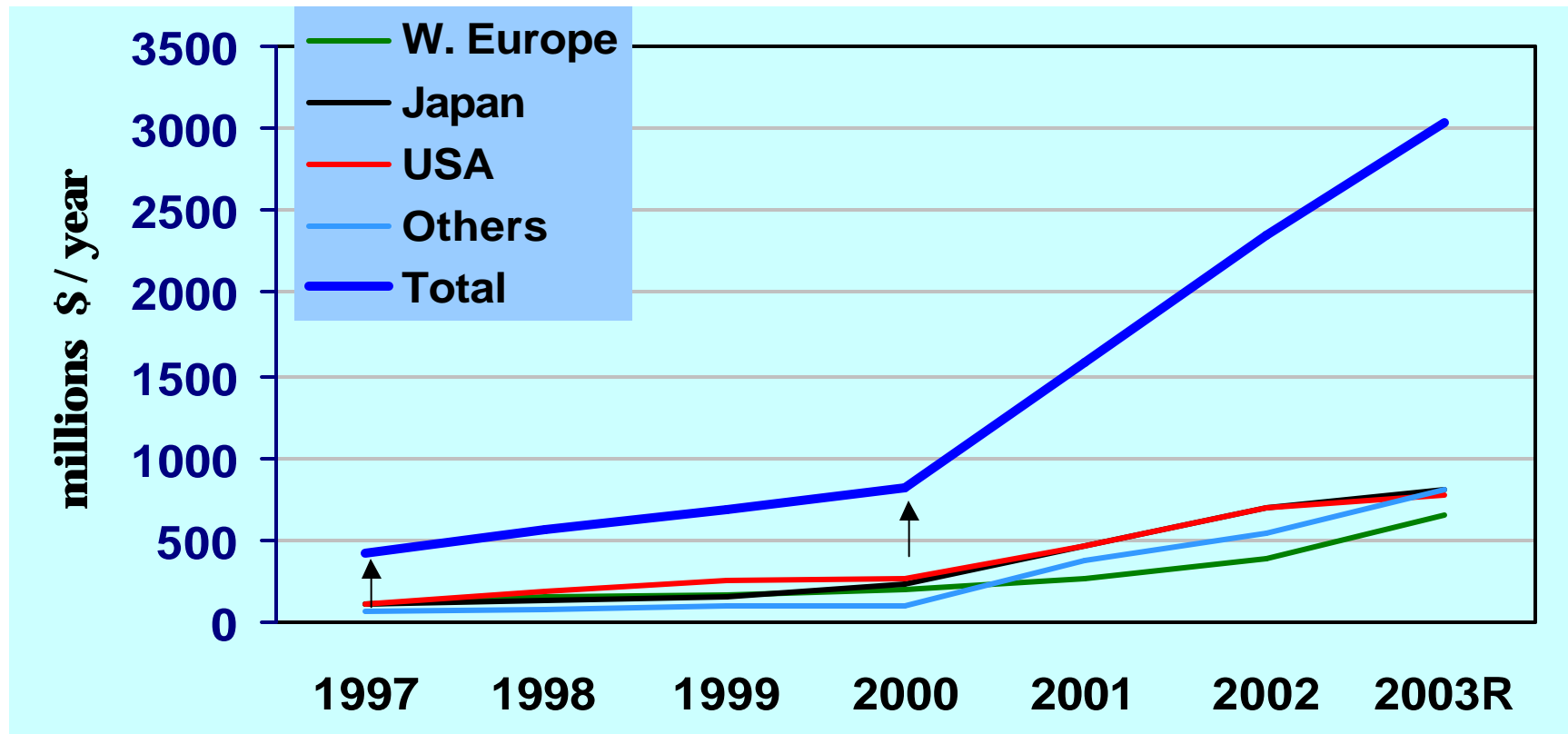
Institution

ACTIVE Nanoscale S&E Awards for Top 15 Institutions by Total Amt. per FY (2001 -2003)



Context – Nanotechnology in the World

Government investments 1977-2003 (estimation NSF)



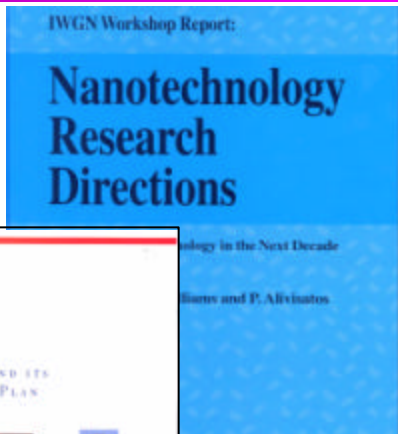
Note:

- U.S. begins FY in October, six months in advance of EU & Japan (in March/April)

Defining the vision

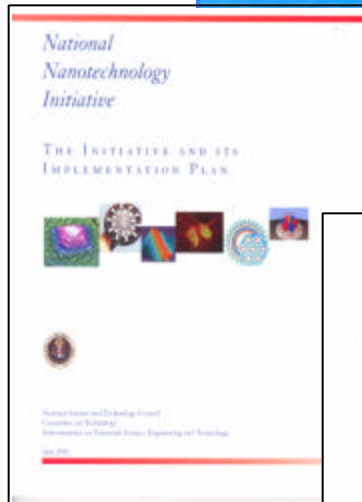
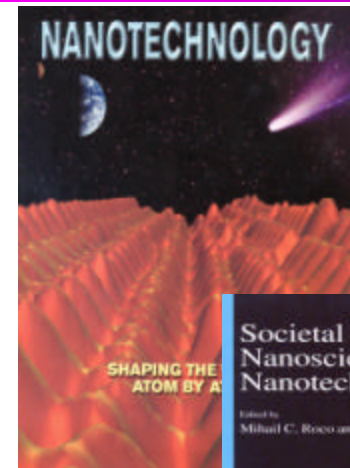
National Nanotechnology Initiative

1999:
10-year
vision

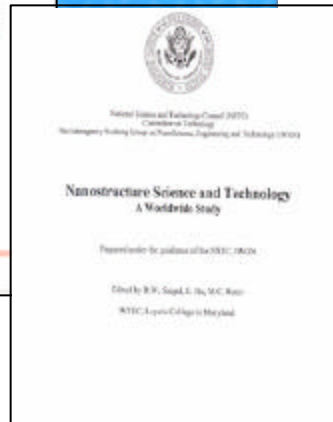


Brochure for
public

Societal
implications

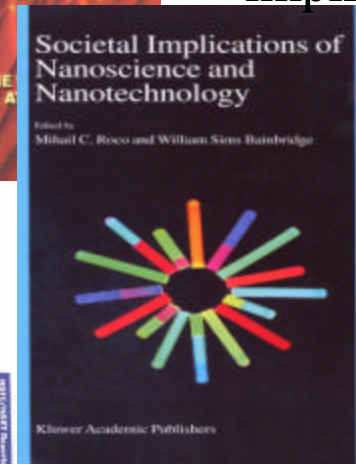


Government
plan

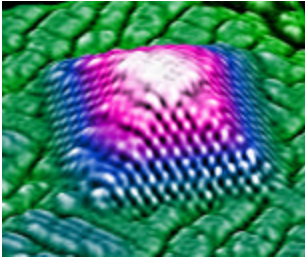


Reports

Worldwide
benchmark



June 2002: “Review of NNI” by U.S. Academies for WH/OSTP
 April 2003: “FY 2004 NNI and Its Implementation Plan”, NSET
 In preparation: Updated 10 year vision



Planning for the future: expanding the frontiers of nanotechnology




Workshops for receiving input from the community (examples):

- † Nanostructured materials "by design" - Workshops on 10/02, 06/03
- † Catalysts that function at the nanoscale - 06/03
- † Nanoelectronics, optoelectronics and magnetics - 11/02, 2/04
- † CBRE protection and detection - 05/02
- † Advanced healthcare, therapeutics, diagnostics - 06/00
- † Nano-biology and medicine - 10/03
- † Environmental improvement - 06/02, 08/02, 07/03, 09/03
- † Efficient energy conversion and storage - 10/02, 02/03
- † Microcraft space exploration and industrialization - Spring 04
- † Manufacturing processes - 01/02, 05/02; Instrumentation – 01/04
- † Agriculture and food systems - 11/02; Converging Technologies – 09/03
- † Societal implications (II) - 12/03; Education (NSEE) – 09/03

“Nanotechnology Research Directions (II)” - Spring 2004

Revisit the NNI long-term vision formulated in January 1999

R&D focus in 2003

-  **Growing area towards technological innovation**
 -  **Materials, including bulk, coating, dispersed systems**
 -  **Chemicals, including catalysts**
 -  **Pharmaceuticals**
 -  **Electronics**
-  **Emerging areas to be addressed in the NNI plan**
 -  **Nanomedicine**
 -  **Energy conversion and storage**
 -  **Agriculture and food systems**
 -  **Molecular architectures**
 -  **Realistic multiphenomena/multiscale simulations**
 -  **Environmental implications**
 -  **Converging technologies from the nanoscale**

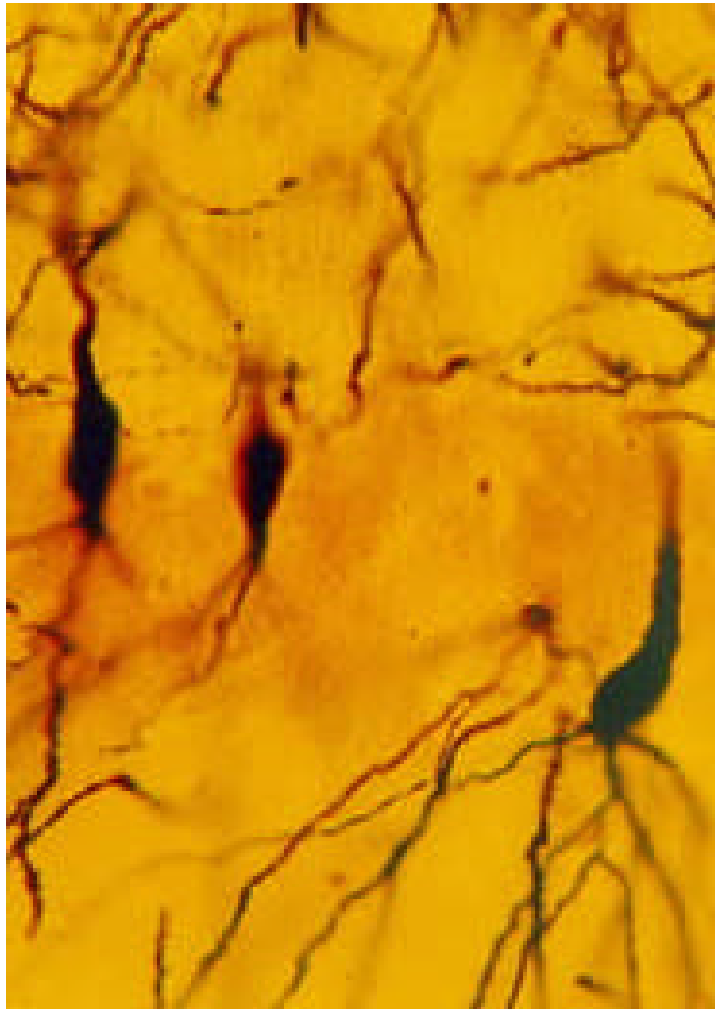
Improving human performance: by technology integration from the nanoscale

- ✍ **Expanding human cognition and communication**
- ✍ **Improving human health and physical capabilities**
- ✍ **Enhancing societal outcomes, incl. new products**
- ✍ **National security**
- ✍ **Unifying science and education**
- ✍ **Reshaping organization and business**

Other societal outcomes, implications

Successive breakthroughs

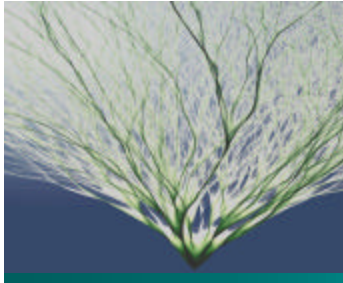
Lasers operate inside single cells



Nanosurgery vaporizes cellular components leaving rest intact

- **Cut a nerve connection without killing it**

Harvard U. (Nature, October 2003)



Outcomes of 2001-2003: R&D Networks and User Facilities

† **Network for Computational Nanotechnology (NCN)**

7 universities (Purdue as the central node)
Nanoelectronic device simulation/modeling

† **National Nanotechnology Infrastructure Network (NNIN)**

User facility
Development measuring & manufacturing tools
Education and societal implications

† **Oklahoma Nano Net (EPSCoR award)**

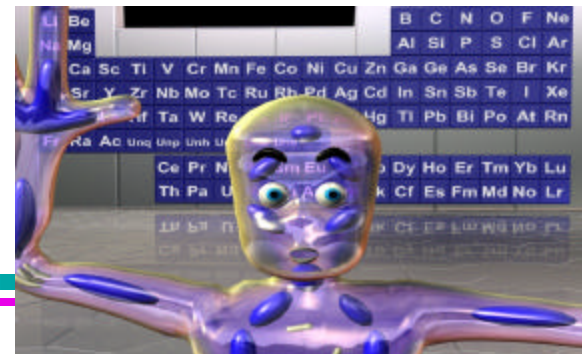
† **DOE network for large scale facilities**

22 new centers and networks supported by NNI since 2001:

10 NSF, 3 DOD, 5 DOE, 4 NASA (at universities); continuing MRSECs



Education and Training



(J. Tour)

- † **Integrated research and education - Make Every Lab a Place of Learning: Aiming at systemic changes**
 - ~ 7,000 students/year, technicians, teachers, and faculty in 2003
- † **Curriculum development: New foundation, Training earlier**
 - Nano- instead of micro-based; From elementary schools to continuing education (Undergraduate education ~ 33 awards in FY 2003; Expand to K -12 education in 2004); Industry fellowships
- † **All NSF centers have education and outreach programs**
 - Including science museums Boston, Chicago, Milwaukee, LA
- † **International education opportunities**
 - Young researchers to Japan and Europe; REU sites; attend courses abroad; PASI - Latin America, NSF-E.C.; bi-lateral workshops and exchanges

Nanotechnology Undergraduate Education (NUE)

New component of the 2003 NSF Nanoscale Science and Engineering (NSF 02-148) program is focused on:

- † Introductory undergraduate courses presented through the development of text, software, laboratory and demonstration experiments, and web-based resources;
- † Development and dissemination of new teaching modules for nanoscale science and engineering that can be used in existing undergraduate courses, particularly during first and second year studies.

33 awards in FY 2003 (www.nsf.gov/nano)

Reviewed by the NSF workshop

on September 11-12, 2002 at NSF

(www.nanofab.psu.edu/education/nsf-nue-program.htm)



Nanoscale Science and Engineering Education program (NSF 03-044, new in FY 2004)

NSEE to produce systemic changes in nanoscale science and engineering education. \$12M in FY 2004. Components:

- † **Centers for Learning and Teaching (NCLT):** Create educational leadership for nanotechnology education (doctoral programs representing collaborations of researchers in nanoscale science and engineering, education, and cognitive and behavioral sciences)
- † **Informal Science Education (NISE):** Foster public awareness and understanding of nanoscale science and engineering through development of media projects (film, radio, television) and exhibits.
- † **Instructional Materials Development (NIMD):** Support development of prototype instructional materials that promote student learning and interest in nanoscale science, engineering, and technology concepts for grades 7-12.
- † **Nanotechnology Undergraduate Education (NUE):** Introduce nanoscale science and technology through a variety of interdisciplinary approaches into undergraduate education, particularly in the first two collegiate years.



K-12 NANOTECHNOLOGY

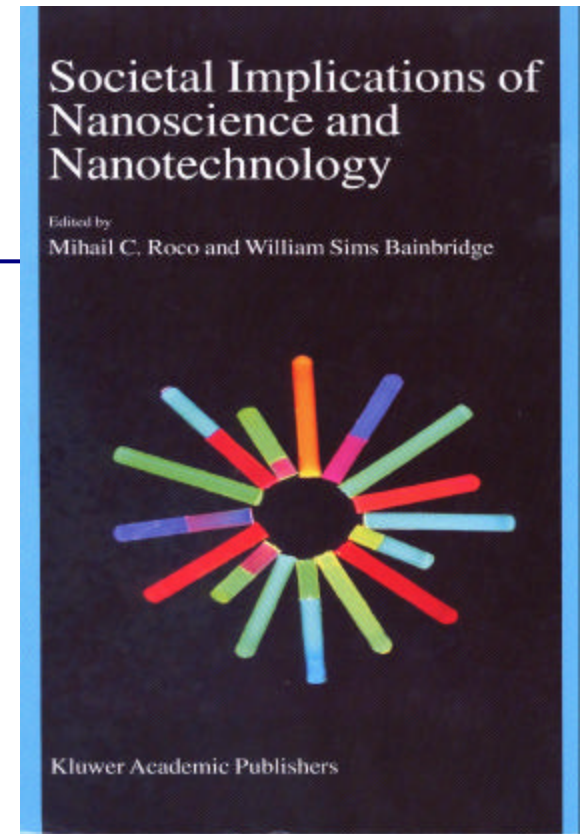
Illustrations of Education Modules

- † **University of Wisconsin - Art Ellis: Nanoworld for kids**
- † **Northwestern University – Bob Chang: Virtual NT Encyclopedia**
- † **Rice University – James Tour: NanoKids**
- † **Cornell University: for nanobiotechnology, and nanoelectronics**
- † **Northwestern University, Chicago: for materials, public museum**
 - » **Harvard University: for nanosystems, public museum**
- † **UNC Nanomanipulator by high school students**
- † **Purdue NanoHub (www.nanohub.purdue.edu)**
- † **RPI “Molecularium” and “Nanoscope” for K-12 students**

NSF plans to have 10 K-12 education modules in 2004

Societal Implications: Follow-up of the September 2000 report

- Make support for social, ethical, and economic research studies a priority:
 - (a) New theme in the NSF program solicitations;
 - (b) Centers with societal implications programs;
 - (c) Initiative on the impact of technology, NBIC, HSD
- NNCO – communicate with the public and address unexpected consequences
- Basic reference for the interaction with the public
- Taking faster advantage of the benefits
- Converging technologies from the nanoscale
- International workshop with EC (2001); Links to Europe and Asia



<http://nano.gov>

State participation

Illustrations from 20 states

†	CA	California NanoSystem Institute	\$100M/ 4 yrs
†	NY	Center of Excellence in Nanoelectronics; Albany Center	\$50M, \$400M/ 5 yrs
†	IL	Nanoscience Center (NU, U III, ANL)	\$63M
†	PA	Nanotechnology Center	\$37M
†	GA	Center at Georgia Tech	\$25M
†	IN	Nanotechnology Center	\$5M
†	TX	Nanotechnology Center	\$0.5M over 2 yrs
†	SC	NanoCenter	\$1M
†	AZ	Nanobio research	\$5M for 20 years
†	NM	Consortium University of NM and National labs	
†	NJ	Support at NJIT and future nanophotonics consortium	
†	FL	Center at the University of South Florida	
†	OK	Nano-Net (~\$3M/yr for 5 years)	
†	OH	(support Center \$27M in Columbus), TN (\$24M), Louisiana, CT, MA, VA, AZ	



NNI challenges

- ✍ **Need for coherent, long-term (5-10 yrs) vision / programs**
- ✍ **Horizontal versus vertical S&T development:**
0.7% (on fundamental research – to continue) versus 5% (plus precompetitive R&D) of US R&D budget
- ✍ **Competitiveness: Strengthening partnership w/ industry**
Need for system-oriented programs, focused on topics such as: the new transistor, new display, new catalyst, conditioning the cell, S&T convergence
Support: Joint R&D in university-industry networks and industry-government laboratories to facilitate new technologies and commercialization