Nanotechnology at NSF

M.C. Roco

National Science Foundation

and National Nanotechnology Initiative

NSF Grantees Conference, December 3, 2007

Benchmark with experts in over 20 countries

"Nanostructure Science and Technology"

Book Springer, 1999

Nanotechnology

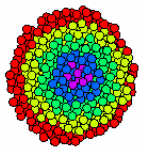
is the ***control and restructuring of matter*** at dimensions of roughly 1 to 100 nanometers (from atomic size to about 100 molecular diameters),

where new phenomena

enable new applications.

(measure- control- manipulate- integrate at the nanoscale)

Four Generations of Products (200-2020): Timeline for beginning of industrial prototyping and nanotechnology commercialization



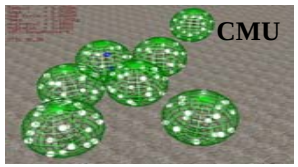
~ 2000

1st: Passive nanostructures (1st generation products)

Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2005

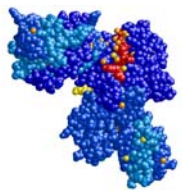
2nd: Active nanostructures Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures



~ 2010

3rd: Systems of nanosystems

Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary



~ 2015-2020

4th: Molecular nanosystems

Ex: molecular devices 'by design', atomic design, emerging functions

New R&D challenges

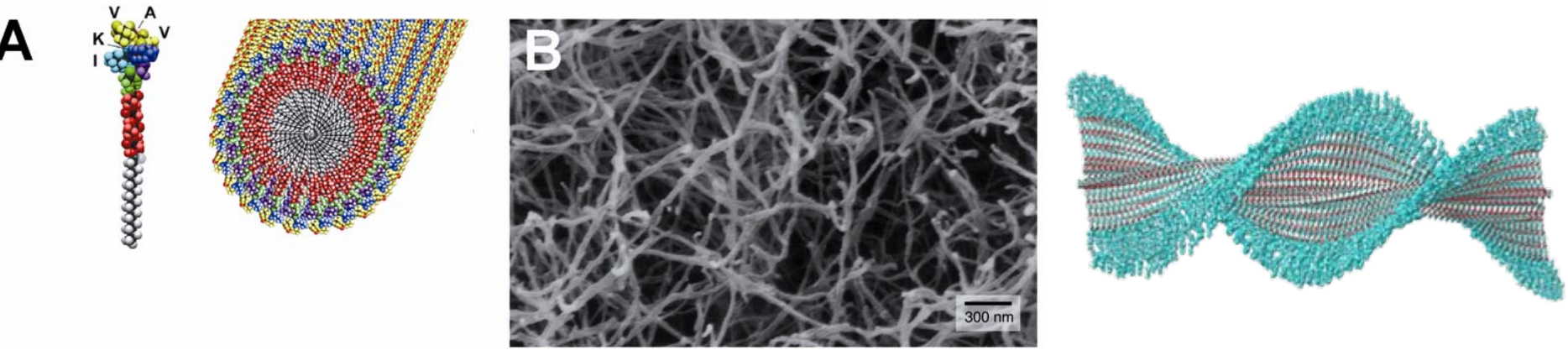
	R&D	→	Broad Use
IT	1960	-	2000
BIO	1980	-	2010
NANO	2000	-	2020

AIChE Journal, 2004, Vol. 50 (5), M. Roco

Example 4th generation (in research)

Designing molecules for hierarchical selfassembling

EX: Biomaterials for human repair (nerves, tissues, wounds), reactive filters, others. Sam Stupp, Northwestern University



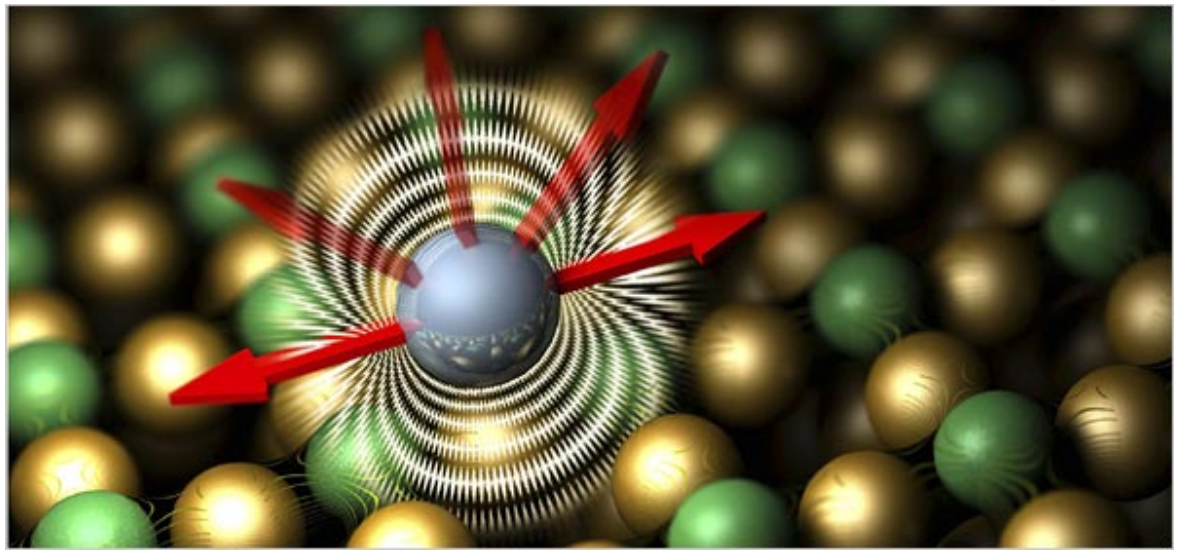
New materials and nanomachines based on DNA architectures (Ned Seeman, Polytechnic Institute);

Designed molecules for selfassembled porous walls, etc. (Virgil Percec, U. PA)

Self-assembly processing for artificial cells, bio-materials and devices (Matt Tirrell, UCSB)

Example 4th generation (in research)

Individual atom information storage



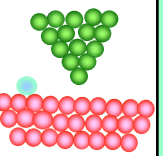
An illustration of I.B.M.'s technique for storing data on a single atom (2007). An iron atom on a copper surface could store a single bit of binary data, with "0" or "1" indicated by the orientation of the atom's magnetic field (Science, 31 August 2007 and N.Y. Times, Sept. 2007).

Magnetic anisotropy of iron atom allows maintaining its direction of magnetization over time. Stable magnetization was obtained at low temperatures for a single atomic spin.

http://www.sciencemag.org/cgi/content/abstract/317/5842/1199

Four stages for nanoscale investigative methods

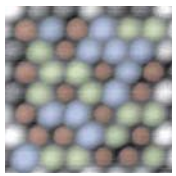
(experiments, theory, design/synthesis of nanostructures)



1st: Passive nanostructures

Mainly empirical, external to nanoscale modules, in isolation

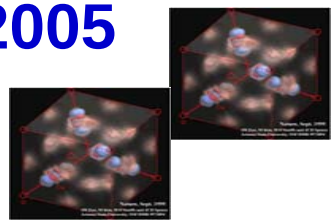
~ 2000



2nd: Active nanostructures

Transition to science-based creation of nanomodules

~ 2005



3rd: Systems of nanosystems

Transition to science-based creation of complex nanosystems

~ 2010

?

4th: Molecular nanosystems

Direct experiments/simulations of nanosystems

~ 2015-2020

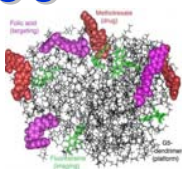
More science - based

Perceived Higher Risks Areas

changing with the four generation of products

1st: Passive nanostructures *Ex: Cosmetics (pre-market tests), Pharmaceuticals (incomplete tests for inflammatory effects, etc.), Food industry (no regulations in many situations), Consumer products*

~ 2000



2nd: Active nanostructures *Ex: Nano-biotechnology, Neuro-electronic interfaces, Nanoelectromechanical systems, Precision eng., Hybrid nanomanufacturing*

~ 2005

3rd: Systems of nanosystems *Ex: Converging technologies, Nanorobotics, Regenerative medicine, Brain-machine interface, Eng. agriculture*

~ 2010

?

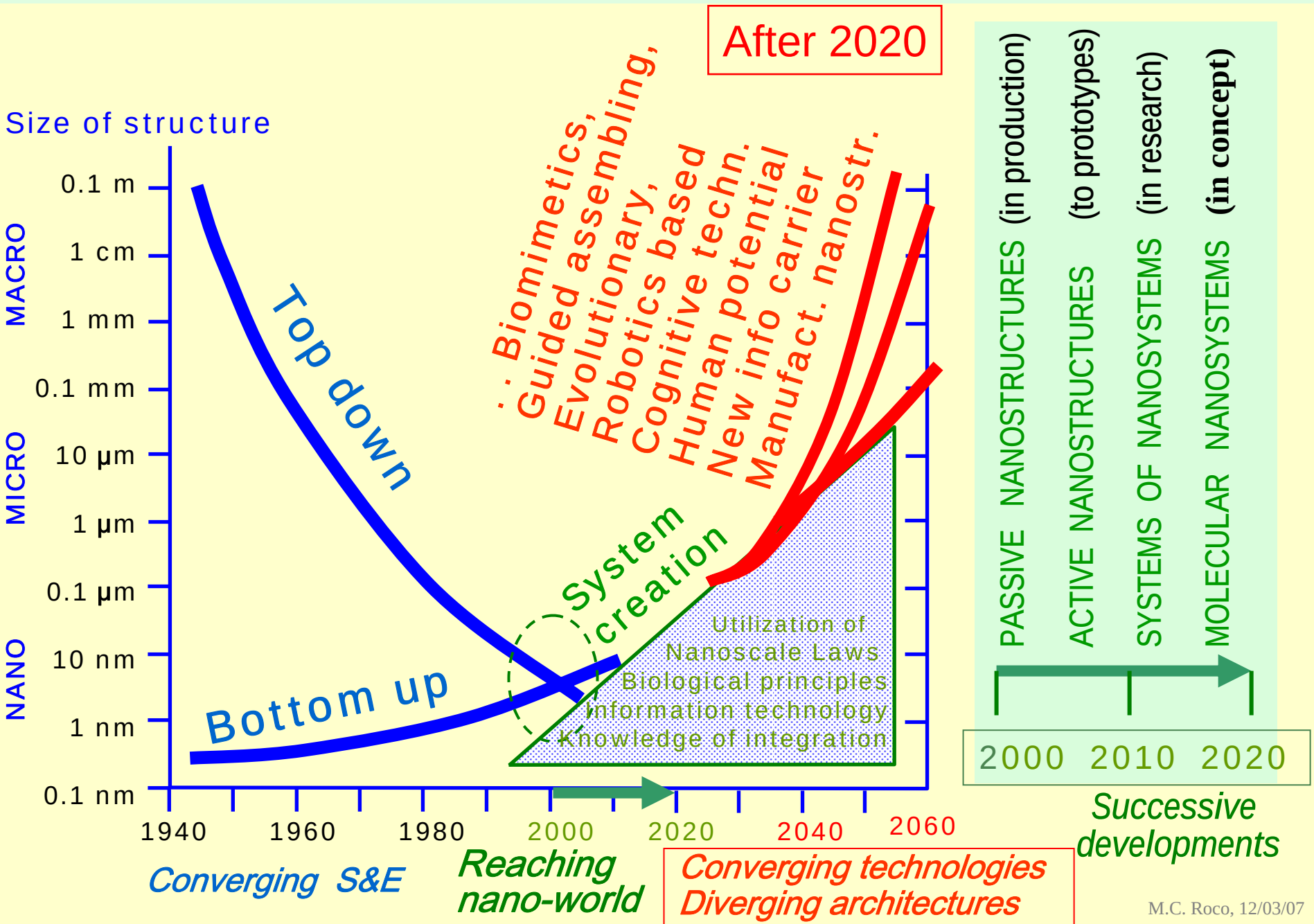
4th: Molecular nanosystems *Ex: Neuromorphic eng., Complex systems, Human-machine interface*

~ 2015-2020

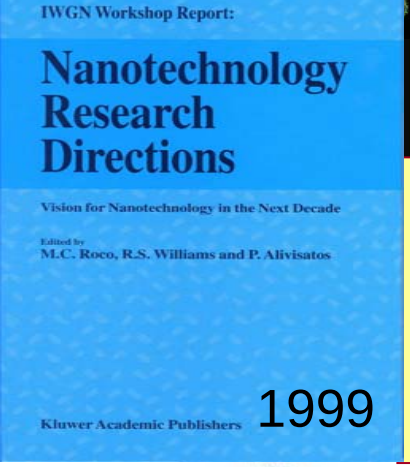
Higher benefits / Higher risk

M.C. Roco, 12/03/07

Nanosystem creation (2000-20) and new architectures (>2020)



M.C. Roco, 12/03/07



Participants in the NNI (NSET)

- FY 2001 - 6 agencies; FY 2007 - 26 NNI agencies
- 4 WG: NEHI (env.), NILI (industry), MANU, GIN (global)

2001: Six Agencies

NIH

NIST

NASA

DOD

DOE

NSF

2002: Seven New Agencies

DOS

DOTr

IC

DOT

USDA

EPA

DOJ

2003-4: Four New Agencies

FDA

NRC

DHS

DOC TA

2005: Six New Agencies

USDA FS

DOC BIS

USPTO

ITC

CPSC

NIOSH

2006: Three New Agencies

USGS

DOL

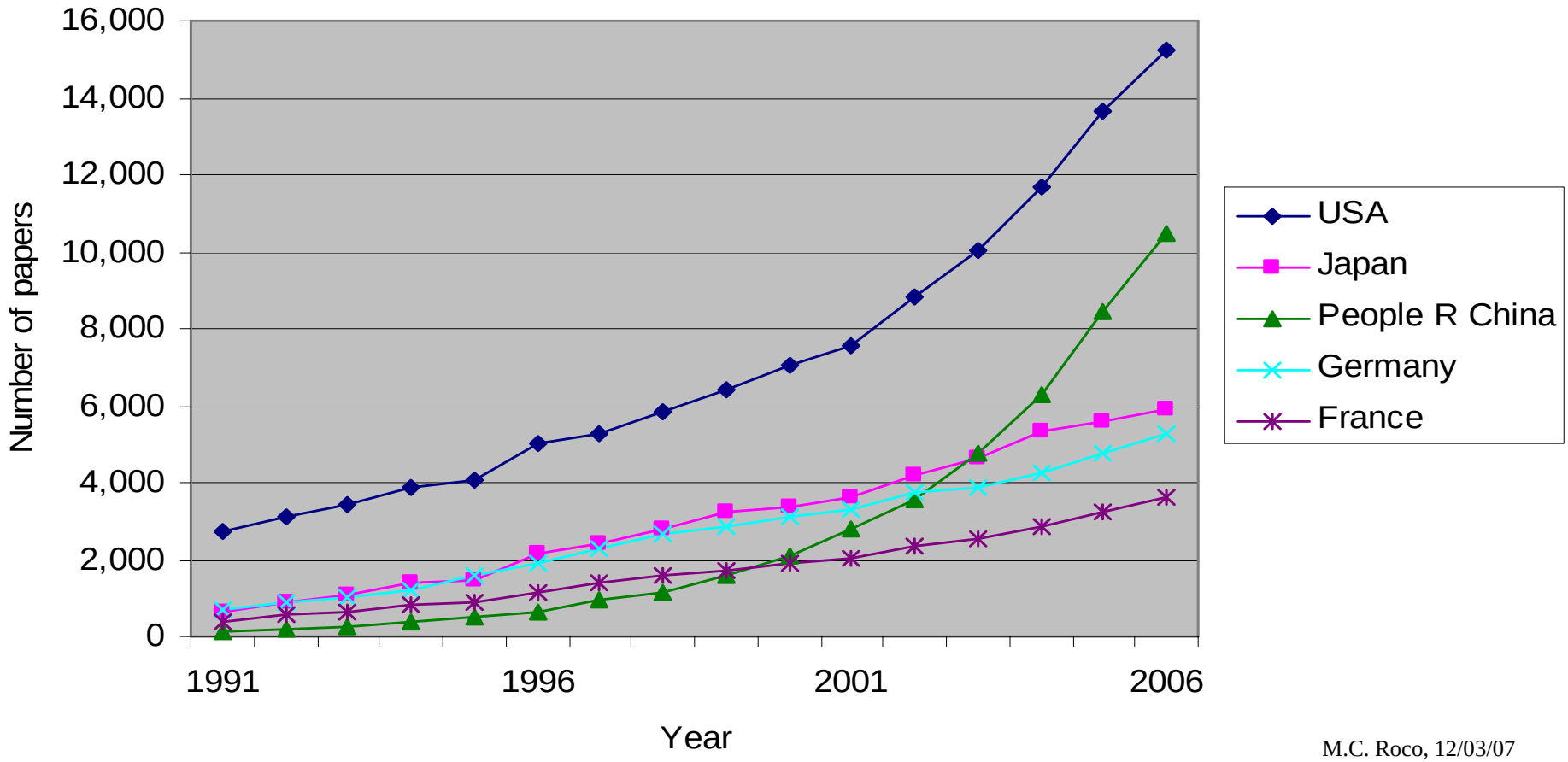
DOEd

Nanotechnology research publications

Top five countries in 2006: USA, China, Japan, Germany, France

using “Title-claims” search in SCI database for nanotechnology by keywords

(using intelligent search engine, update J. Nanoparticle Research, 2004, 6 (4))



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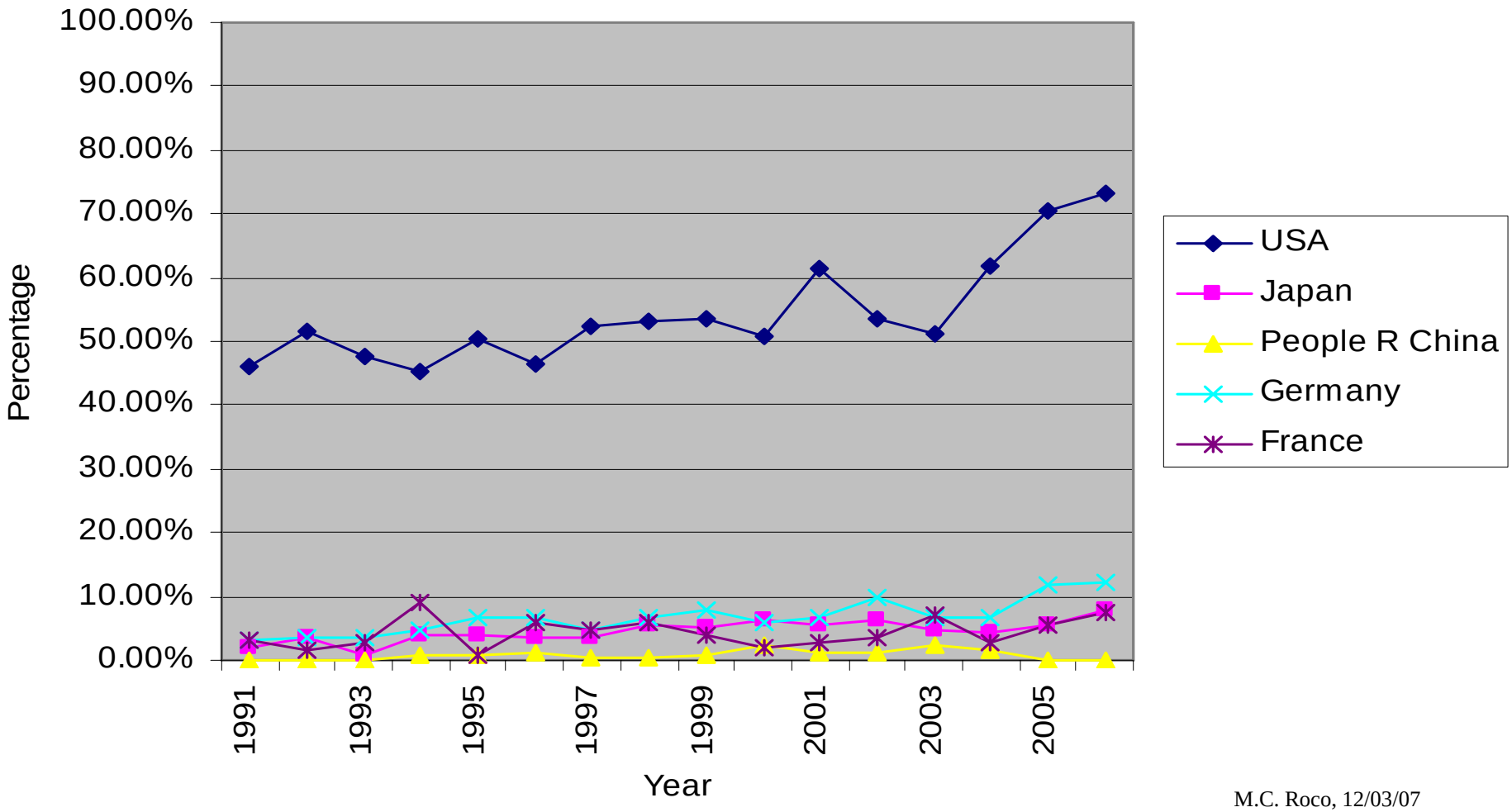
Highly cited nanotechnology related papers published in Science, Nature and PNAS

using “Title-abstract” search in SCI database for nanotechnology by keywords (using intelligent search engine, update J. Nanoparticle Research, 2004, 6(4))



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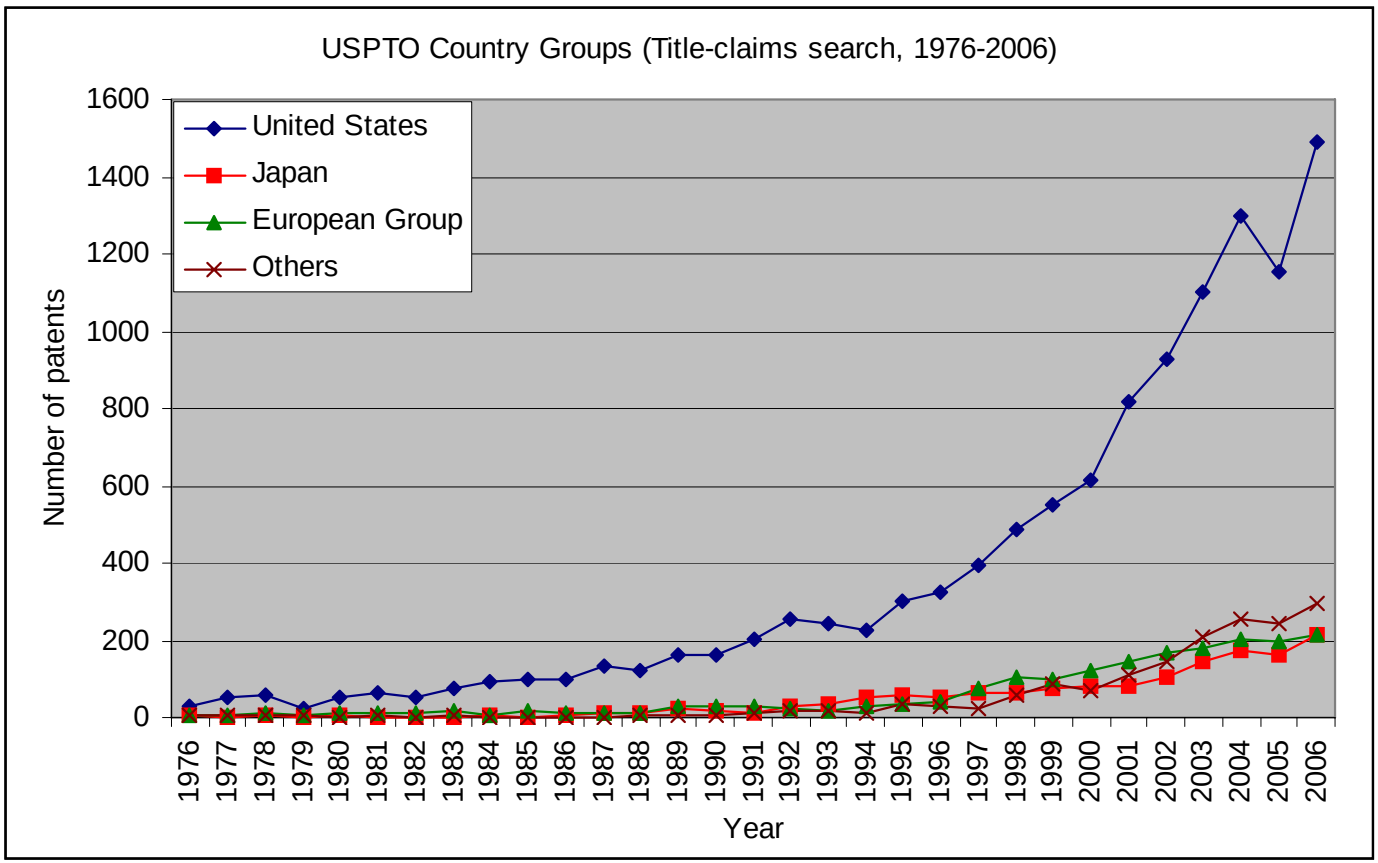
NSE patents at USPTO by country group

Assignee country group analysis by year, 1976-2006 ("title-claims" search)

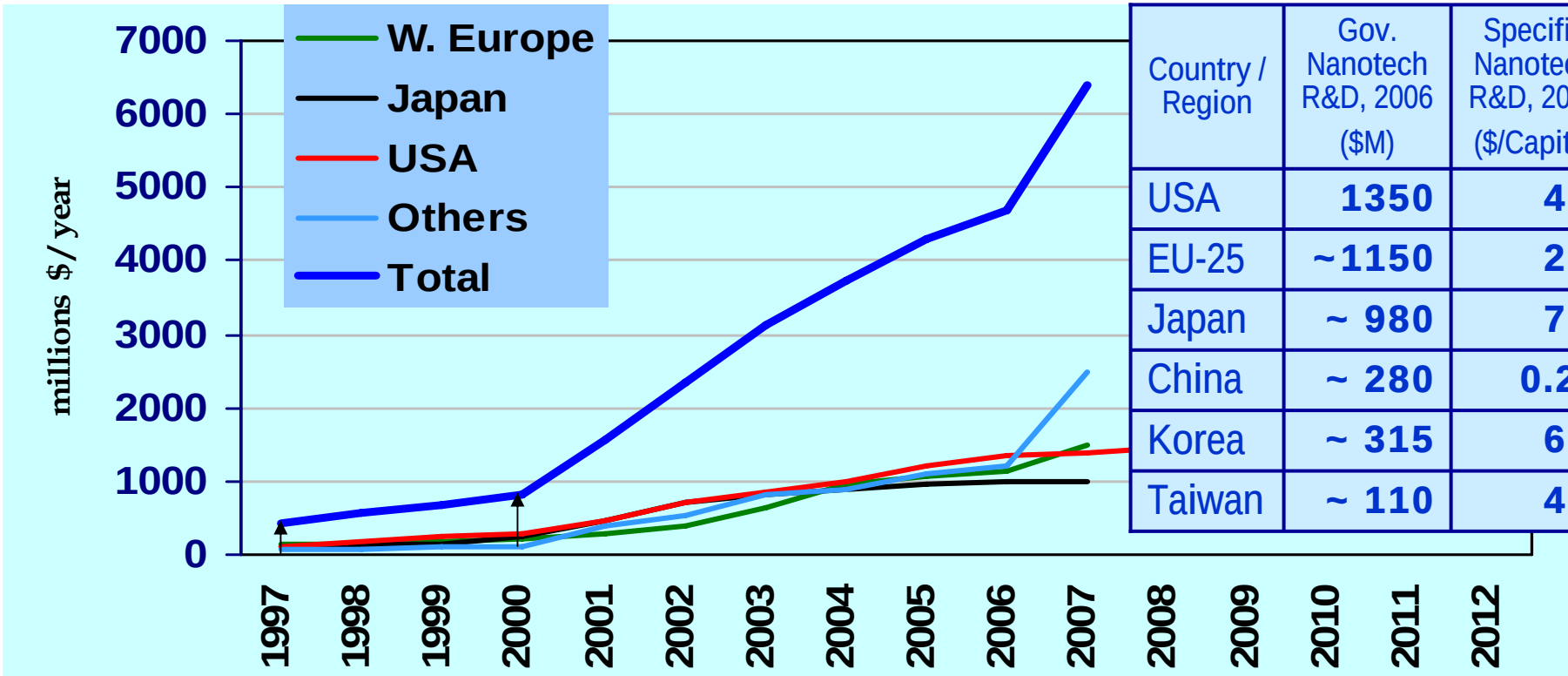


Year	United States	Japan	European Group	Others
1976	30	3	3	6
1977	53	2	3	3
1978	58	3	9	3
1979	26	2	7	3
1980	50	3	9	0
1981	61	1	10	3
1982	51	1	13	1
1983	73	1	15	4
1984	93	4	8	0
1985	97	2	16	1
1986	100	6	11	1
1987	132	12	11	0
1988	124	10	10	6
1989	162	21	28	4
1990	164	17	28	7
1991	204	14	28	9
1992	256	31	26	19
1993	244	36	20	18
1994	227	51	28	10
1995	302	57	33	36
1996	325	52	40	27
1997	393	62	73	25
1998	486	65	103	56
1999	548	75	96	85
2000	612	81	122	68
2001	818	84	147	112
2002	926	102	168	144
2003	1103	143	182	207
2004	1300	172	203	257
2005	1155	160	198	245
2006	1488	212	214	298
Total	11661	1485	1862	1658

MC Roco, 12/03/07

Context – Nanotechnology in the World

National government investments 1997-2006 (est. NSF)



Country / Region	Gov. Nanotech R&D, 2006 ($M)	Specific Nanotech R&D, 2006 ($/Capita)
USA	1350	4.5
EU-25	~1150	2.5
Japan	~ 980	7.6
China	~ 280	0.23
Korea	~ 315	6.5
Taiwan	~ 110	4.7

Seed funding (1991 -)

NNI Preparation (vision / benchmark)

1st Strategic Plan (passive nanostructures)

2nd Strategic Plan (active ns. & systems)

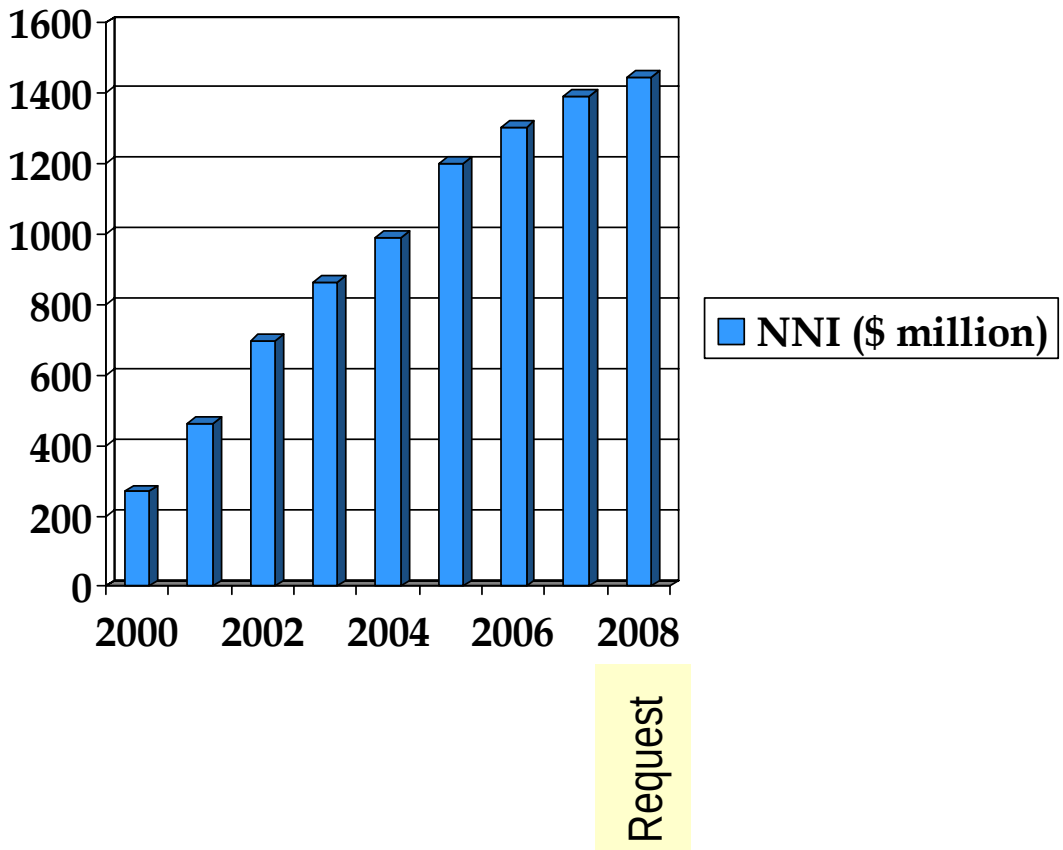
Industry R&D ($6B) has exceeded national government R&D ($4.6B) in 2006

J. Nanoparticle Research, 7(6), 2005, MC. Roco

FY 2008 NNI Budget Request $1,445 million

Average rate of increase since 2000: over 30% per year
using bottom-up project based approach

Fiscal Year	NNI
2000	$270M
2001	$464M
2002	$697M
2003	$862M
2004	$989M
*2005	$1,200M
*2006	$1,303M
2007	$1,392M
R 2008	$1,445M



* Includes Congressionally directed additional funding

February 5, 2007

A sampling of NSET Subcommittee publications for second strategic plan (2006-2010)

Societal Implications (II)

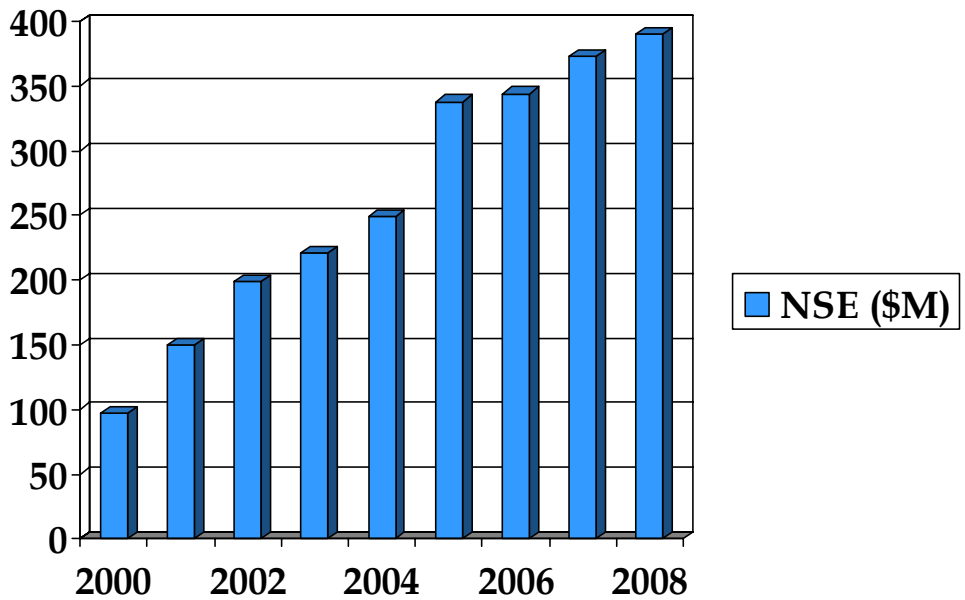
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

www.nsf.gov/nano , www.nano.gov

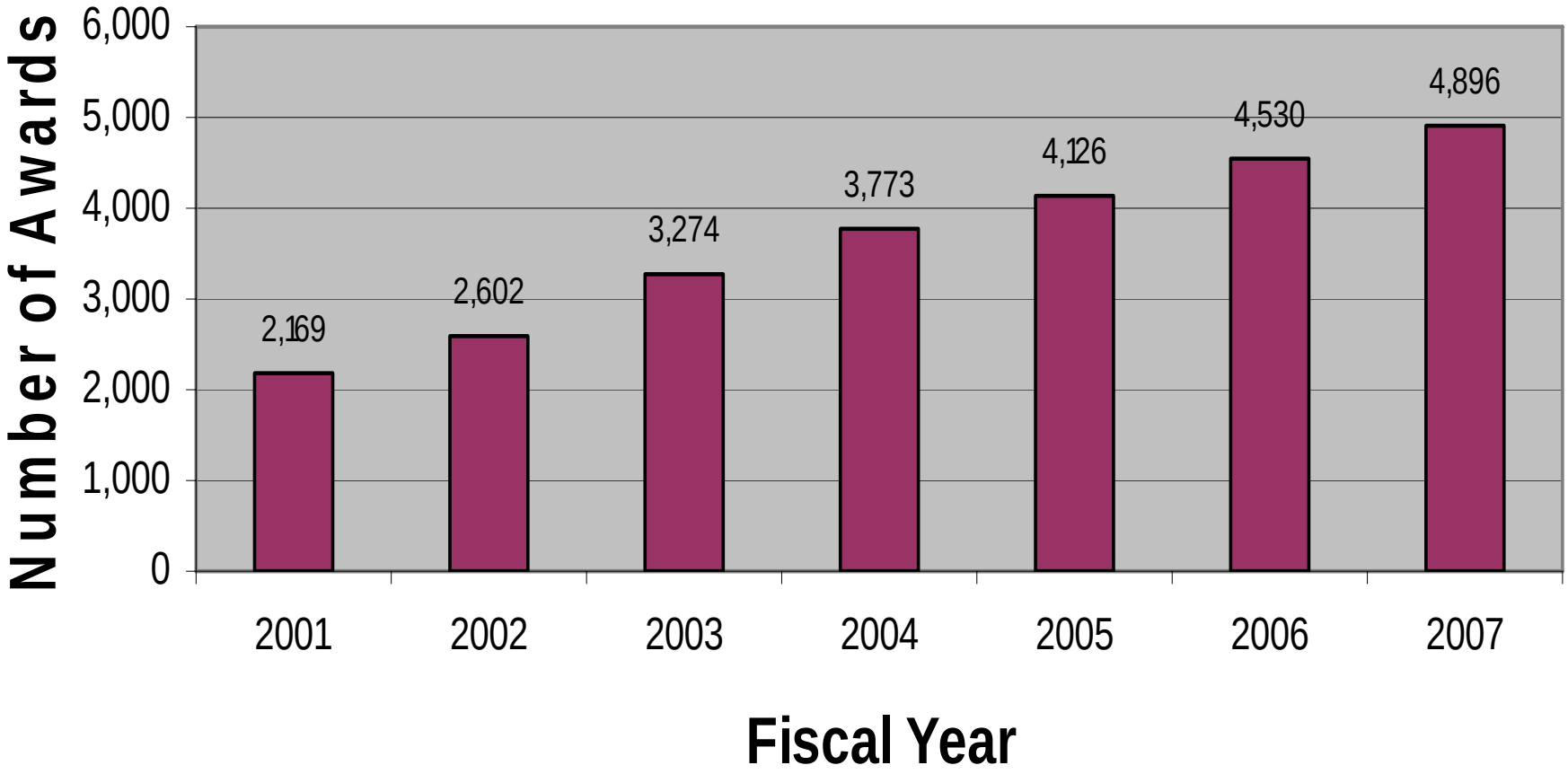
FY 2008 Request: $390M ~1/4 of Federal and ~1/12 of World Investment

- Fundamental research - seven PCAs with new priorities
- Establishing the infrastructure - over 3,500 active projects; 24 large centers, 2 user facilities (NNIN, NCN), multidisciplinary teams
- Training and education – over 10,000 students and teachers/yr

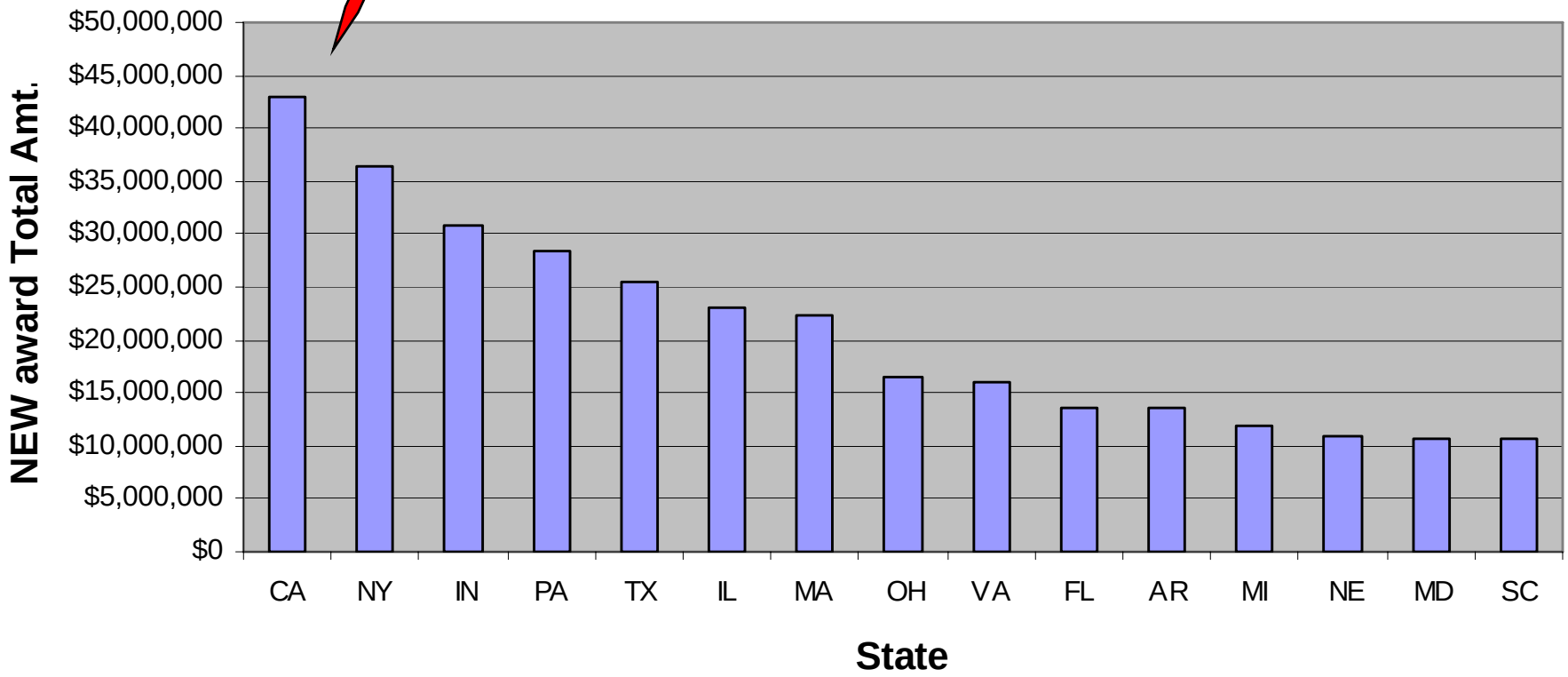
Fiscal Year	NSF
2000	$97M
2001	$150M
2002	$199M
2003	$221M
2004	$254M
2005	$338M
2006	$344M
2007	$373M
R 2008	**$390M**



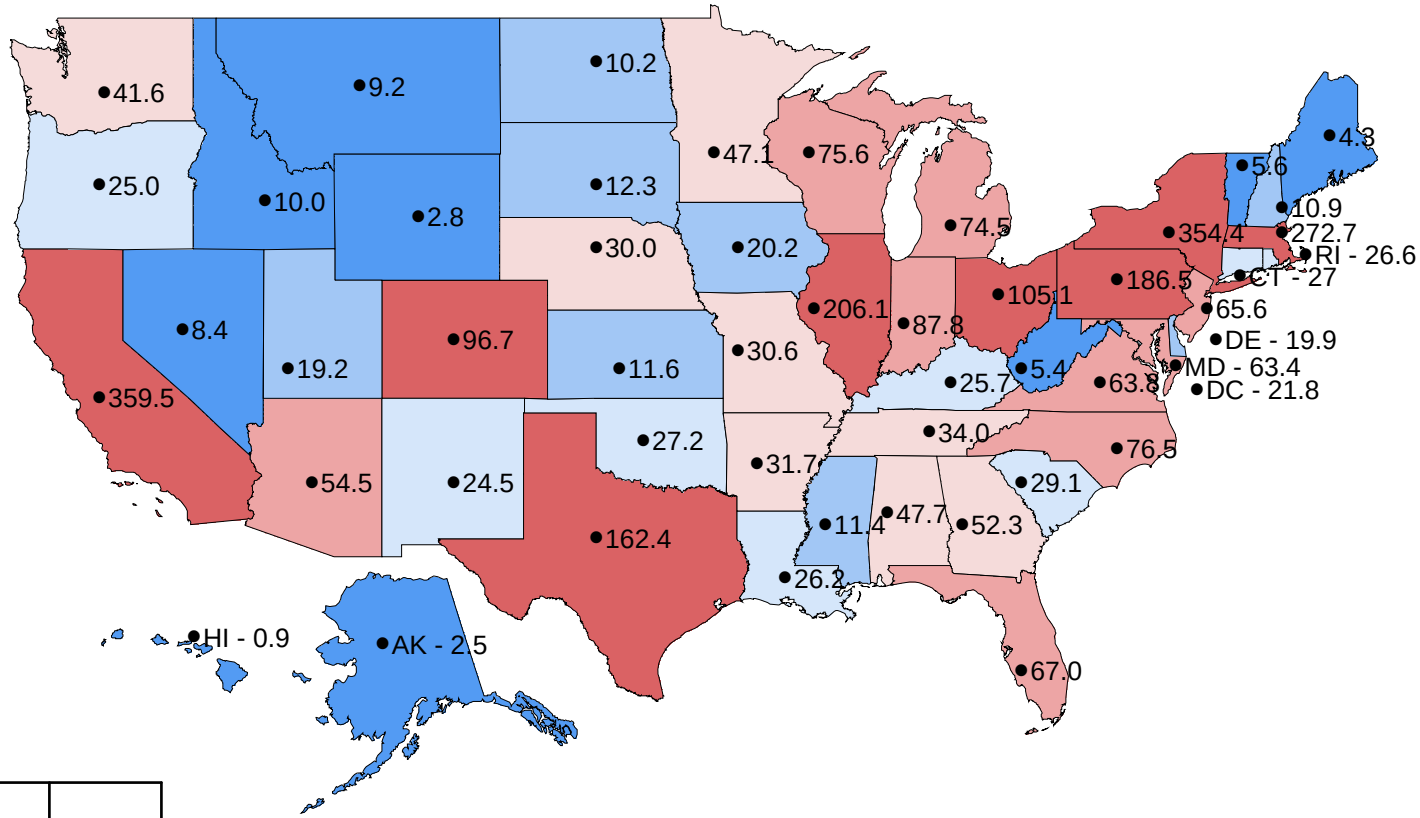
ACTIVE Nanoscale Science & Engineering Awards (FY 2001 - 2007)



States (15) with $10 Million or More in NEW NS&E Awards (FY 2007)



Total Amount for NEW NS&E Awards FY 2001 – 2007 by State



State	NEW FY 2001-2007	Rank
CA	$359,529,514	1
NY	$354,432,745	2
MA	$272,681,724	3
IL	$206,073,629	4
PA	$186,473,981	5

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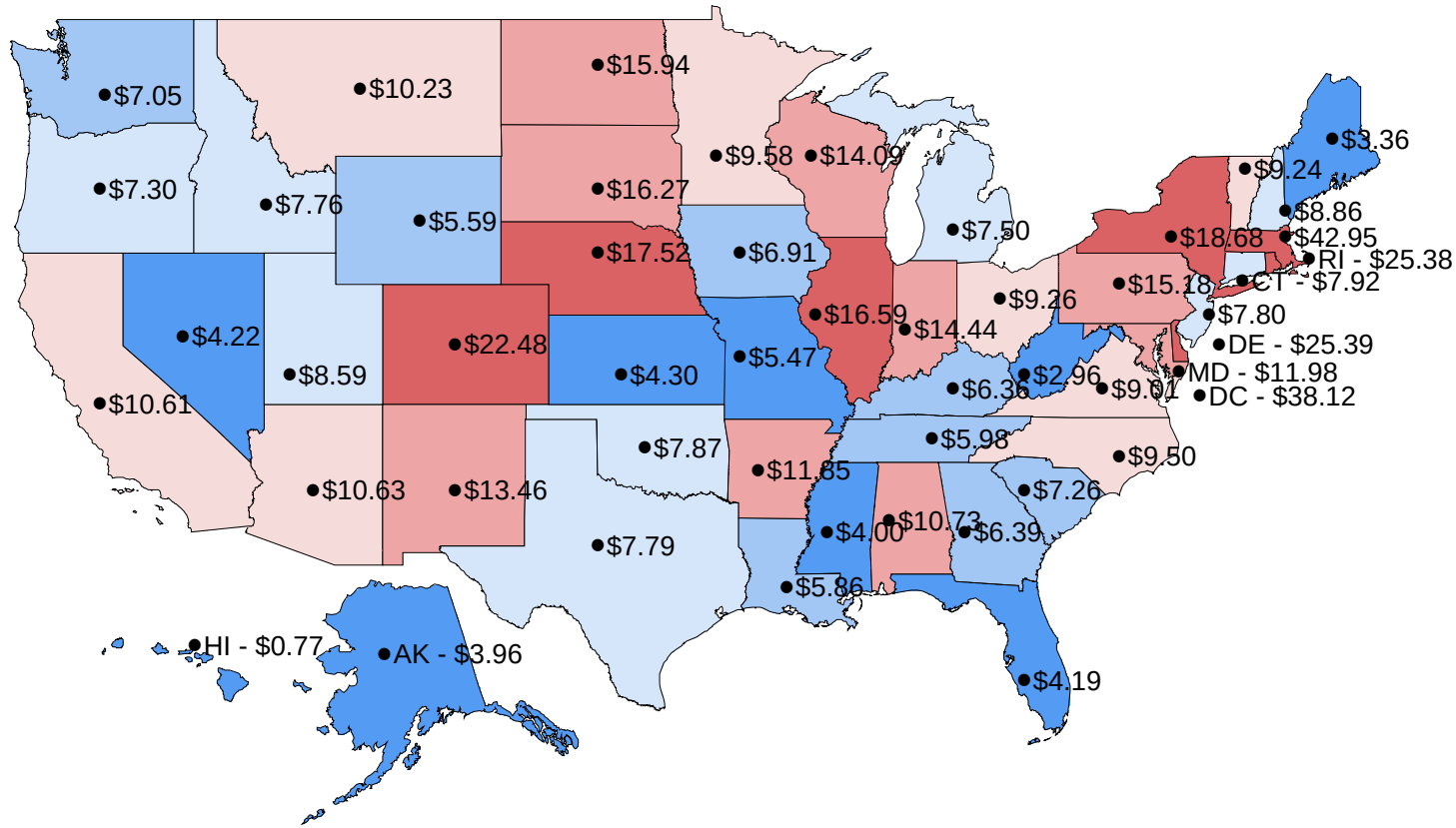
Per Capita Amount for NEW NS&E Awards FY 2001 – 2007 by State



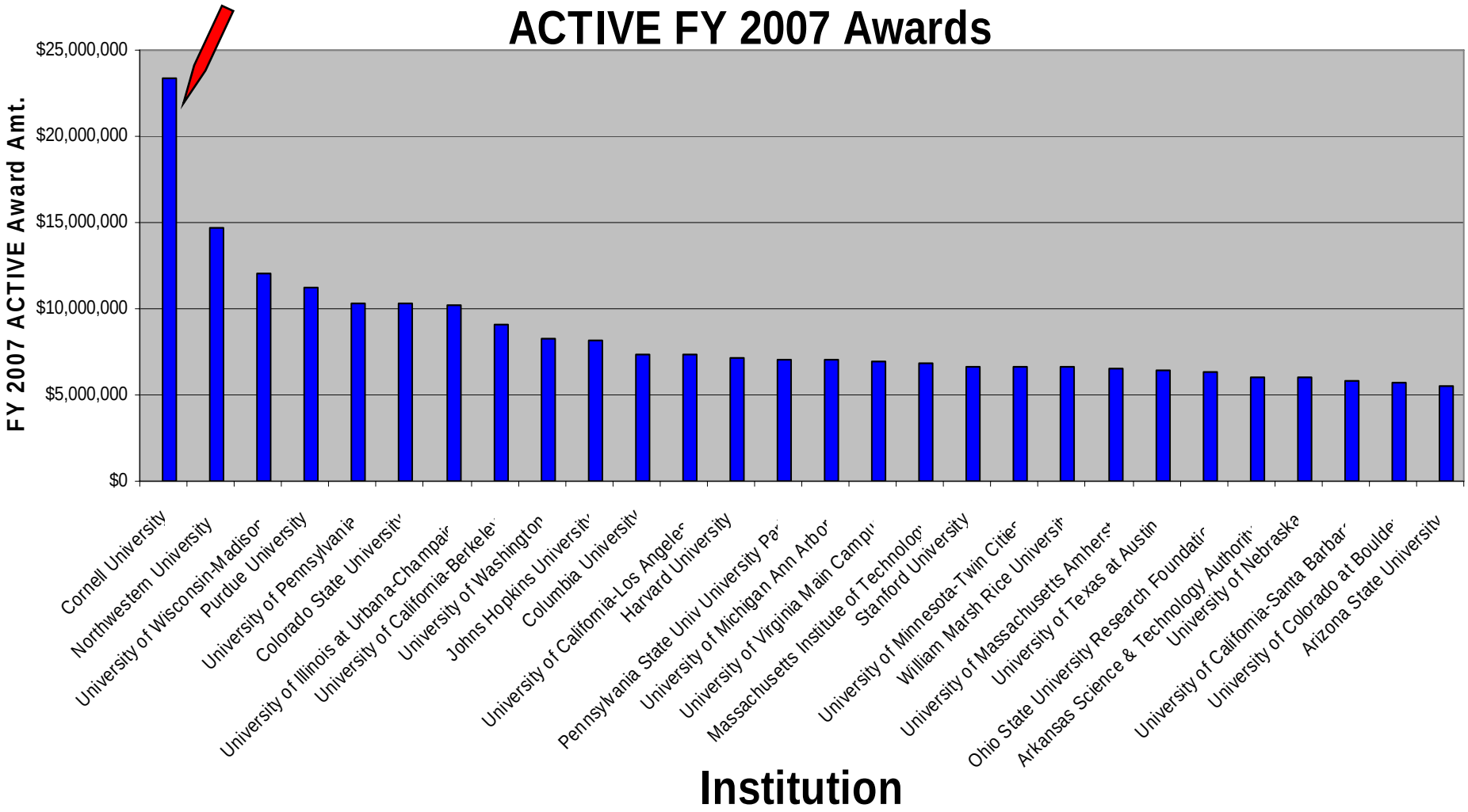
State	NEW FY 2001-2007	$ Per Capita	Rank
MA	$272,681,724	$42.95	1
DC	$21,804,945	$38.12	2
DE	$19,893,702	$25.39	3
RI	$26,604,737	$25.38	4
CO	$96,677,354	$22.48	5

FY01-07 PerCapita NEW Amt.

- <= 5.466
- 5.466 - 7.262
- 7.262 - 8.859
- 8.859 - 10.63
- 10.63 - 16.27
- 16.27 - 42.95

M.C. Roco, 12/03/07

Institutions (28) with $5 Million or More (NSE Portion) in ACTIVE FY 2007 Awards



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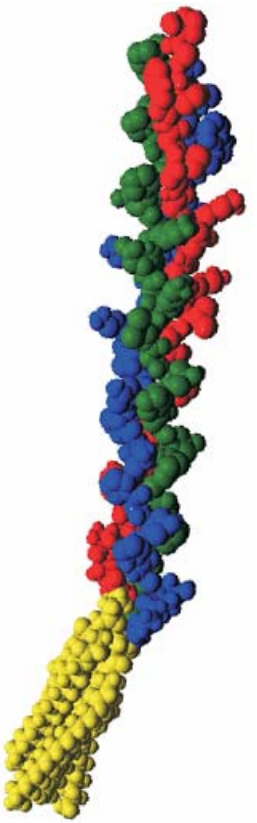
National Nanotechnology Initiative at NSF

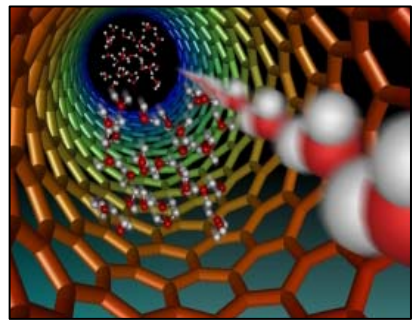


Designed molecule for selfassembling (UCSB)

- A priority in OSTP, thematic cross-cut in OMB, 26 agencies, Nanotechnology 21st Century R&D Act in WH and Congress
- Nanotechnology adopted by industry in 2002-2003, and by medical field in 2003-2004 as condition for competitiveness
- Nanotechnology is a priority in the ACI (American Competitiveness Initiative)
- New research priorities (theory, change focus from passive nanostructures to active nanostructures and nanosystems)
- Interaction with industry (with electronic SIA, chemical CCR, business IRI, and other industry sectors)
- International collaboration (International Dialogue, OECD, UNESCO, ISO, IRGC, bilateral agreements, workshops)

FY 2008 NS&E Priorities Research Areas (1)

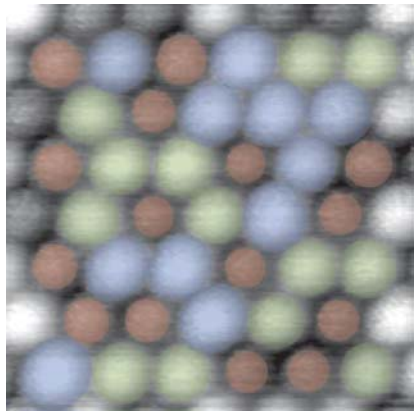
The long-term objective is building a foundation of fundamental research to understand and restructure matter at nanoscale in all areas of S&E



A. Scientific challenges

- New theories at nanoscale
  Ex: transition from quantum to classical physics, collective behavior, for simultaneous phenomena
- Non-equilibrium processes
- Designing new molecules with engineered functions
- New architectures for assemblies of nanocomponents
- The emergent behavior of nanosystems

FY 2008 NS&E Priorities Research Areas (2)

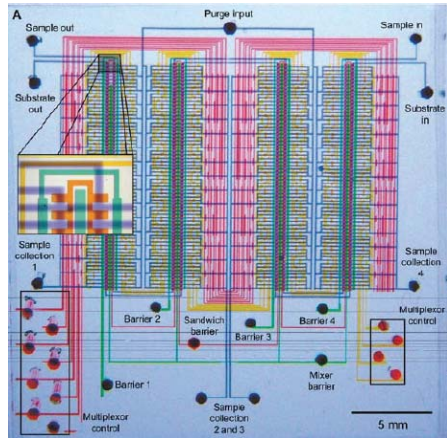


B. Development of nanotechnology

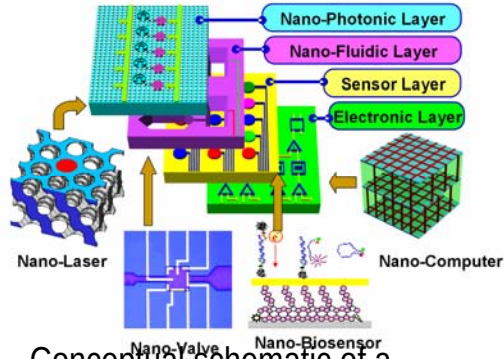
- Tools for measuring and restructuring
  with atomic precision
  and time resolution of chemical reactions
- Understanding and use of quantum phenomena
- Understanding and use of multi-scale selfassembling
- Nanobiotechnology – sub-cellular and systems approach
- Nanomanufacturing of active nanostructures and
  nanosystems; ex: use of catalysts

Challenges for Systems Nanotechnology

- Understanding mechanisms and patterns of system behavior as a function of components, interaction forces and networks at the nanoscale. Two priorities are understanding and use of quantum phenomena and evolutionary dynamics in nanosystems
- Emerging behavior of systems with large number of nano-components and non-linear interactions
- Tools for measuring, simulation and



Integrated circuits that are smaller and faster are possible with microfluidics systems built from or incorporating nanocomponents. *Ferreira, 0328162.*

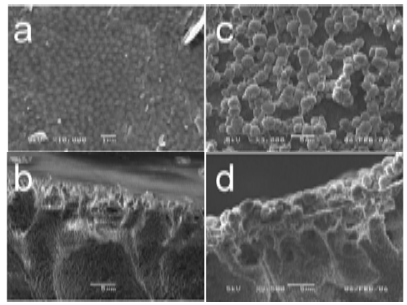


Conceptual schematic of a manufactured nanosystem. The hope for this device is its use to identify the molecular signature of breast tumors. *X Zhang, 0725886*

FY 2008 NS&E Priorities Research Areas (3)

C. Integration of nanotechnology in application areas

- Replacing electron charge as the information carrier in electronics
- Energy conversion, water filtration / desalinization using new principles



SEM micrographs of membranes (UIUC)

- Efficient nanomanufacturing and sustainable environment
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for better communication and nanosystem design

FY 2008 NS&E Priority Research Areas (4)

D. Societal dimensions of nanotechnology

- Understanding & sustainable ENV; EHS including research for natural/ incidental/ manufactured nanomaterials
- Formal (earlier K-12 and public education integrated in K – Gray) and informal education
- Social issues and public engagement

Key EHS priorities (for knowledge creation, infrastructure, and education):

- New instrumentation for nanoparticle characterization and nanotoxicity
- Transport phenomena and physico- chem.- biological processes of nanoscale dispersions in the natural and working environments
- Predictive models for interaction of nanomaterials with cells/living tissues
- Separation of nanoparticles from fluids
- Safety of manufacturing nanoparticles (is being investigated at NSECs at Rice U., NE U., U.PA and U.WI, and NNIN)

Key societal issues in long term (NSF, since 2000)

- **Respect human right to: access to knowledge and welfare; human integrity, dignity, health and safety**
- **Balanced and equitable R&D nanotechnology investment**
- **Environment protection and improvement (water, air, soil) Sustainable development, life-cycle of products, global effects (weather), eliminate pollution at the source**
- **Economic, legal, ethical, moral, regulatory, social and international (developed-developing countries) aspects**

  Interacting with the public and organizations
- **Adaptive/corrective approach for a complex system**

Immediate and continuing issues

- ***EHS in research laboratories and industrial units***
- ***Harmonizing nomenclatures, norms and standards***
- ***Primary data and methodology for risk analysis***

NSF Overview on nano ENV/EHS (1)

- "Upstream" research and education since 2000
  - 1990 – hazardous emissions (toxic materials)
    - Workshop on submicron particles and emissions
    - *Solicitation for high rate production of nanoparticles*
  - 2000 – nanoparticles and other passive nanostructures
    - *NSE program solicitations with two main themes:*
    - *- Nanoscale processes in the environment*
    - *- Societal implications*
  - 2003 – nanomanufacturing safety; NISE, NCLT, NSEC
    - Nanomanufacturing program
    - All NSEC centers asked to address implications
  - 2006 – added focus on the 2nd-3rd generations (ANN solicit.)
  - 2010 – to focus on nanosystems (more complex, dynamic)

NSF Overview on nano ENV/EHS (2)

- Main topics funded in 2006-2007 in the EHS NNI cross-cut

  (a) instrumentation, metrology, and analytical methods;

  (b) effects on biological systems and human health;

  (c) effects on the environment;

  (d) monitoring methods for health / env. surveillance; and

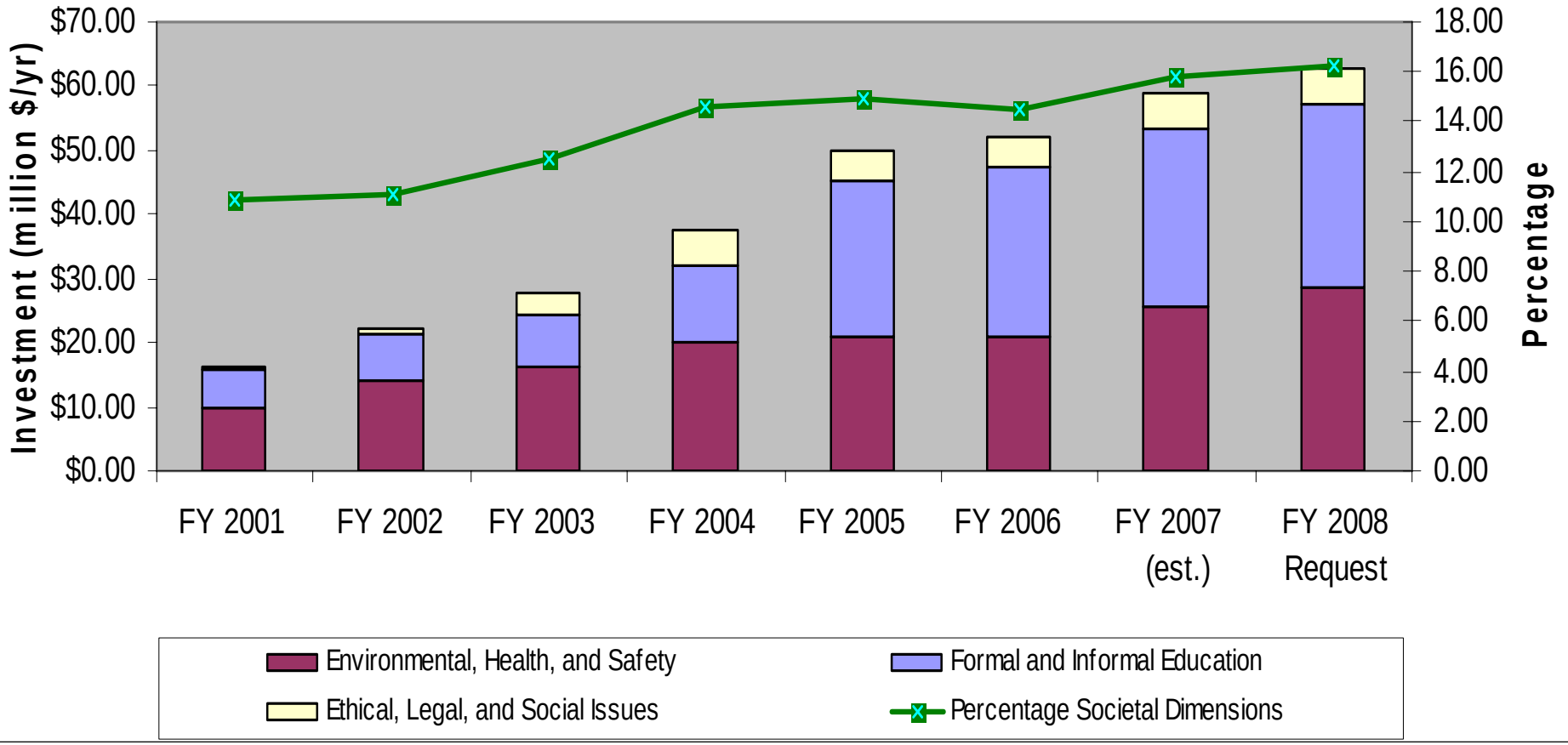
  (e) risk assessment and management methods.

NSF Overview on nano ENV/EHS (3)

- Societal Dimensions in FYs 2007 estimate & 2008 request:
  - 2007: $59.0 million (69%) of all NNI - $85.9 million
  - 2008: $62.9 million (65%) of all NNI - $97.5 million
- ENV/EHS: NSF dedicates about 7% of its NNI budget for projects with a primary focus on fundamental aspects of environmental implications and applications of nanomaterials:
  - 2007: $25.7 million (6.9%) of the total NSF/NNI estimate
  - 2008: $28.8 million (7.4%) of the total NSF/NNI request
- These topics are supported through all NSF programs

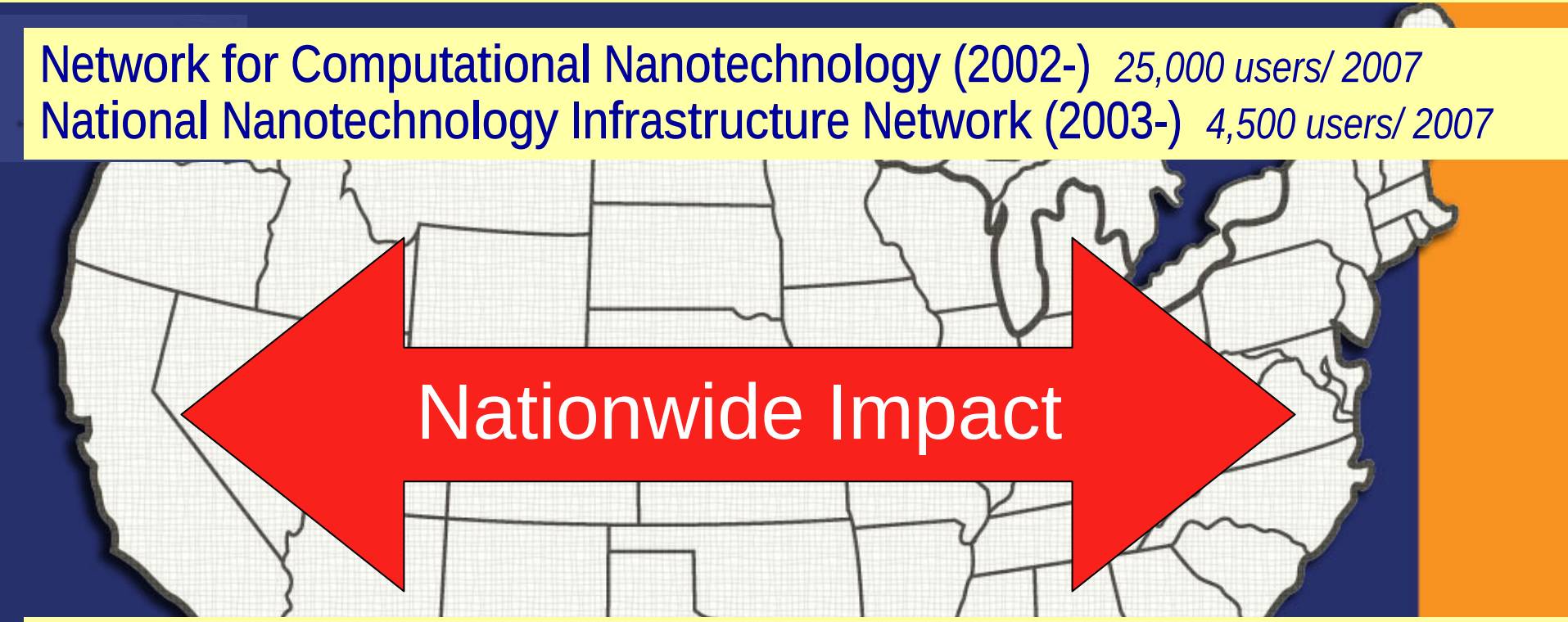
NSF Investment in Societal Dimensions of NT

Of FY 2008 NNI/NSF request of $390 M, $63 M or 16.1% is for SI, and $28.8 M (7.4%) for nano ENV/EHS



Eight Nanoscale Science and Engineering networks with national outreach

Network for Computational Nanotechnology (2002-) *25,000 users/ 2007*
National Nanotechnology Infrastructure Network (2003-) *4,500 users/ 2007*

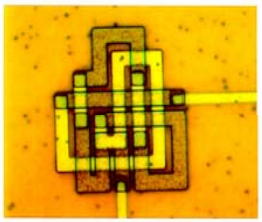


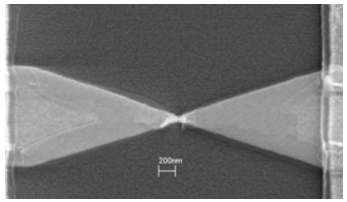
Nanotechnology Center Learning and Teaching (2004-) *1 million students/ 5yr*
Center for Nanotechnology I Science Education (2005-) *100 sites/ 5yr*
Network for Nanotechnology in Society (2005-) *Involve academia, public, industry*
National Nanomanufacturing Network (2006-) 4 NSETs , DOD centers, and NIST

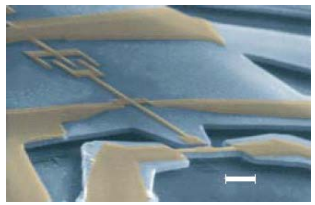
NSEC Network (2001-) *17 research & education centers*
MRSEC Network (2001-) *6 new research & education centers since 2000*

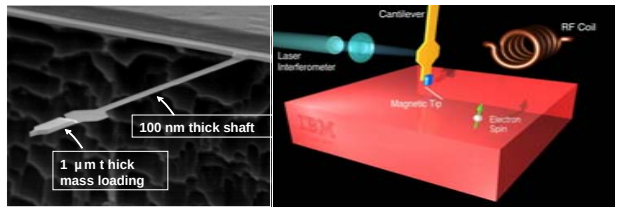
MC Roco,
12/03/07

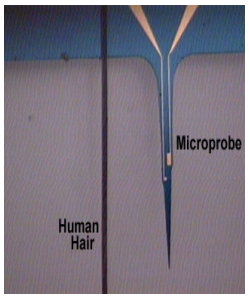
National Nanotechnology Infrastructure Network (NNIN)

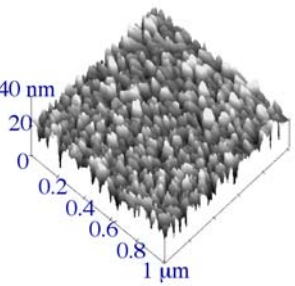


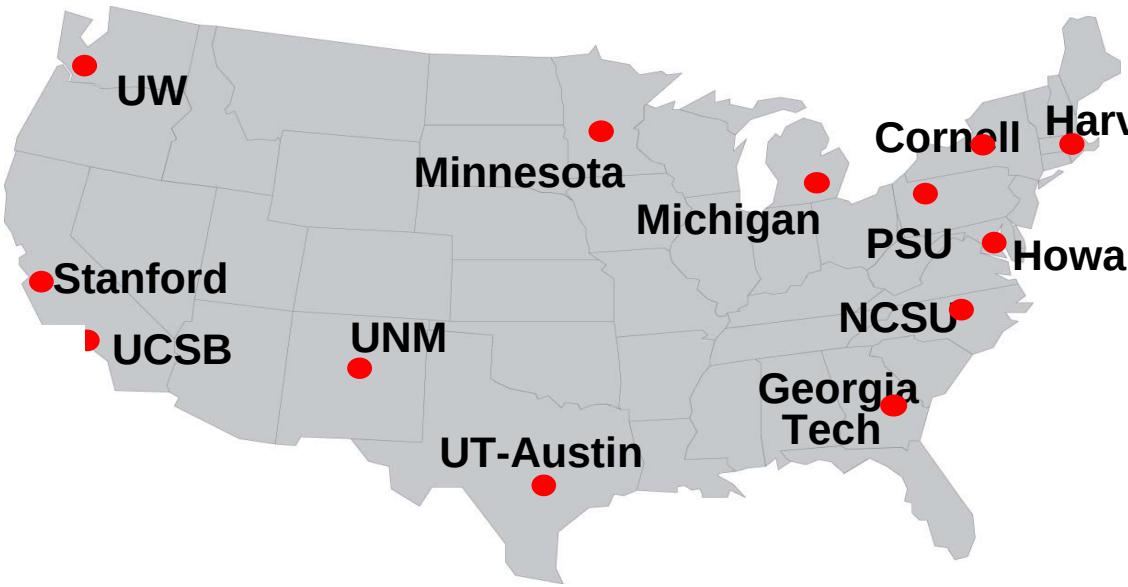












Cornell U (Lead)
Stanford U
U Michigan
Georgia Tech
U Washington
Penn State U
UC Santa Barbara
U Minnesota
U New Mexico
U Texas –Austin
Harvard U
Howard U
No. Carolina State U

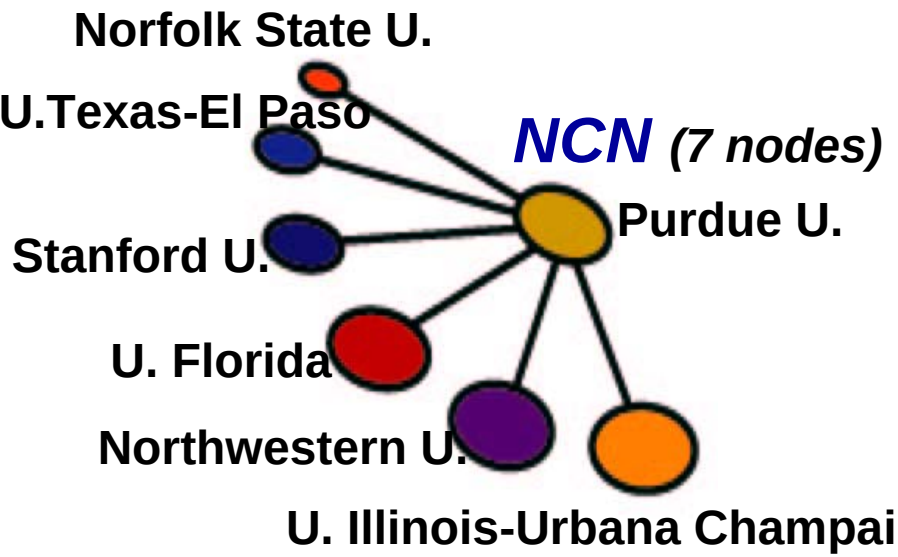
An integrated national network of user facilities providing researchers open access to resources, instrumentation and expertise in all domains of nanoscale science, engineering and technology

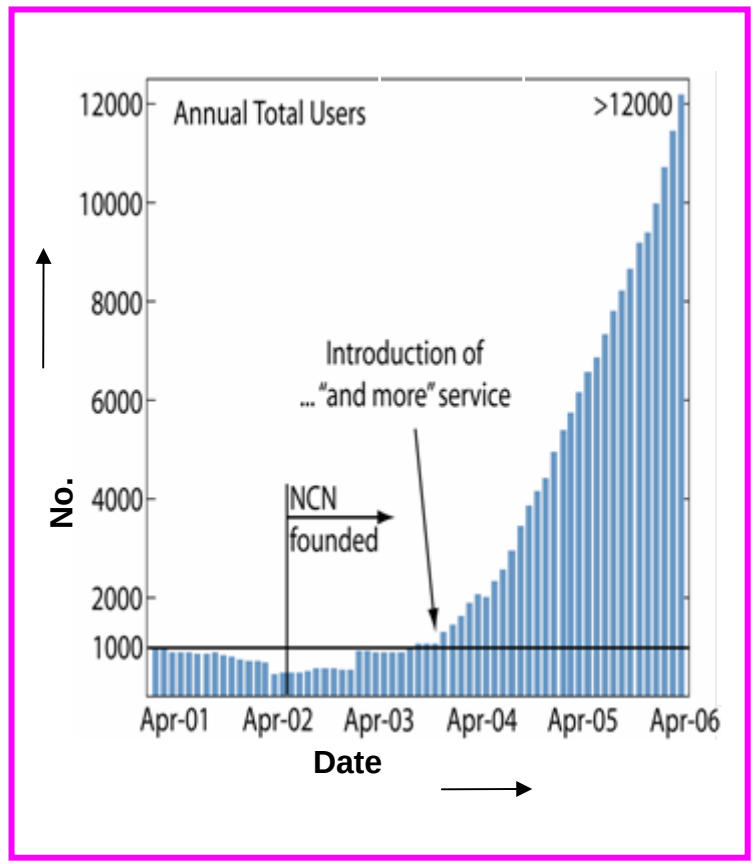
http://www.NNIN.org; Est. 4,500 users in 2006, NSF $3,500/ user

MC Roco, 12/03/07

Network for Computational Nanotechnology

A national resource for research, education and user-facility to accelerate the transformation of nanoscience to nanotechnology through theory, modeling, and simulation and collaboration enabled by cyberinfrastructure





Focus: "from atoms to systems";
"same equations for various applications"

http://www.nanoHUB.org

Est. 25,000 users / 2007; NSF $200 / user

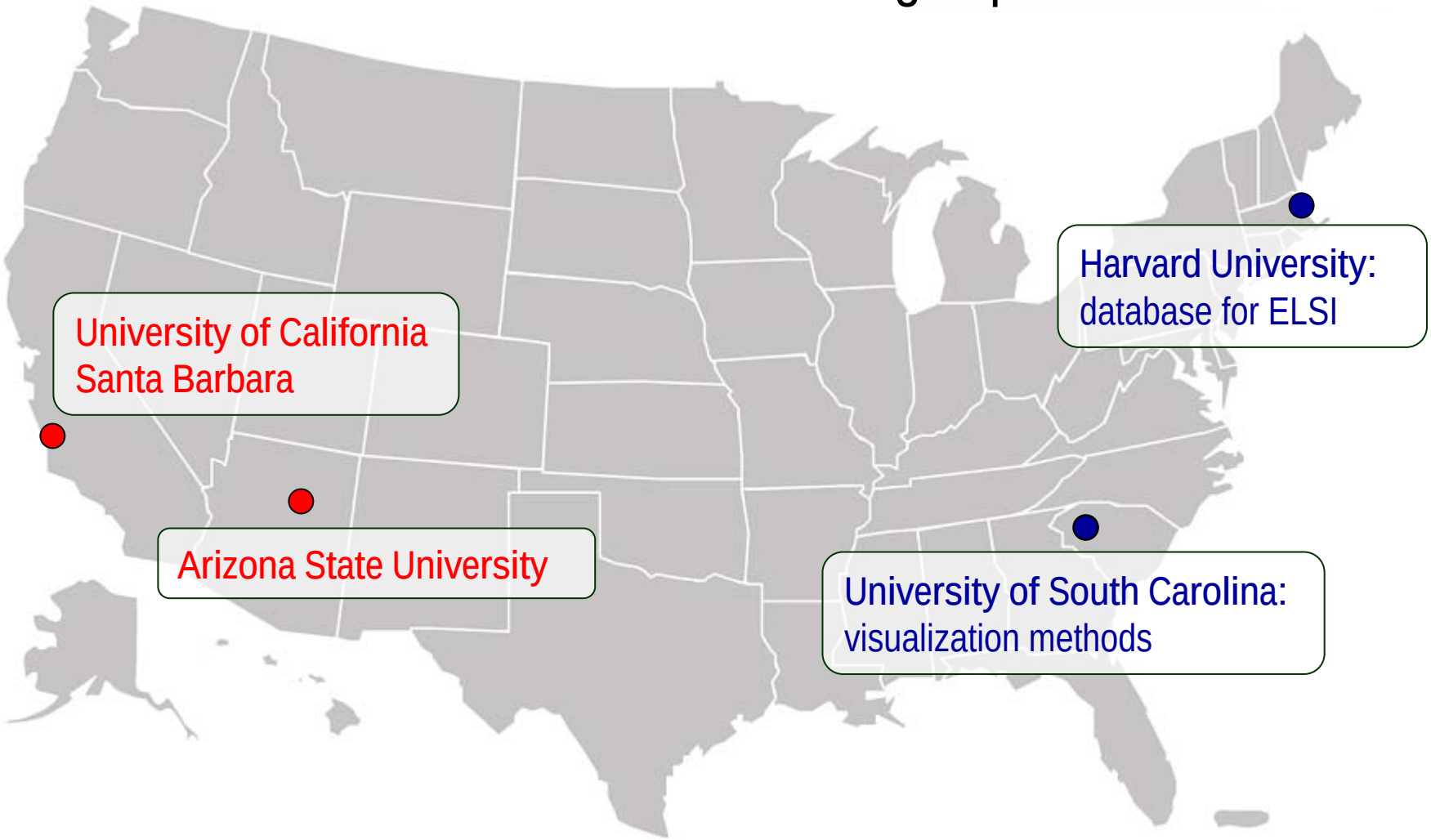
National Nanomanufacturing Network (NNN)

- NSF: Four NSECs
  - Center for Scalable and Integrated Nanomanufacturing, UCLA (2004-)
  - Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, University of Illinois at Urbana-Champaign (2005-)
  - Center for High Rate Nanomanufacturing, Northeastern University (2005-)
  - Network for Hierarchical Manufacturing U. Mass. - Amherst (2006-) *(Main Node of NNN)*
- DOD
- NIST, Laboratory for Nanoscale Science and Technology

NSEC: Nanotechnology in Society

Four nodes established in September 2005:

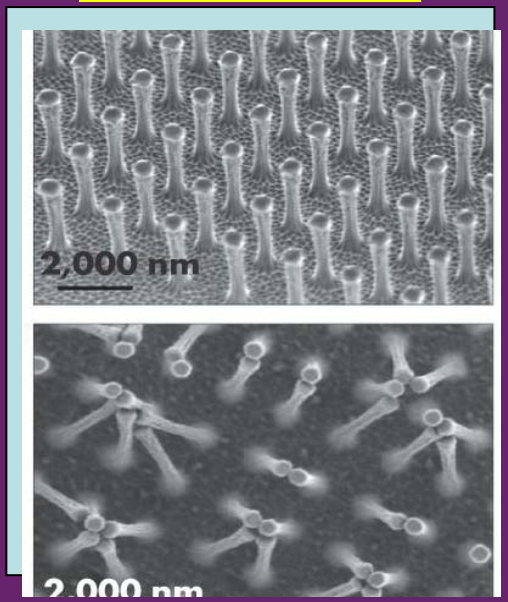
● 2 centers and ● 2 small-groups



To address Ethical, Legal and other Social Issues related to Nanotechnology

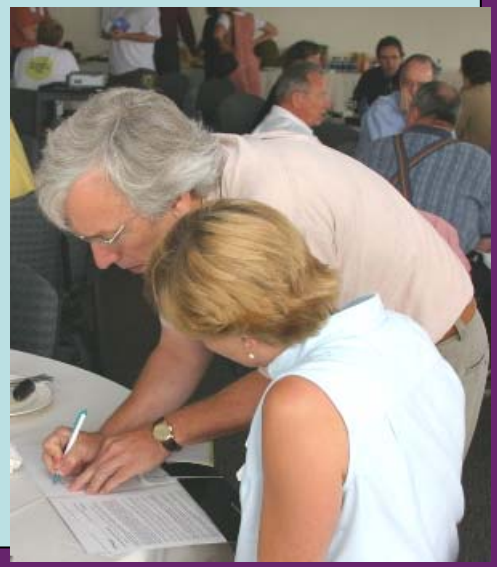
Nanotechnology Informal Science Education Network

Center for NISE Research
Exploratorium San Francisco



- **Visualization Lab**
- **Resource Center**
- **Research and Evaluation**
- **Professional Development**
- **Public Website**

Center for Public Engagement
Museum of Science Boston



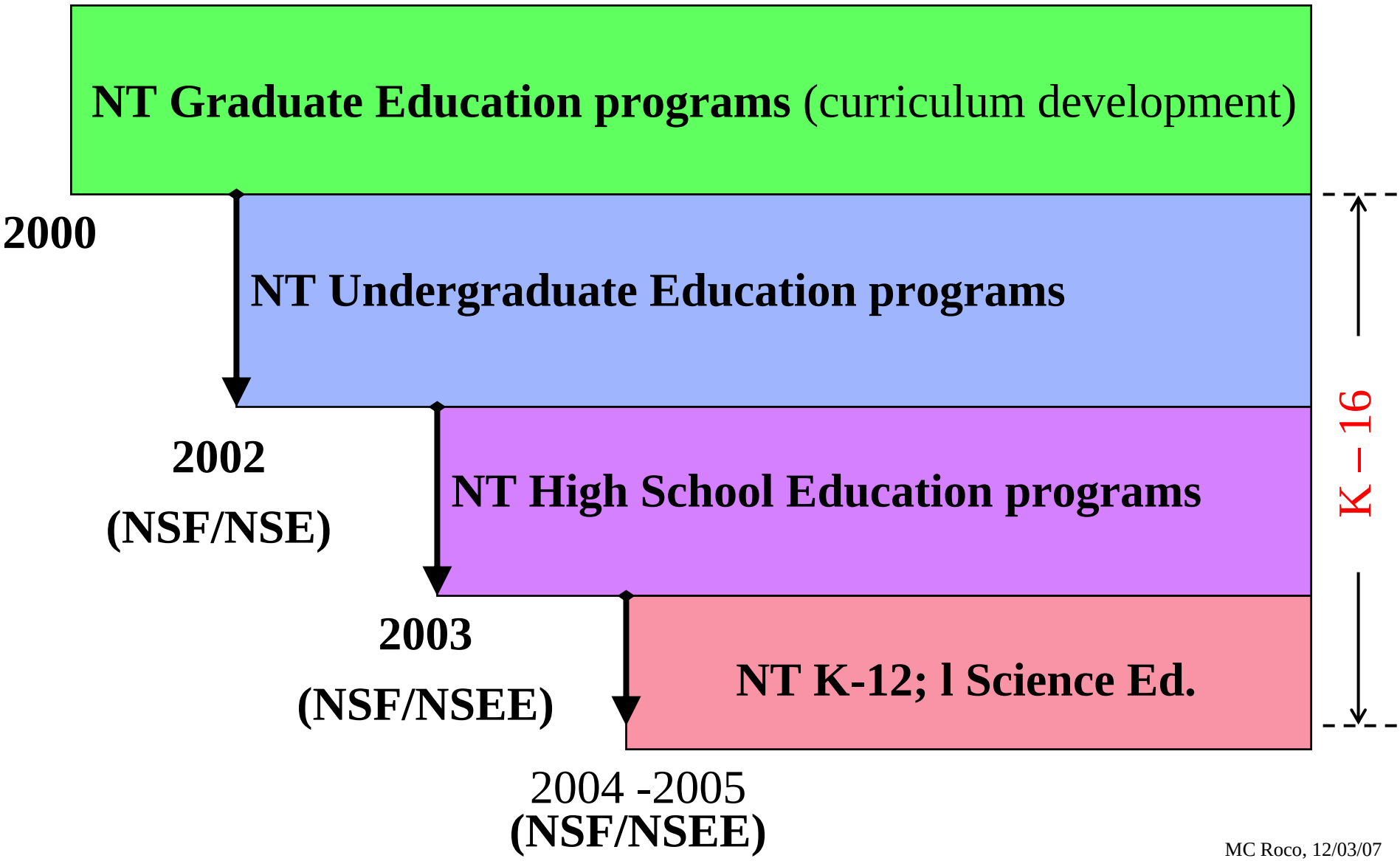
- **Network Media**
- **Forums**
- **Network Administration**

Center for Exhibits & Programs
Science Museum of Minnesota

- **Exhibit and Program Packages**

To create 100 science museum sites in U.S. by 2010

Introducing earlier nanotechnology education
(NSF: Nanoscale Science and Engineering Education)



Nanotechnology education: What to do in the future?

- **Developing coherent, longitudinal program** with proper bridges between K-12, UG, G, postdoctoral, and continuing education, and encouraging earlier nanotechnology education
- **Targeting systemic changes K-16**
- Priority to unifying S&E and broad relevance courses
- Partnering for cross-disciplinarity, cross-relevance, and sharing resources (such as facilities and expertise, remote)
- Enabling the teachers
  - Training activities periodical available (ex: RET, at centers)
  - Create educational materials (modules, hand-on-kits, course notes)
  - Access to experimental facilities and specialized museums
- International education opportunities Young researchers to Japan and EU; PASI - Latin America, NSF-E.C.

NNI-Industry Consultative Boards for Advancing Nanotech

Key for development of nanotechnology, Reciprocal gains

- **NNI-Electronic Industry (SRC lead), 10/2003 -**
  - Collaborative activities in key R&D areas
  - 5 working groups, Periodical joint actions and reports
  - NSF-SRC agreement for joint funding; other joint funding

- **NNI-Chemical Industry (CCR lead)**
  - **Joint road map for nanomaterials R&D; Report in 2004**
  - **2 working groups, including on EHS**
  - **Use of NNI R&D results, and identify R&D opportunities**

- **NNI – Organizations and business (IRI lead)**
  - **Joint activities in R&D technology management**
  - **2 working groups (nanotech in industry, EHS)**
  - **Exchange information, use NNI results, support new topics**

- **NNI – Forestry and paper products (AF&PA lead, 4/2007), 10/2004-** **Workshop / roadmap for R&D**
  - **Exchange information**

American Forest & Paper Association

FY 2007 NSF's Grantees Meeting

- Review awards from the NSE solicitations
  FY 2006 NIRTs and NSECs
- Posters, keynotes and panels to facilitate exchanges, partnerships, and research planning
- Presentations from the NIH and NIST
- To strengthen a NSE trans-disciplinary community

US NSF - Nanoscale Science and Engineering - NSF ACTIVITIES, Solicitations and Their Outcomes - Microsoft I...

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WHERE DISCOVERIES BEGIN

www.nsf.gov/nano
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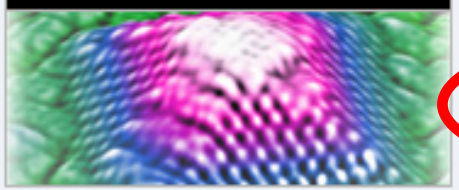
NNI



Solicitations & Outcomes
New Items

Activities
Program Reviews
NSF & NNI Symposia

NSF & NNI Reports
NSF & NNI Reports
Links to Related Reports
NNI Endorsements
NNI Presentations

NSF National Nanotechnology Initiative (NNI)

Search for NSF awards by keywords
(go to the "Full text search", and complete the box with your keywords; Examples of keywords are nano*, selfassembl* and nanoparticle)

NSF press releases on Nanotechnology Research since January 2004

NSF press releases on Nanotechnology Research from 2003 to 2001

SOLICITATIONS AND OUTCOMES IN FY 2005

NSF Announcement 05-543: Nanoscale Science and Engineering Education (NSEE)
"Preparation workshop: Public Engagement in Nanoscale Science and Engineering"(PDF, 776KB)

NSF Announcement 04-043: Nanoscale Science and Engineering (NSE)
NSEC on "Nanotechnology in Society" workshop

Joint EPA-NSF-NIOSH solicitation for research in Environmental and Human Health Effects of Manufactured Nanomaterials