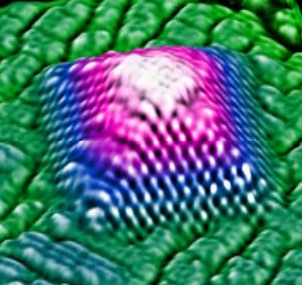
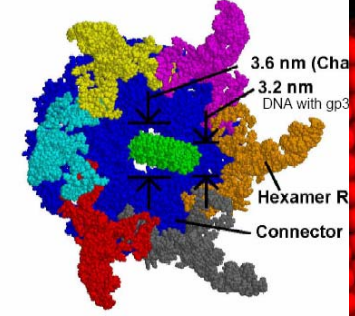
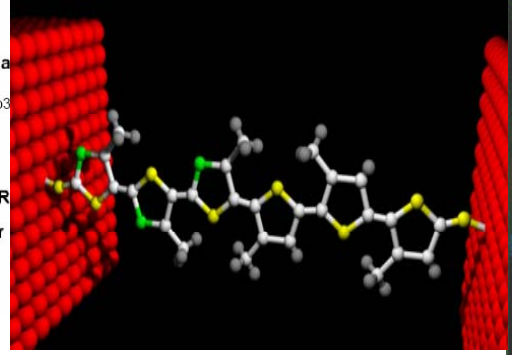
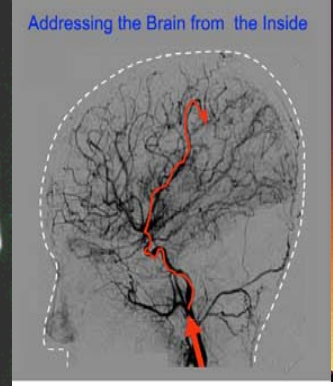







The Changing Face of Nanotechnology

M.C. Roco

National Science Foundation (NSF) and
U.S. National Nanotechnology initiative (NNI)

Korea-US Nanotechnology Workshop,
April 17-18, 2008

Benchmark with experts in over 20 countries

"Nanostructure Science and Technology"

Book Springer, 1999

Nanotechnology

is the ***control and restructuring of matter***
(measure – manipulate – integrate)

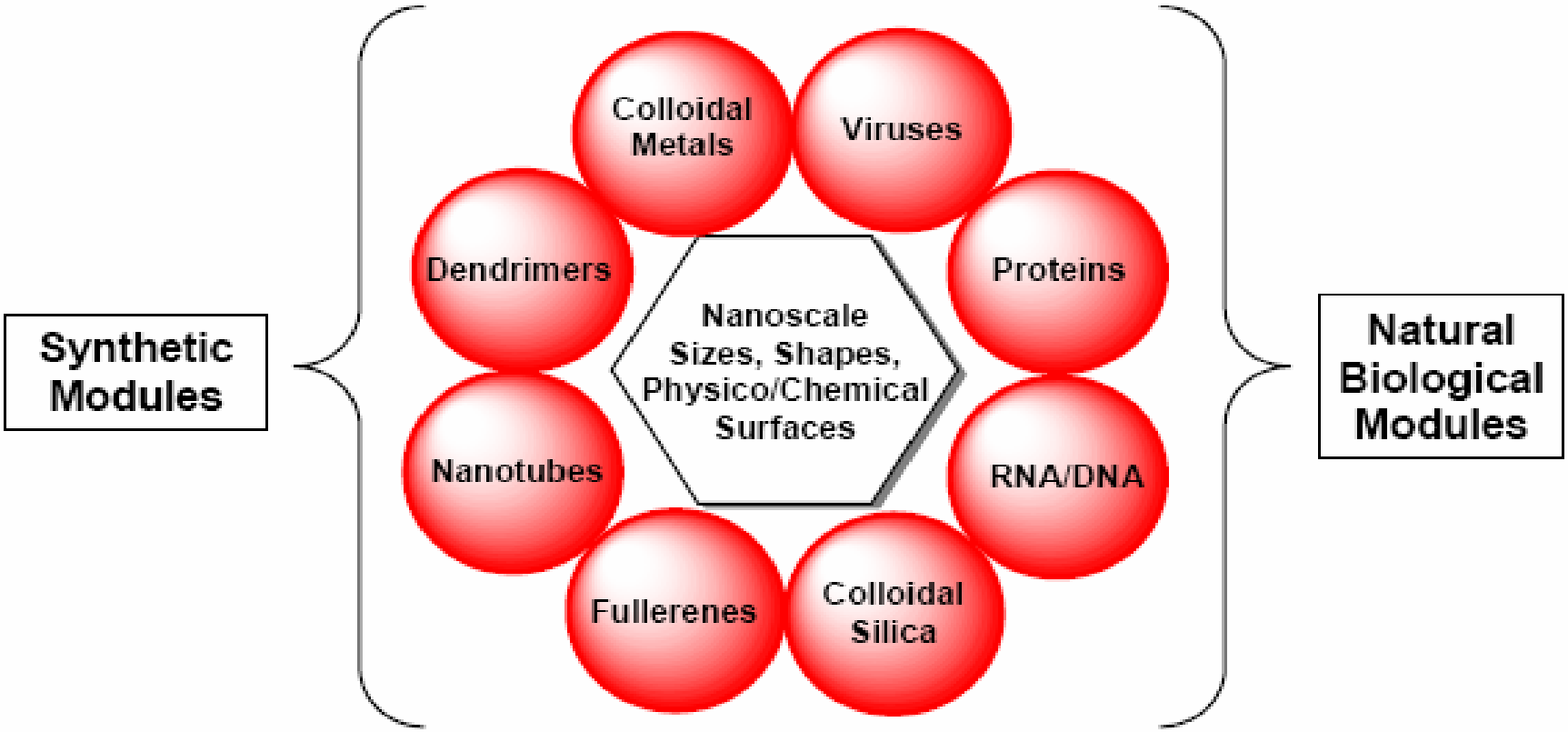
at dimensions of **roughly 1 to 100 nanometers**
(from atomic size to about 100 molecular diameters),

where **new phenomena** enable new applications
(where nanoscale modules are established).

Nanoscale modules / building bocks

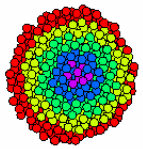
NATURAL THRESHOLD

from individual to collective behavior,
at the first level of organization of atoms and molecules



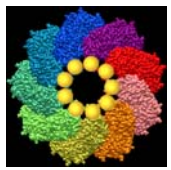
Five Generations of Products and Productive Processes

Timeline for beginning of industrial prototyping and nanotechnology commercialization (2000-2020; 2020-)



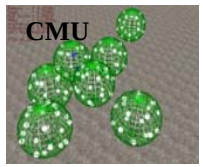
1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2000



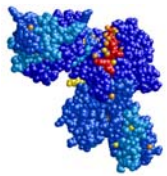
2nd: Active nanostructures Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures

~ 2005



3rd: Systems of nanosystems
Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

~ 2010



4th: Molecular nanosystems
Ex: molecular devices 'by design', atomic design, emerging functions

~ 2015-2020

5th: Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

New R&D challenges

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

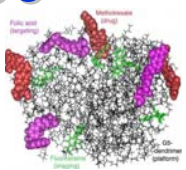
Reference: AIChE Journal, Vol. 50 (5), 2004

Perceived Higher Risks Areas (2000-2020; 2020-)

as a function of the generation of products

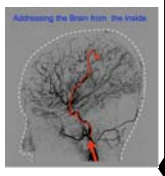
1st: Passive nanostructures *Ex: Cosmetics (pre-market tests), Pharmaceuticals (incomplete tests for inflammatory effects, etc.), Food industry , Consumer products*

~ 2000



2nd: Active nanostructures *Ex: Nano-biotechnology, Neuro-electronic interfaces, NEMS, Precision engineering, Hybrid nanomanufacturing*

~ 2005



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

~ 2010

?

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

~ 2015-2020

5th: Converging technologies *Ex: Hybrid nano-bio-info-medical-cognitive applic.*

Higher risk

Fifth generation - After 2020

NT convergence with bio, info and cogno,
and bifurcation of nanosystem architectures

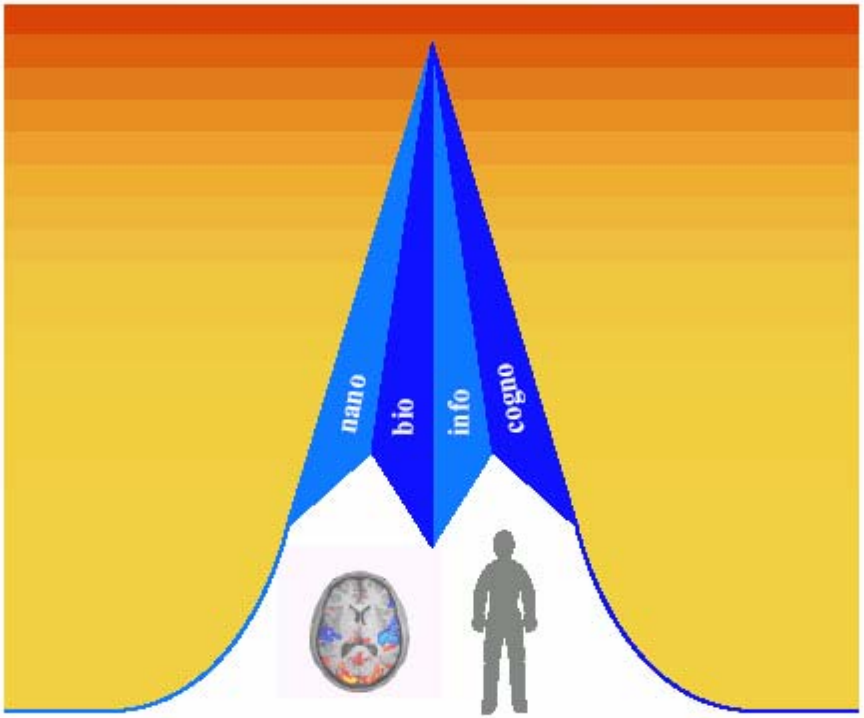
- Guided assembling
- Evolutionary
- Engineered molecular design and guided hierarchical selfassembling
- Robotics based
- Biomimetics . . . .

- ? New carrier of information instead of electron charge
- ? Manufacturing by nanomachines
- ? Extending human potential
- ? Collective cognitive capabilities . . . .

Fifth generation of nano products:

Four volumes on Convergence

2003, 2006 and 2007 Springer; 2004 NYAS



CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

Workshop, Dec. 2001

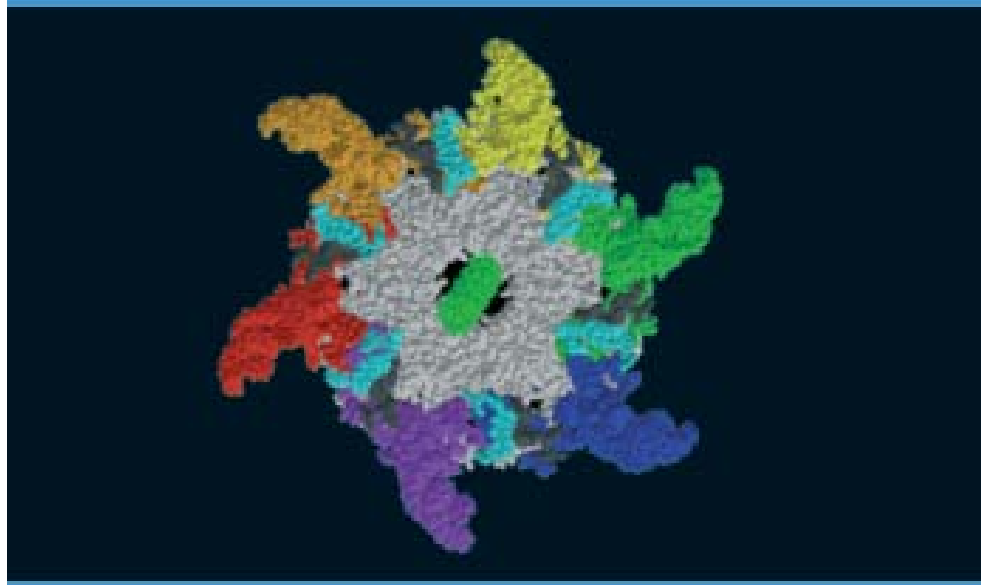
www.nsf.gov/nano

Springer, 2003

MANAGING NANO-BIO-INFO-COGNO INNOVATIONS

CONVERGING TECHNOLOGIES IN SOCIETY

MIHAIL C. ROCO AND WILLIAM SIMS BAINBRIDGE (EDS.)



Springer

November 2006

Expanding nanotechnology domains since 2000

2000-2001: nano expanding in almost all disciplines

2002-2003: industry moves behind nano development

2003-2004: medical field sets up new goals

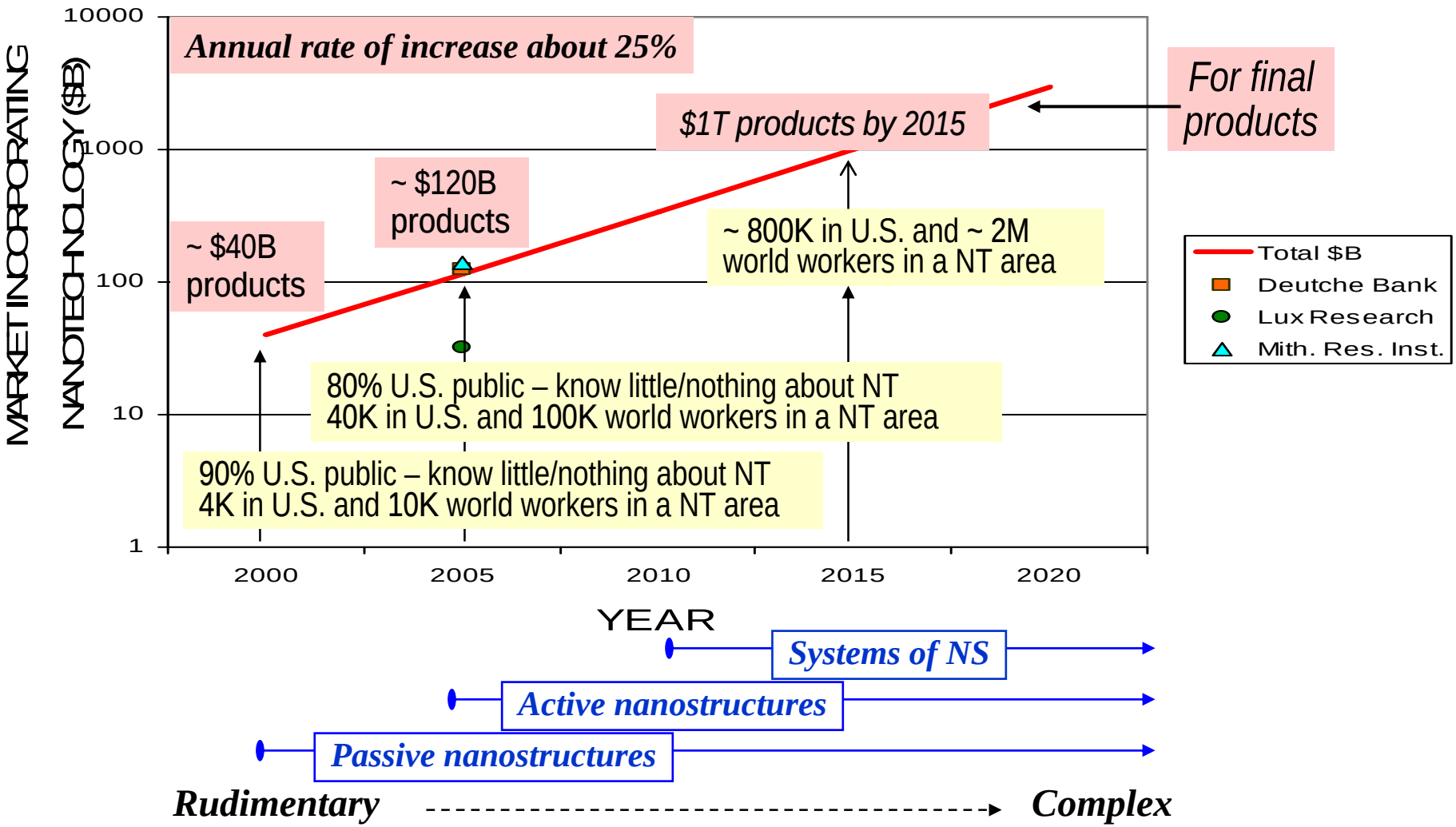
2004-2005: media, NGOs, public, international organizations get involved

2006-2007: new focus on common Earth resources - water, food, environment, energy, materials

2007-2008: increased relevance to economic-politic-military-sustainability

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY (2000-2015)

Estimation made in 2000 after international study in > 20 countries



Reference: Roco and Bainbridge, 2001

Changing research frontier focus

2000-2002

Nanoparticles, nanotubes, quantum dots, coatings

2003-2005

Self- and guided molecular assembling Expands nanobio technology and medicine

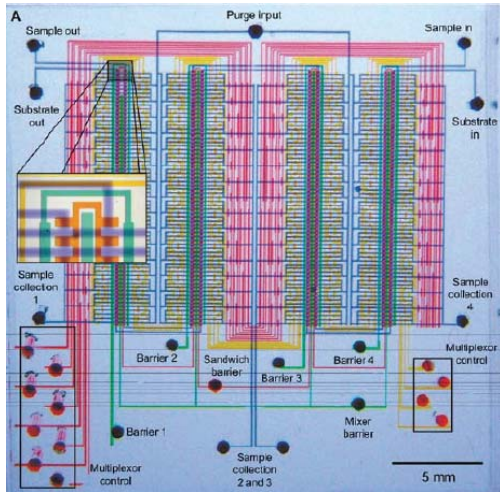
2006-2008

Focus on nanodevices and components of nanosystems

> *2008* from COMPONENT to SYSTEM NANOTECHNOLOGY

Challenges for Systems Nanotechnology

- Understanding mechanisms and patterns of system behavior as a function of components, interaction forces and networks at the nanoscale. Consider systems with large number of nano-components and non-linear interactions
- Tools for measuring, simulation and manufacturing of bio/engineering nanosystems
- Development of a new framework for risk assessment to address emerging functions of nanosystems with potential use in consumer products, medical treatments, food industry and other areas



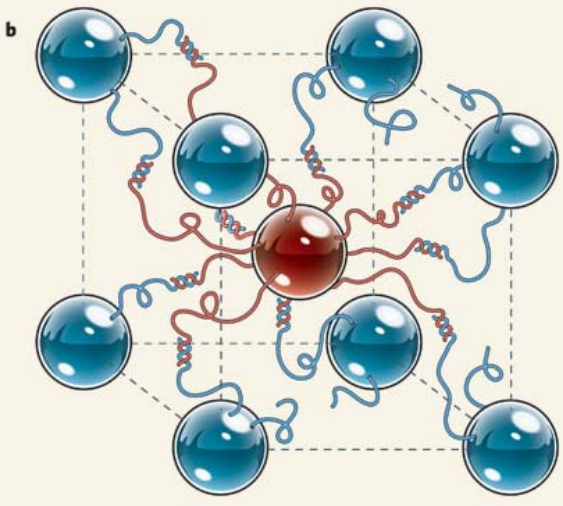
Integrated circuits that are smaller and faster are possible with microfluidics systems built from or incorporating nanocomponents. *Ferreira, UIUC, 0328162.*

Examples new topics in 2008

Nanodevices and components of nanosystems

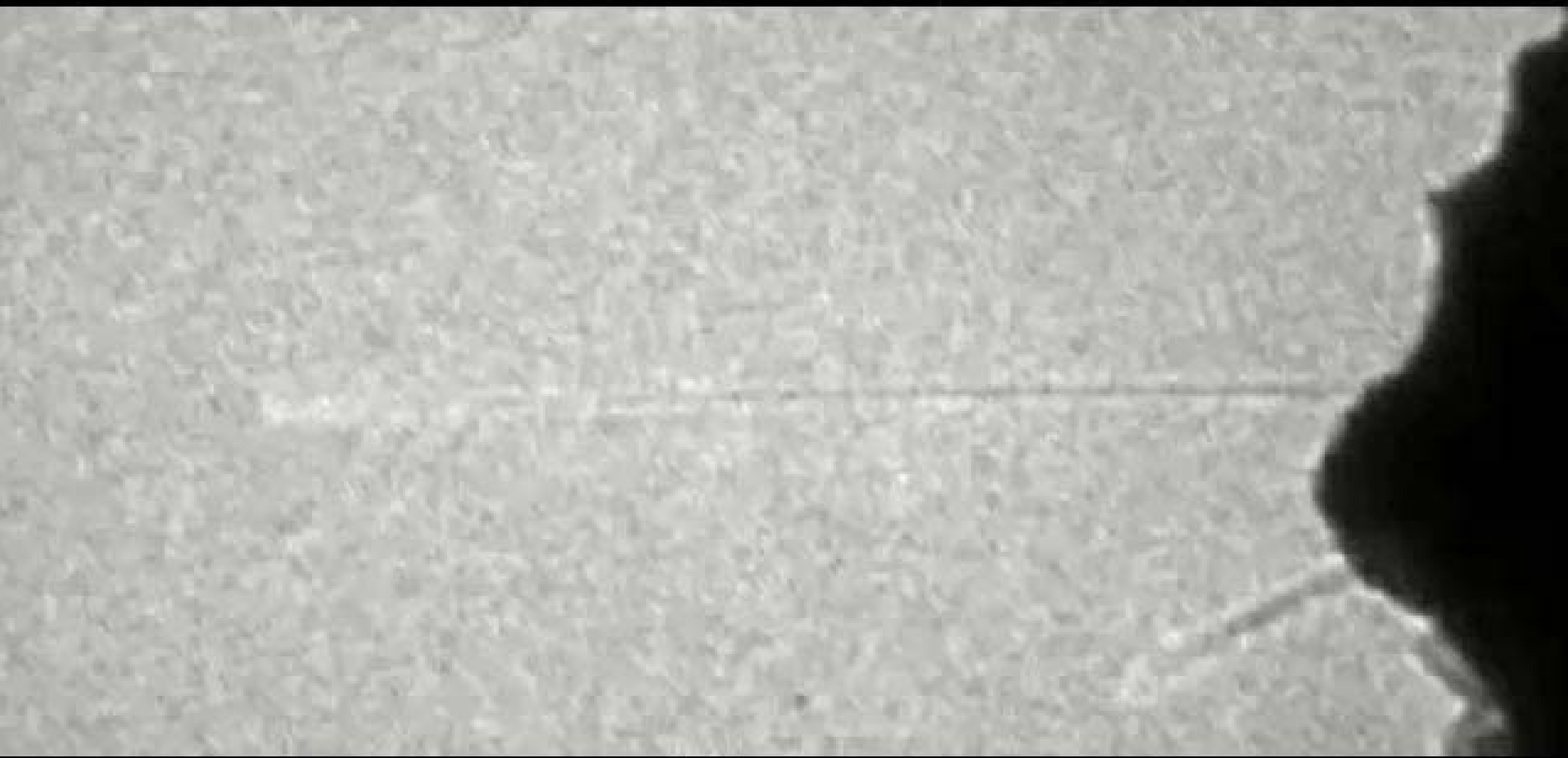
- A. Zettl (UCB), J. Rogers (U Illinois):
  nano radio = antenna, filter, amplifier
- IBM: **Manipulation with atomic precision**
- C. Mirkin (NU), O. Gang (BNL)
  Architectures for new, designed crystals

This image, taken by a transmission electron microscope, shows the carbon-nanotube radio (UCB)



Selfassembling of atoms through DNA strands

- Graphene to build electronic systems
- Informatics for nanosystem design
- Nanolayers for energy conversion
- Water filtration using nano membranes

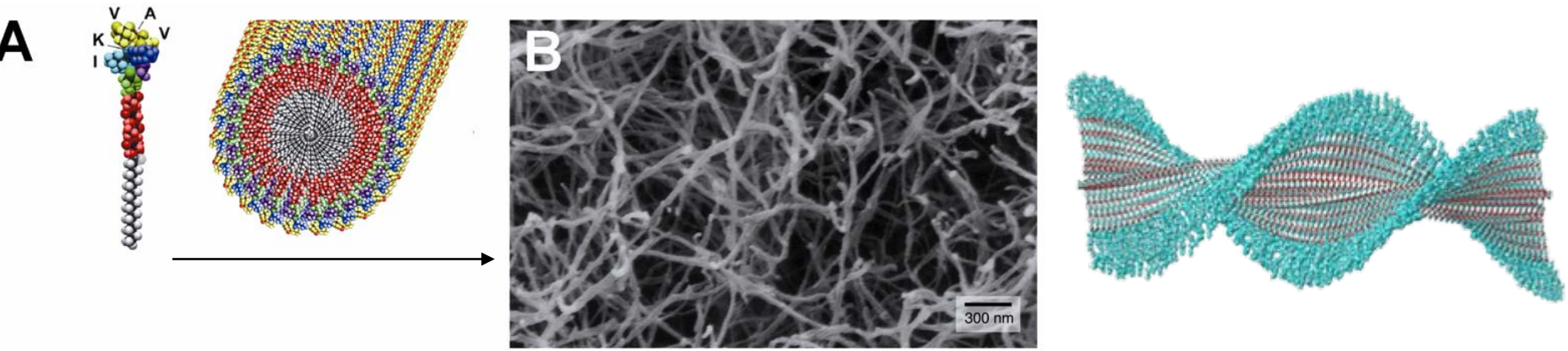


Nano radio (by Zettl Group, UCSB)

Example 4th generation (in research)

Designing molecules for hierarchical selfassembling

EX: - Biomaterials for human repair: nerves, tissues, wounds (Sam Stupp, NU)



- New nanomachines based on DNA architectures (Ned Seeman, Poly. Inst.)
- Designed molecules for self-assembled porous walls (Virgil Percec, U. PA)
- Self-assembly processing for artificial cells (Matt Tirrell, UCSB)
- Block co-polymers for 3-D structures on surfaces (U. Mass, U. Wisconsin)

Changing R&D infrastructure since 2000
Ex: US - NNI Infrastructure

- **Over 80 nanotechnology research centers, networks, and user facilities linked in a world-class interdisciplinary infrastructure**
- **Over 4500 active research projects in 2007 at over 500 universities, Government labs, and other research institutions in all 50 states**

Source: NNCO

NNI Networks and User Facilities

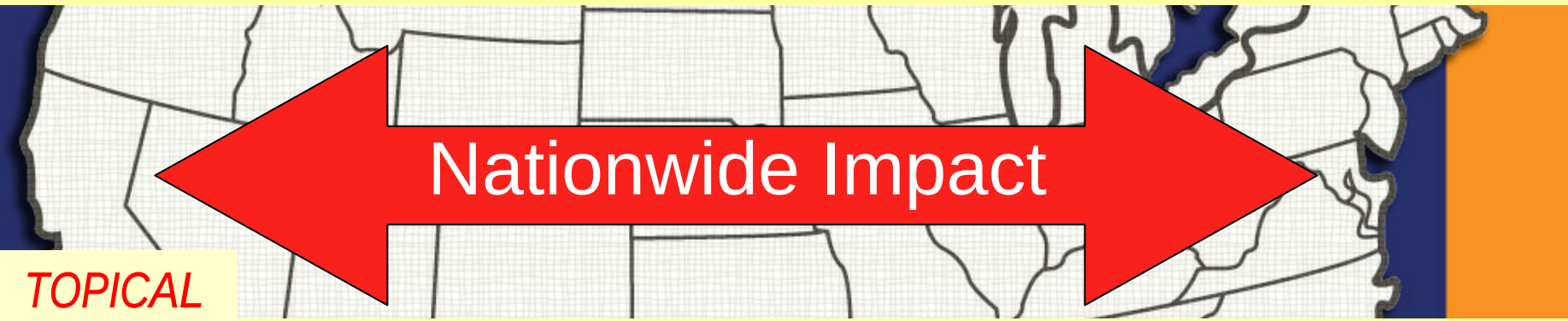
- NSF: eight networks with national goals and service
- NIH: four for medical research, cancer and metrology
- DOE: one network with five large facilities
- NASA: network of four centers on convergence
- DOD: three centers on nanoscience
- NIST: instrumentation and manufacturing user facilities
- NIOSH: particle characterization center

Nine Nanoscale Science and Engineering networks with national outreach

TOOLS

Network for Computational Nanotechnology (2002-) > *50,000 users/ 2007*

National Nanotechnology Infrastructure Network (2003-) *4,500 users/ 2007*



TOPICAL

Nanotechnology Center Learning and Teaching (2004-) *1 million students/ 5yr*

Center for Nanotechnology Informal 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

Environmental Implications of Nanotechnology (2008-) with EPA

GENERAL RESEARCH AND EDUCATION

NSEC Network (2001-) *17 research & education centers*

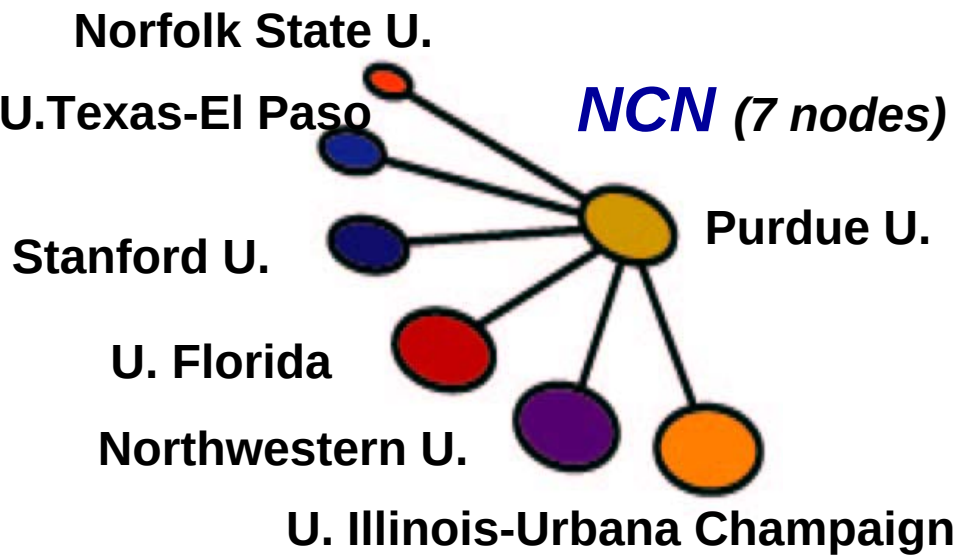
MRSEC Network (2001-) *6 new research & education centers since 2000*

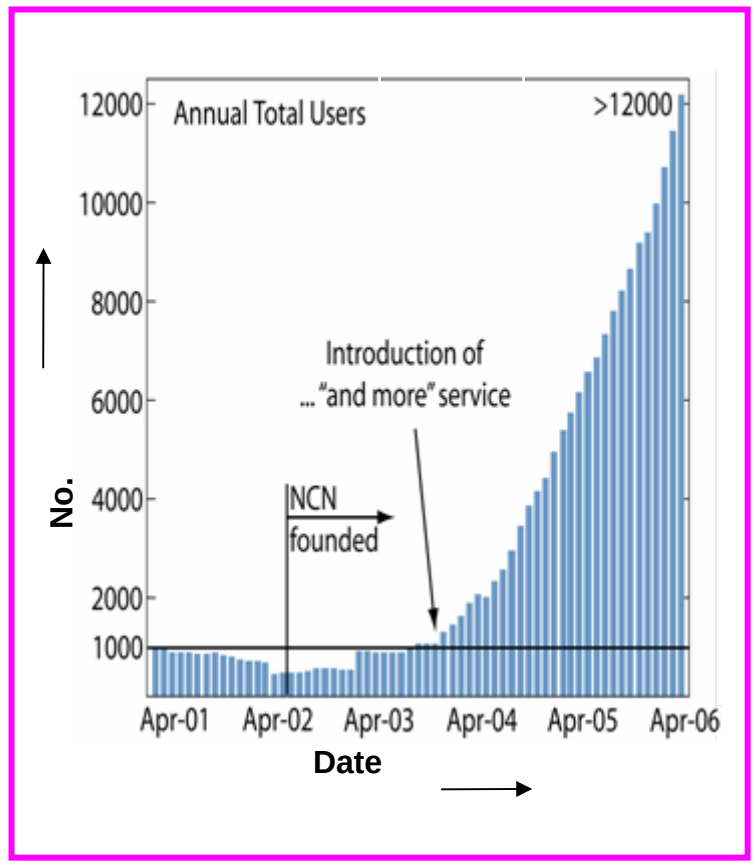
MC Roco, 4/18/2008

Network for Computational Nanotechnology

A national resource for research, education and user-facility

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





http://www.nanoHUB.org – Open-source

> 50,000 users / 2007; NSF cost ~ $100 / user

MC Roco, 4/18/2008

National Nanomanufacturing Network
Its core: Four Nanomanufacturing NSECs

- Center for Hierarchical Manufacturing (CHM)
  - U. Mass Amherst/UPR/MHC/Binghamton

CHM
Center for Hierarchical Manufacturing
University of Massachusetts Amherst

- Center for High-Rate Nanomanufacturing (CHN)
  - Northeastern/U. Mass Lowell/UNH

Center for High-rate Nanomanufacturing

- Center for Scalable and Integrated Nanomanufacturing (SINAM)
  - UC Berkeley/UCLA/UCSD/Stanford/UNC Charlotte

SINAM
CENTER FOR SCALABLE AND INTEGRATED NANOMANUFACTURING

- Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS)
  - UIUC/CalTech/NC A&T

Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems

Open-access network
www.nanomanufacturing.org *beta.internano.org*

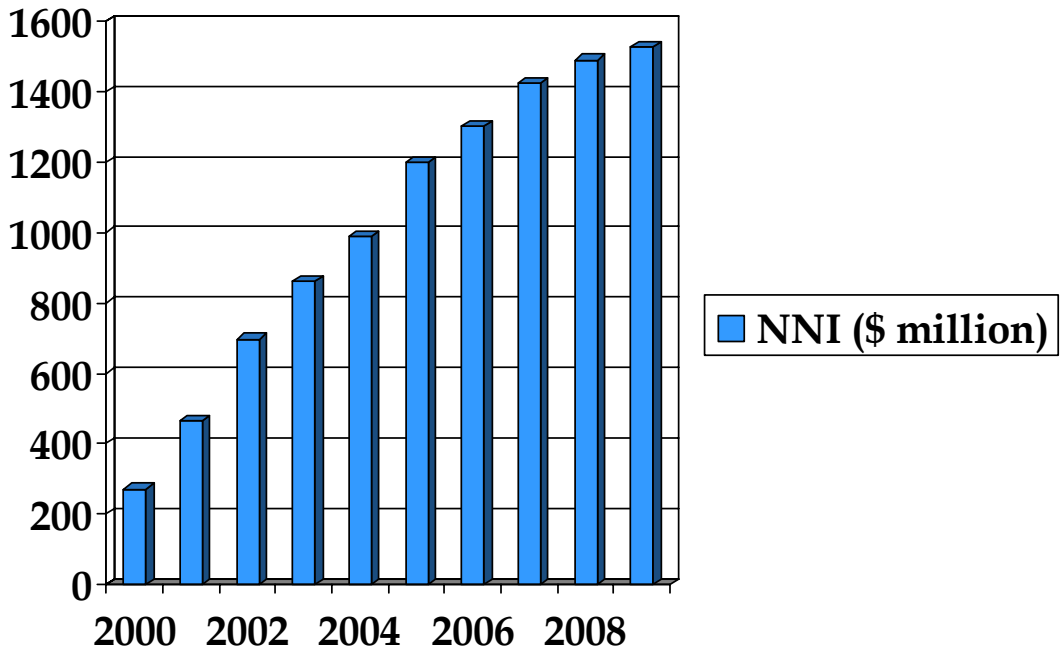
National Nanomanufacturing Network

Changing national investment

FY 2009 NNI Budget Request - $1,527 million

MC Roco, 01/10/2008

Fiscal Year	NNI
2000	$270M
2001	$464M
2002	$697M
2003	$862M
2004	$989M
2005	$1,200M
2006	$1,303M
2007	$1,425M
2008	$1,491M
R 2009	$1,527M



EHS 2006: $38M (primary; $68M total eff.)
2007: $48M (primary; $86M total est.)
2008: $57M (primary; $102 total est.)
2009: $76M (primary - planned)

NNI / R&D ~ 1/4 of the world R&D

NNI / EHS > 1/2 of the world EHS R&D

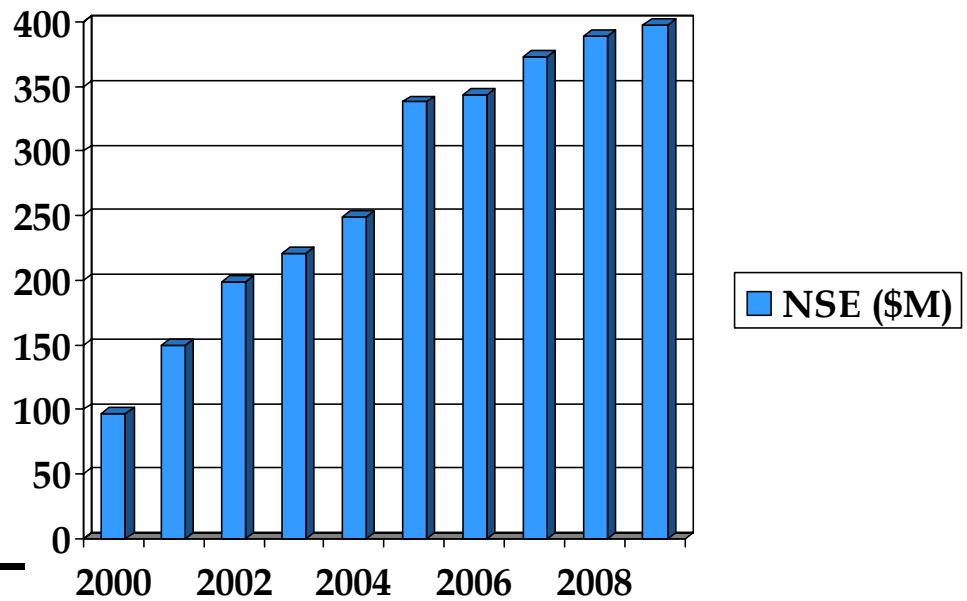
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

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

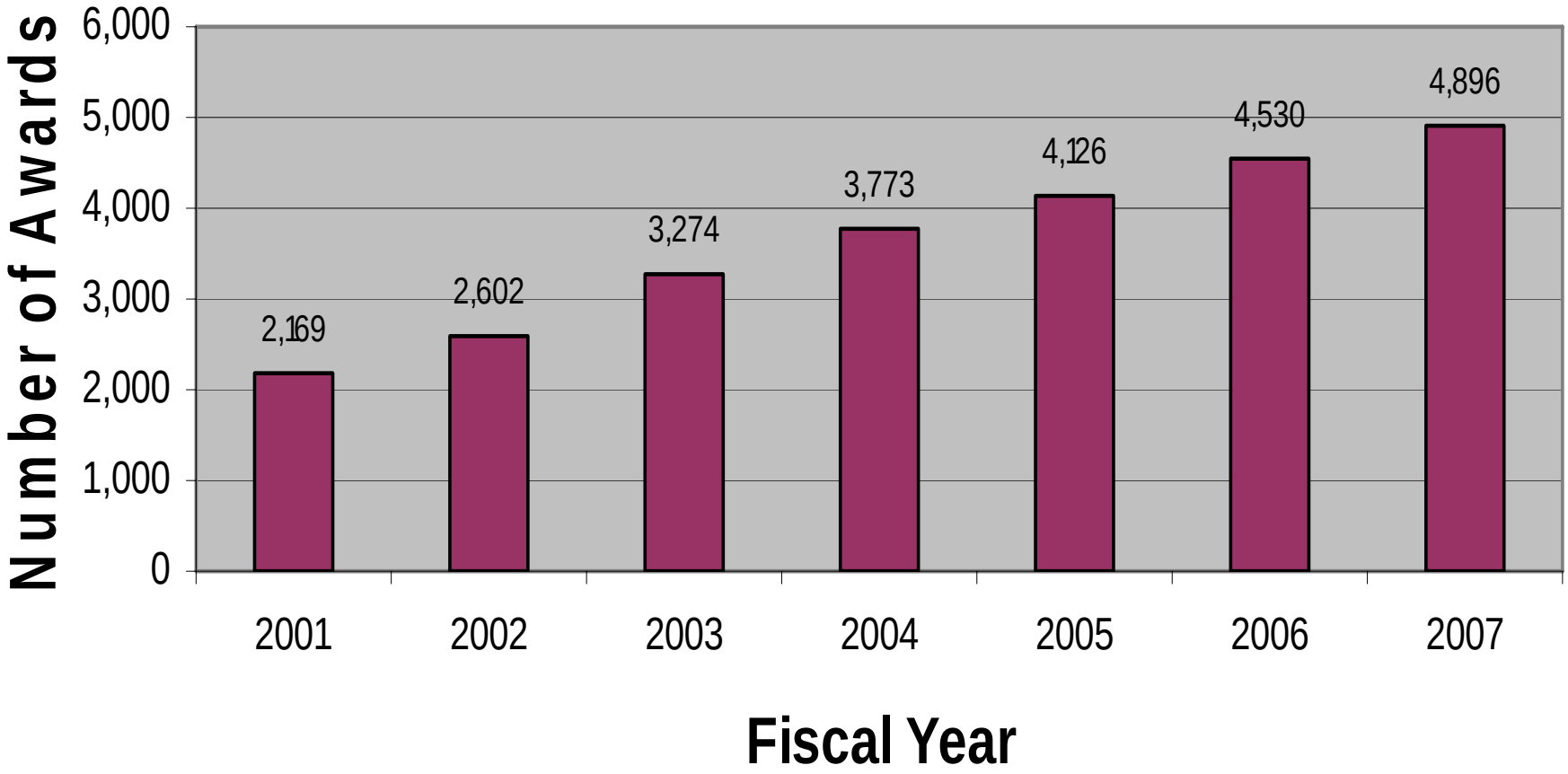
FY 2009 Request: $397M ~1/4 of Federal and ~1/12 of World Investment

- Fundamental research - new priorities as compared to 5 years ago
- Establishing the infrastructure - over 4,000 active projects; 24 large centers, 3 user facilities (NNIN, NCN, NNN), multidisc. teams
- Training and education – over 10,000 students and teachers/yr

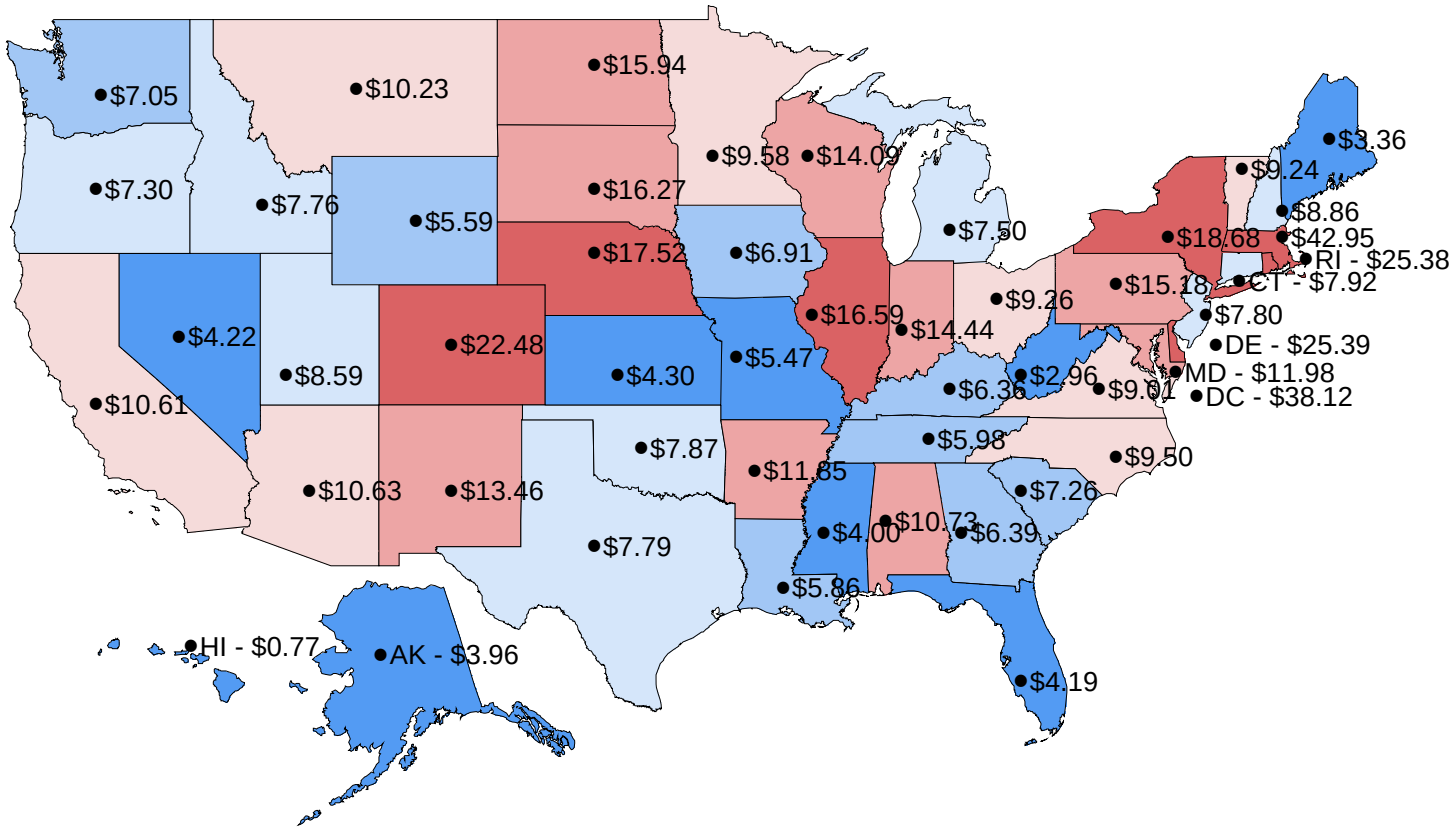
Fiscal Year	NSF
2000	$97M
2001	$150M
2002	$199M
2003	$221M
2004	$254M
2005	$338M
2006	$344M
2007	$373M
2008	$389M
R 2009	**$397M**



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



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



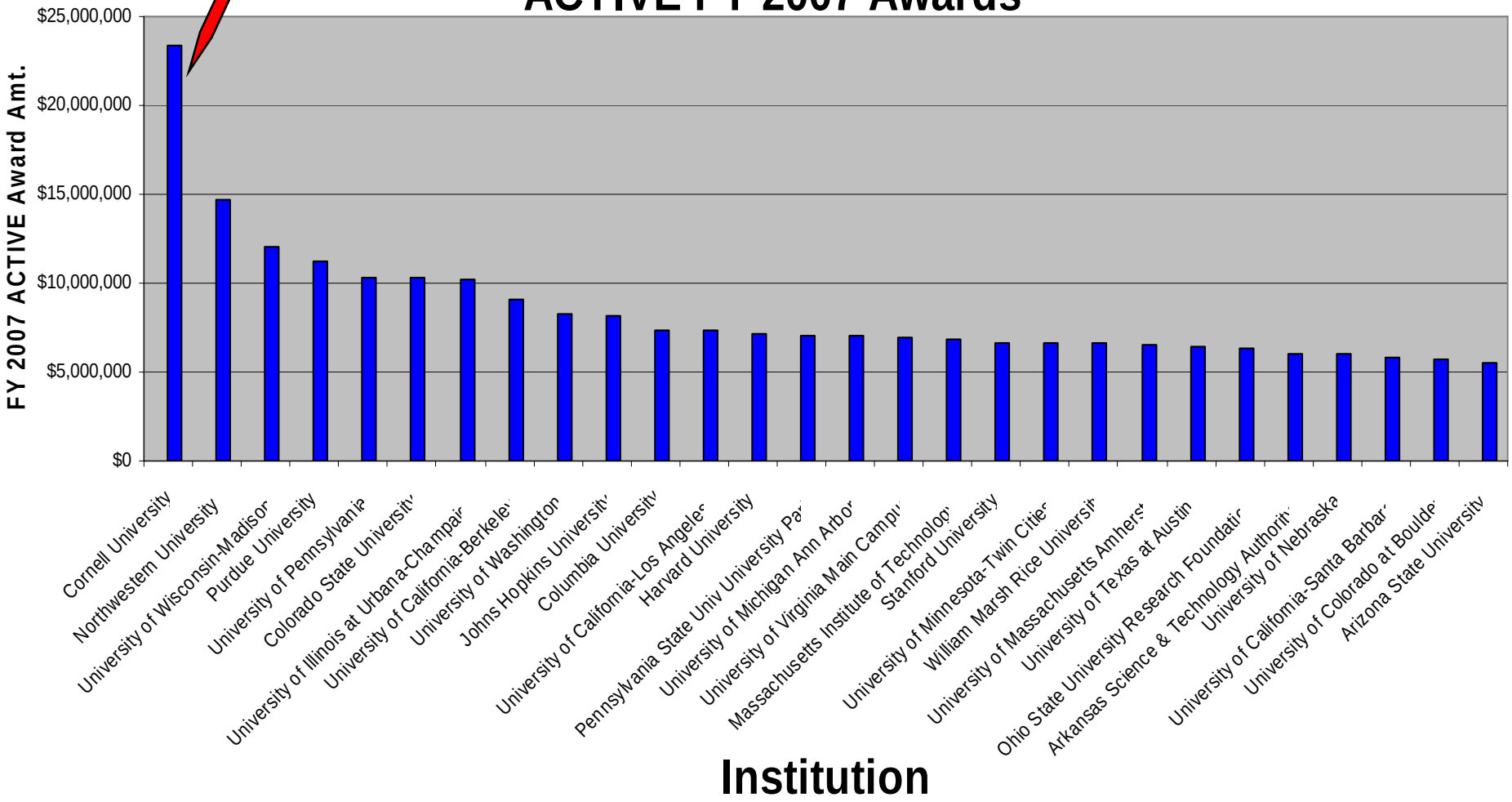
State	NEW FY 2001-2007	$ Per Capita	Rank
MA	$272,681,724	$42.95	1
DC	$21,804,945	$38.12	2
DE	$19,893,702	$25.39	3
RI	$26,604,737	$25.38	4
CO	$96,677,354	$22.48	5

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, 4/18/2008

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



M.C. Roco, 4/18/2008

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

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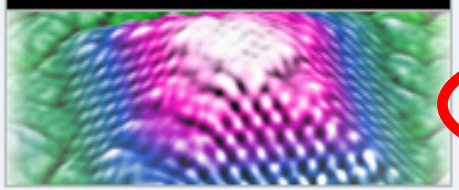
National Science Foundation
WHERE DISCOVERIES BEGIN

www.nsf.gov/nano
or link www.nano.gov

HOME | FUNDING | AWARDS | DISCOVERIES | NEWS | PUBLICATIONS | STATISTICS | ABOUT | FastLane

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

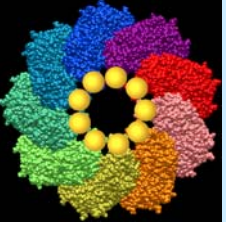
NSF press releases on Nanotechnology Research from 2003 to 2001

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

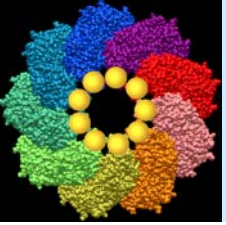


NNI Accomplishments (1)

- Developed foundational knowledge for control of matter at the nanoscale:
  about 4,000 active projects in > 500 universities, private sector institutions and gov. labs in all 50 states
- "Created an interdisciplinary nanotechnology community" [1]
- R&D / Innovation Results: With ~25% of global government investments, the U.S. accounts worldwide for
  - ~ 50% of highly cited papers,
  - ~ 60% of USPTO patents[2], and
  - ~ 70% of startups[3] in nanotech.

  Over 2,000 U.S. nanotech companies in 2006;
  ~ $60B products incorporating essential nano components
- Infrastructure:
  over 80 new large nanotechnology research centers, networks and user facilities; five large networks of user facilities

([1]) NSF Committee of Visitors; ([2]) Journal of Nanoparticle Research, 2006; ([3]) NanoBusiness Alliance, 2006



NNI Accomplishments (2)

- Partnerships: with industry (Consultative Boards for Advancing Nanotechnology - CBAN), regional alliances (25), international (over 30 countries), numerous professional societies
- Societal implications and applications - since 2000, about 15% of NSF / NNI budget has relevance to environmental health, and safety, and other societal and educational concerns; NNI estimates ~ $100 million in FY 2008 (primary/secondary)
- Nanotechnology education and outreach - impacting over 10,000 graduate students and teachers in 2007; expanded to undergraduate and high schools, and outreach; create national networks for formal and informal education
- Global outreach: The U.S. NNI has catalyzed global activities in nanotechnology and served as a stimulus for other programs.

Industry-academe-government R&D partnerships for common goals

- Increased role of industry in funding nanotechnology R&D ; changes in gov. funding
- Special role of local governments for infrastructure, education and small business
- Global partnerships for nanotechnology knowledge, markets and organizations
- Cross-industry R&D consortia

NNI-Industry Consultative Boards for Advancing Nanotech

Key for development of nanotechnology, Reciprocal gains

- **NNI-Electronic Industry (SIA/SRC lead), October 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), 2004-**
  - **Joint activities in R&D technology management**
  - **2 working groups (nanotech in industry, EHS)**
  - **Exchange information, use NNI results, support new topics**

- **NNI-Biotechnology (BIO lead), October 2004-**
  - Collaborative activities in key R&D areas
  - 2 working groups, R&D collaboration and EHS; joint funding

Changing international context since 2000

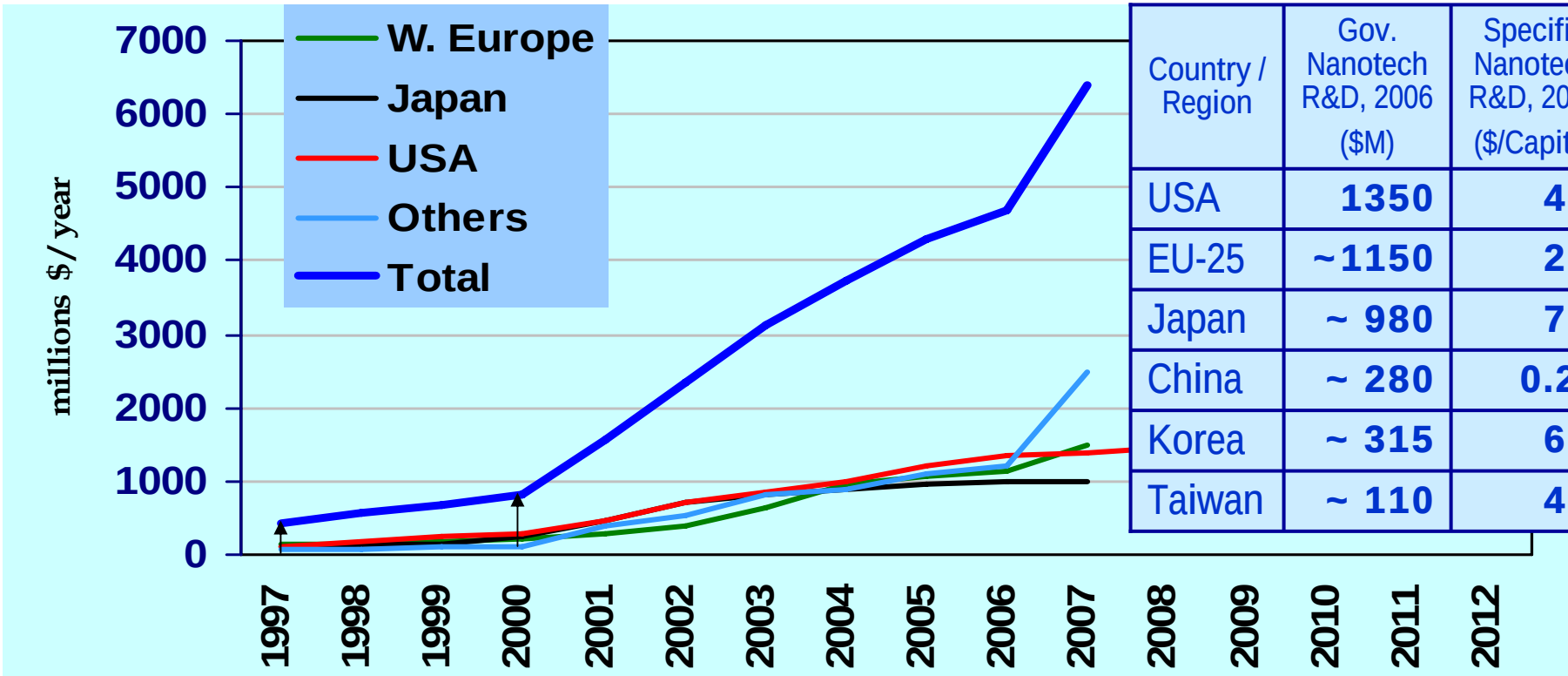
~ *2000*: Focus on discovery , 'wait & see' if applied

> *2005*: Nano as a technological, economical and strategic advantage for nations and large businesses

Expanding open-source
horizontal growth
communication
governance

Context – Nanotechnology in the World

National government investments 1997-2007 (estimation 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)

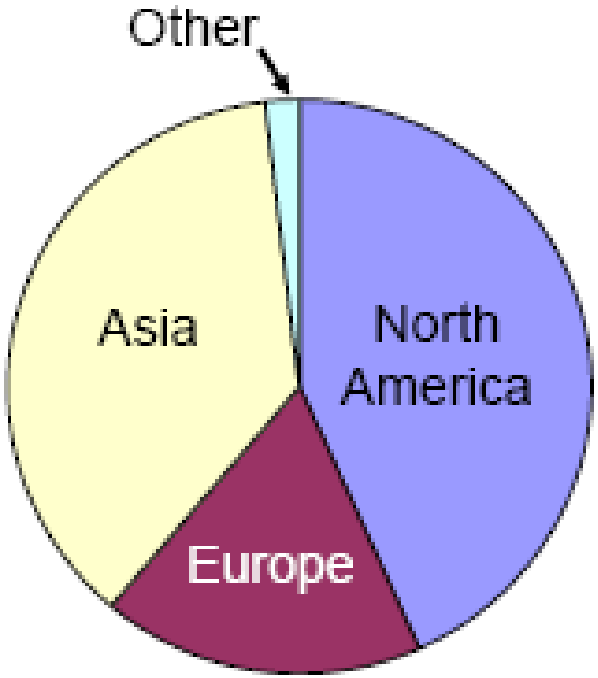
1st Strategic Plan (passive nanostructures)

2nd Strategic Plan (active ns. & systems)

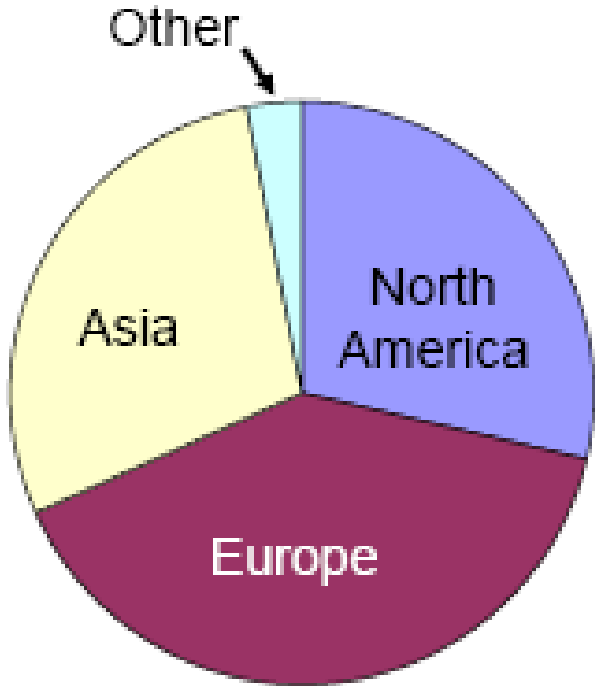
Industry R&D ($6B) has exceeded national government R&D ($4.6B) in 2006

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

Growing nanotechnology R&D investment - $12.6 billion in 2006



Private (Corp. + VC)
Total = $6 billion

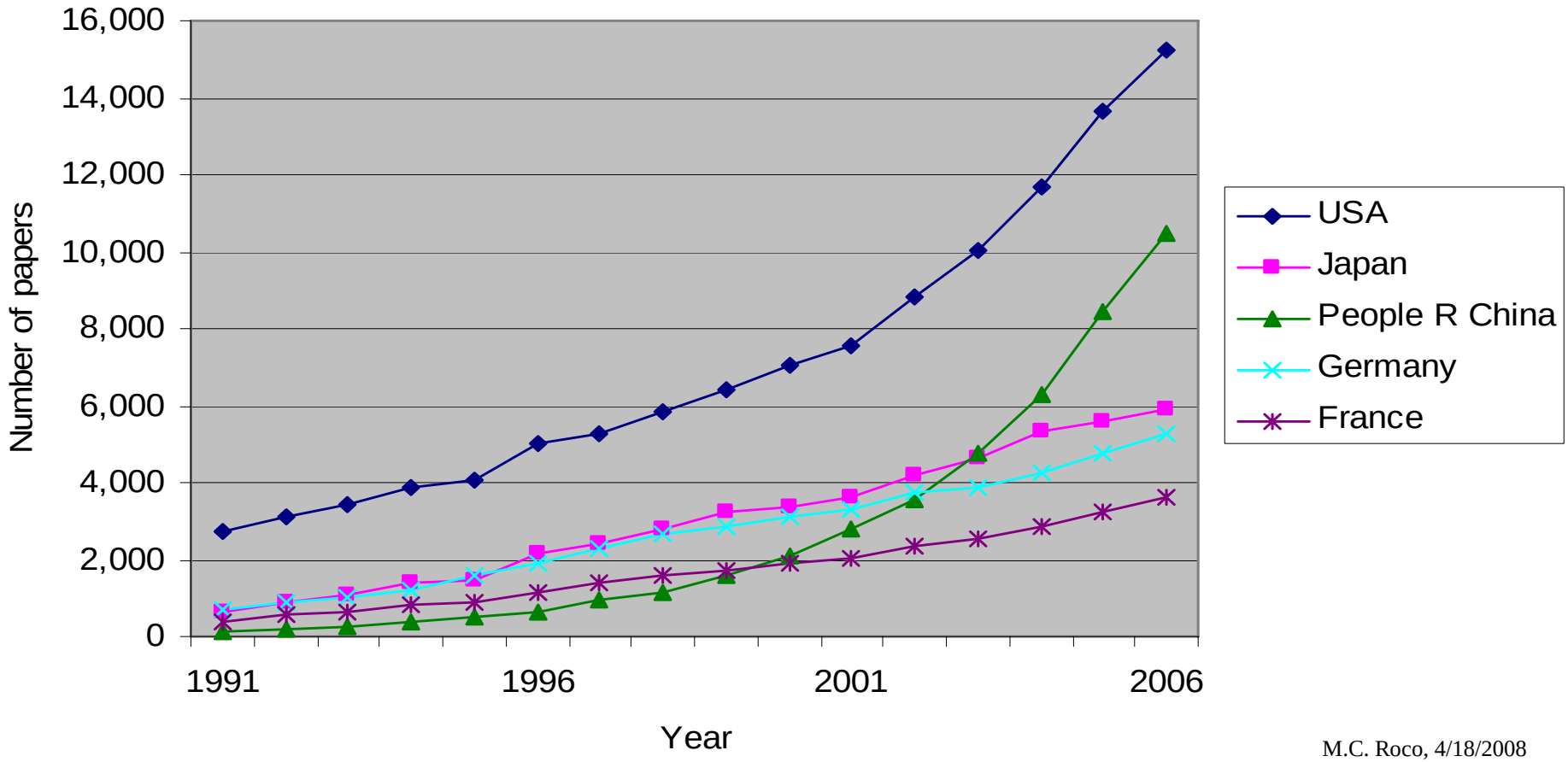


Public (National, regional, state)
Total = $6.4 billion

National governments ~ $4.6 billion
Local governments and organizations ~ $1.8 billion

Source: Lux Research

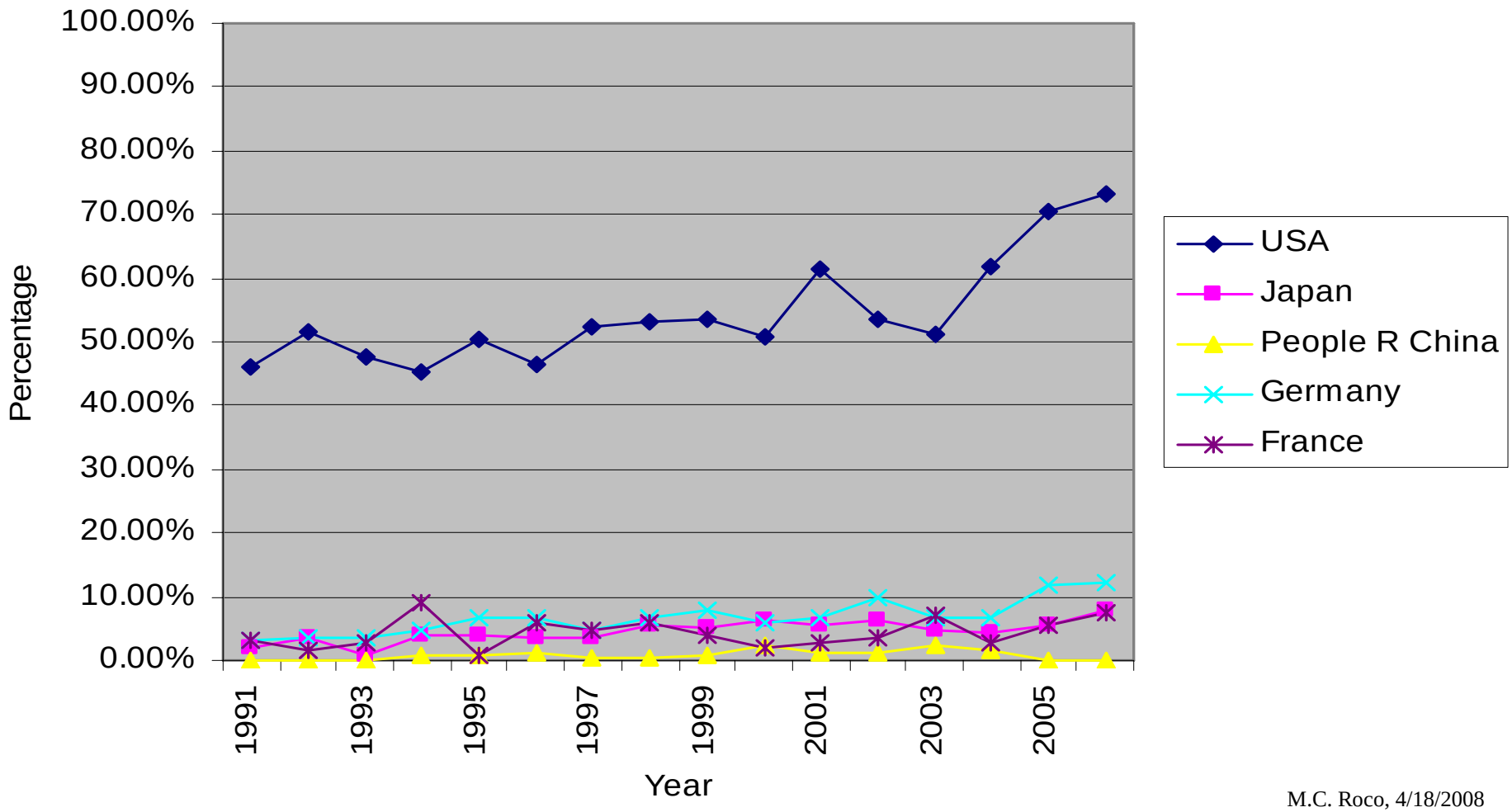
Nanotechnology research publications
Top five countries in 2006: USA, China, Japan, Germany, France
using “Title-claims” search in SCI database for nanotechnology by keywords
(using intelligent search engine, update J. Nanoparticle Research, 2004, 6 (4))



M.C. Roco, 4/18/2008

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

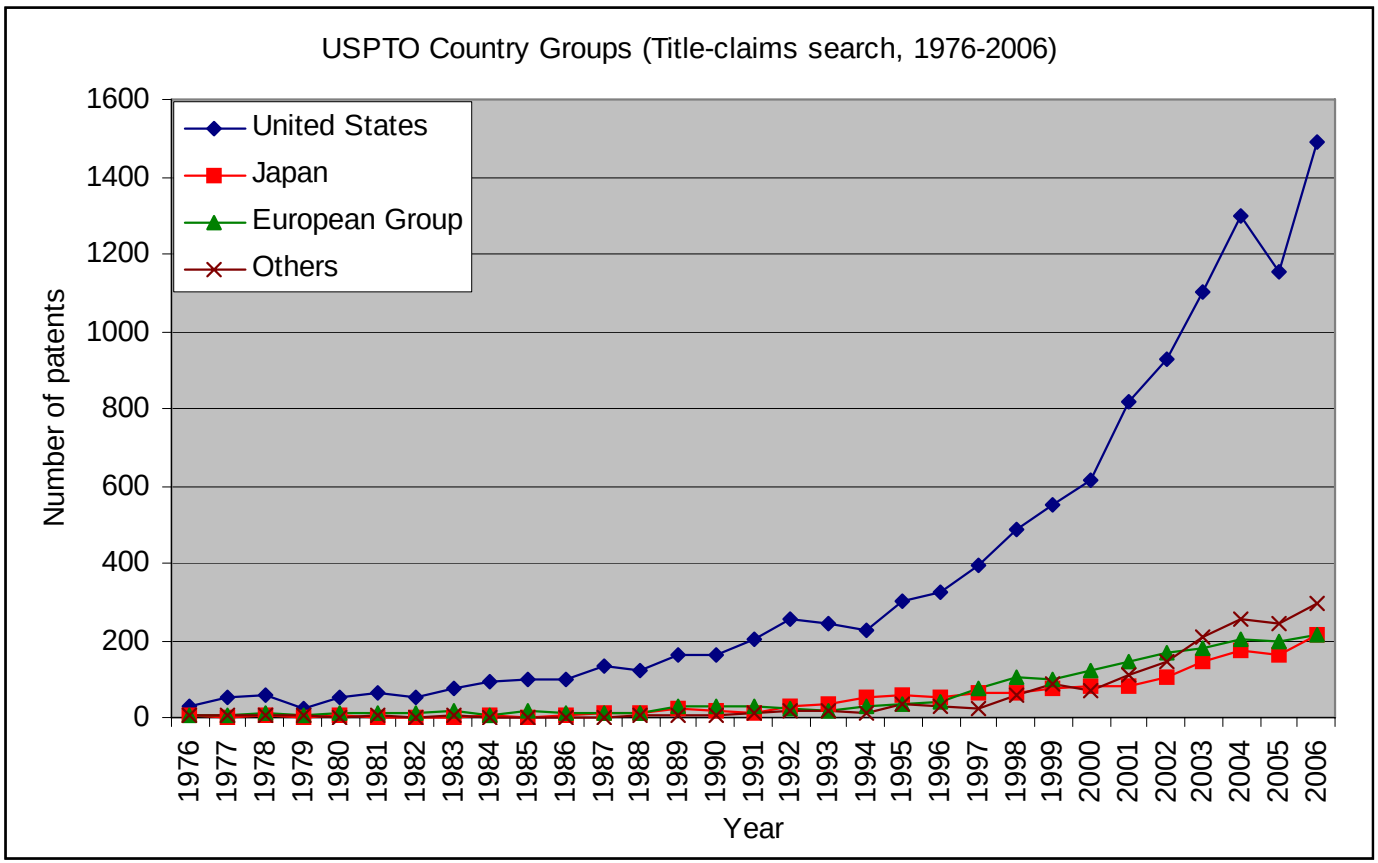
using "Title-abstract" search in SCI database for nanotechnology by keywords (using intelligent search engine, update J. Nanoparticle Research, 2004, 6(4))



M.C. Roco, 4/18/2008

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

M.C. Roco, 4/18/2008

U.S. International partnerships for Nanotechnology

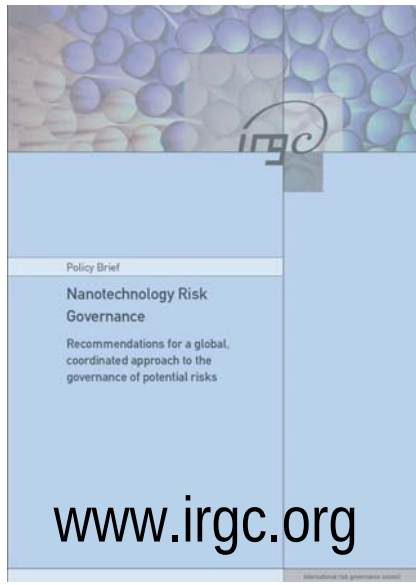
- Nanotechnology included in bilateral (e.g. U.S.- Japan, EU, India, etc.), and international organizations (e.g. OECD, APEC, etc.) S&T agreements
- Typical NSF activities
  - Bottom-up by individual partnerships in research
  - Periodical NanoForums (annual); other workshops
  - Using networks: NNIN / NCN and partner networks / facilities
  - Young scientists exchange programs
- Areas and modes of increased collaboration:

- fundamental knowledge (precompetitive) - *by twinning and networking*
- education - *by visits, int. courses, books, int. accreditation, study institutes*
- broad societal implications: health, environment, energy, water filtration, ethics - exchanges
- contribute to international S&T "grand challenges"
- industry partnerships, precompetitive nanotechnology platforms

Changing public perception and governance since 2000

Before 2000: Is anything special at nanoscale?
Is nanotechnology important?
When the first products?

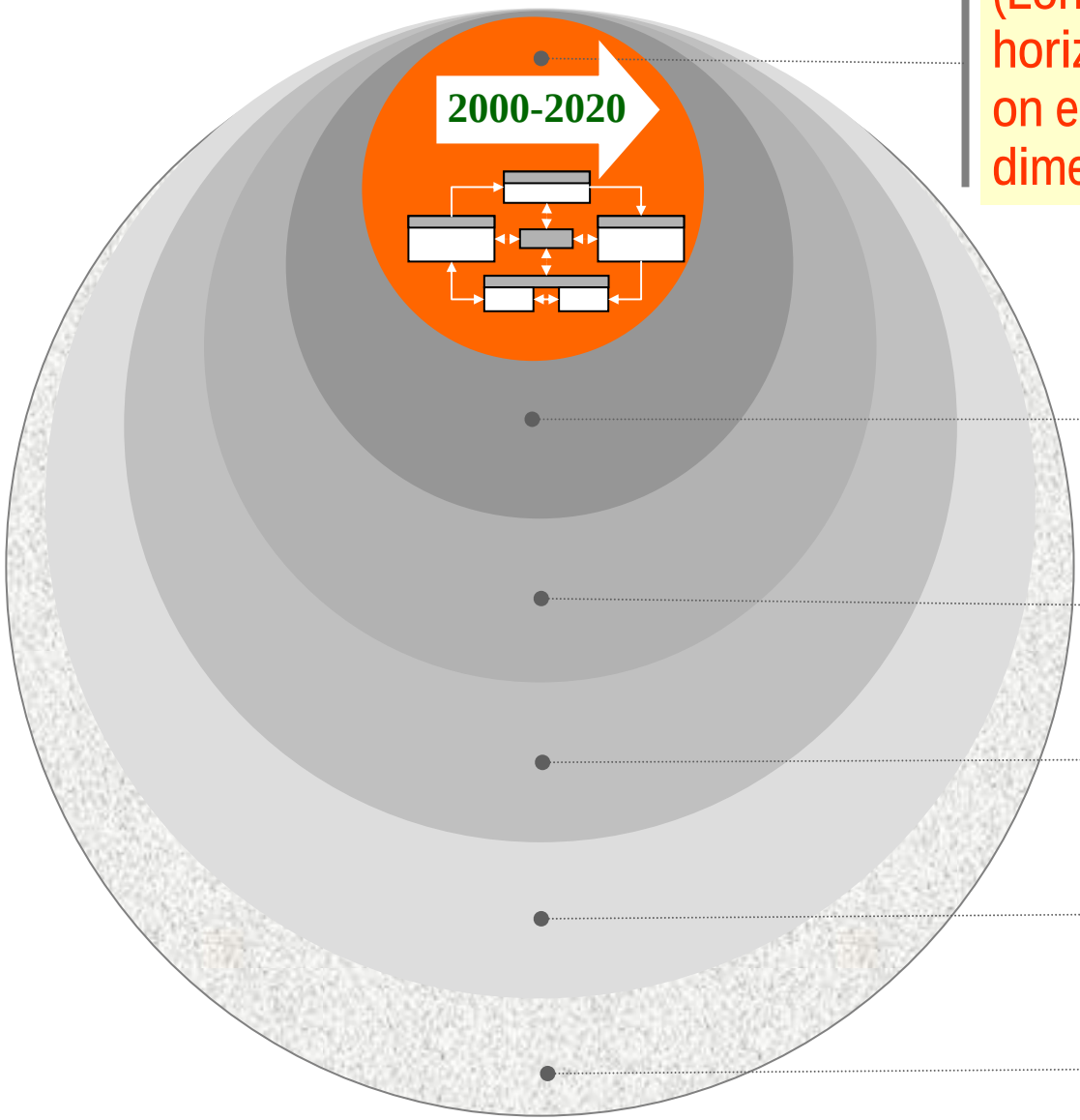
2000-2003: Are there self-duplicating nano-bots?



> *2003*: What are the risks of "long-term / catastrophic environmental and health events" of nanoparticles?

> *2005*: Nanotechnology can help sustainable management of global resources (water, energy, ..)
Concern on using nanotechnology in food, others

NANOTECHNOLOGY GOVERNANCE OVERVIEW



Core Governance Process
(Long-term view, transforming, horizontal/vertical, inclusive, priority on education, addressing societal dimensions, risk governance)

R&D Organizations
(Academe, industry, gov.)

Implementation Network
(Regulators, business, NGOs, media, public)

Social Climate
(Perceived authority of science, civil involvement)

National Political Context

International Interactions

Reference: "NNI: Past, Present Future", Handbook of Nanoscience, Eng. and Techn., MC Roco., Taylor and Francis, 2007

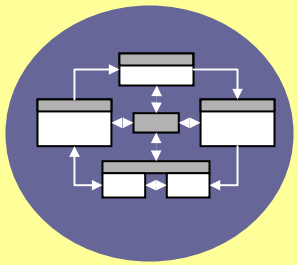
NT Governance and Risk Governance

2000-2020

NT
GOVERNANCE

- Investment policy
- Science policy
- Risk governance
- Others

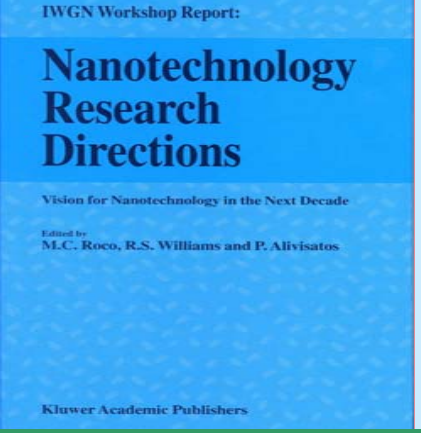
Four key functions



NANOTECHNOLOGY
RISK
GOVERNANCE (IRGC)

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

Societal Implications (II)

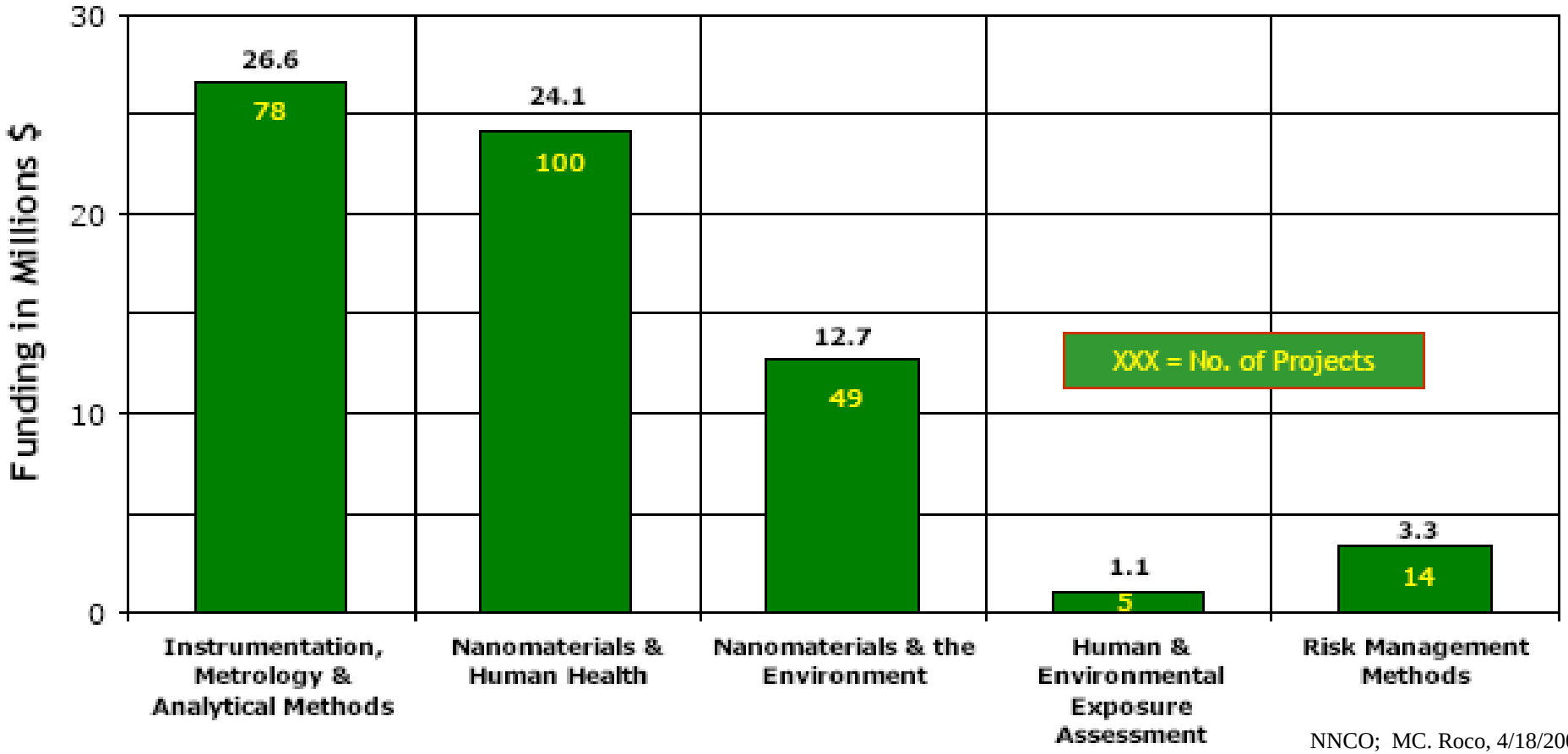


Inclusive: industry, academe, government

Participants in the National Nanotechnology Initiative

Overview of NNI EHS funding in 2006

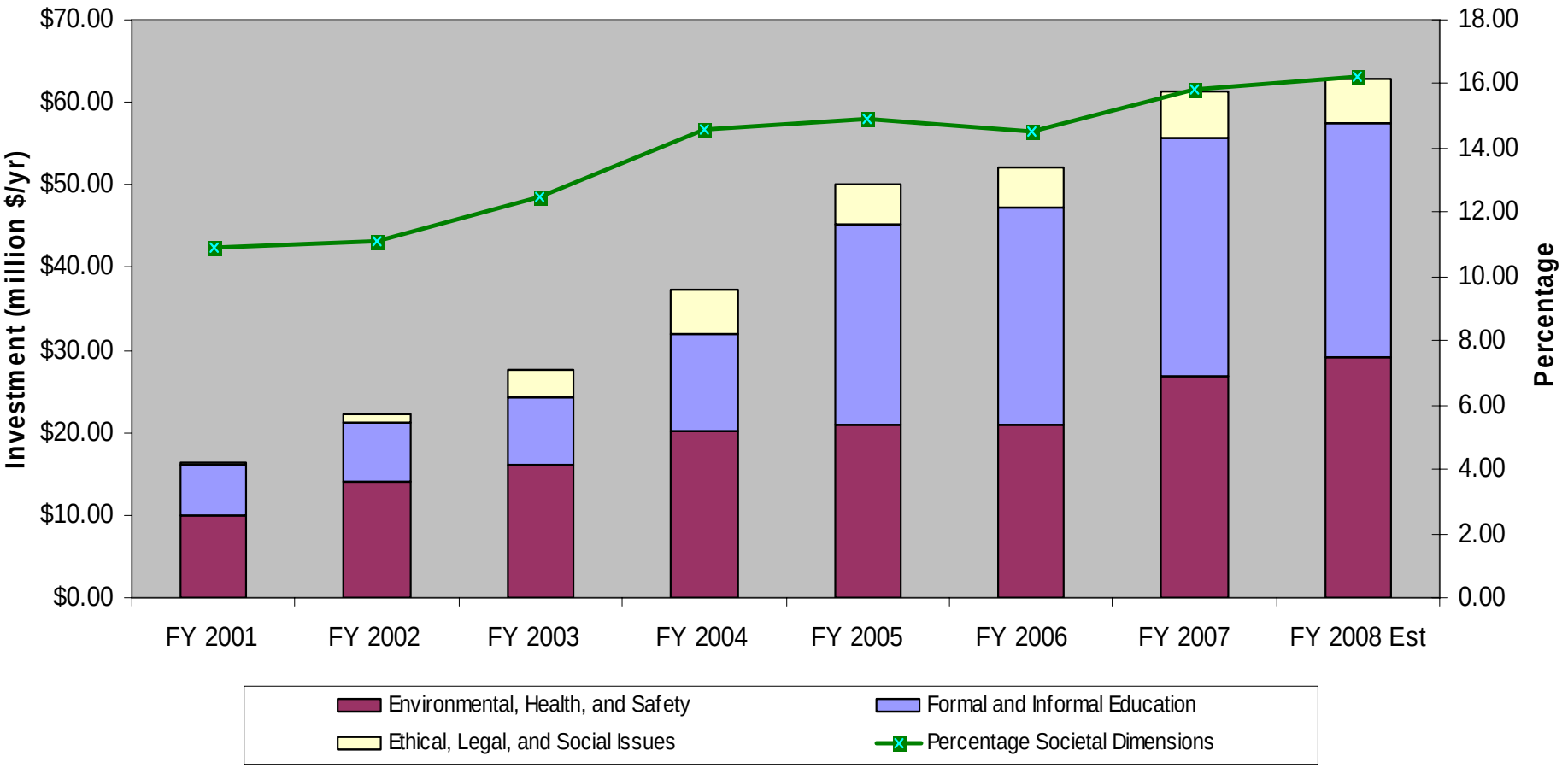
- $68 million funding for 246 nanotechnology-related EHS research projects at seven NNI member agencies
- *Consensus among NEHI Working Group that instrumentation, metrology, and analytical methods category is cross-cutting and generally a high priority*



NSF Investment in Societal Dimensions of NT

Of FY 2008 NNI / NSF of $390 M, $63 M or 16.2% is for SI, and $29.2 M (7.5%) for nano EHS

New NSEC in 2008: Environmental Implications of Nanotechnology (NSF, EPA)



Five possibilities for global nanotechnology governance

1. *Establish models for the global self-regulating ecosystem* to enhance discovery, education, innovation, nanoinformatics and commercialization
2. *Create and leverage S&T nanotech platforms* for new products in areas of highest societal interest
3. Develop NT for *common resources and EHS requirements*
4. Support *global communication and international partnerships*, facilitated by international organizations
5. Commitment to *long-term, priority driven, global view* using scenarios and anticipatory measures

Reference: "Global Governance of Converging Technologies", MC Roco, J. Nanoparticle Research, 2008, 10 11-29