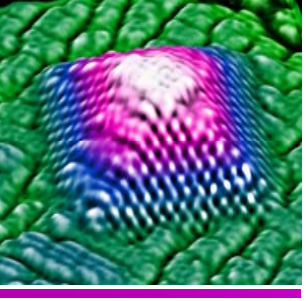
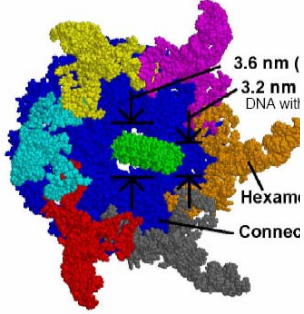
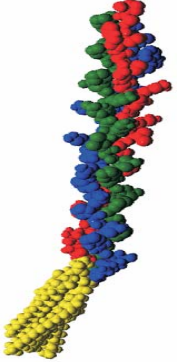
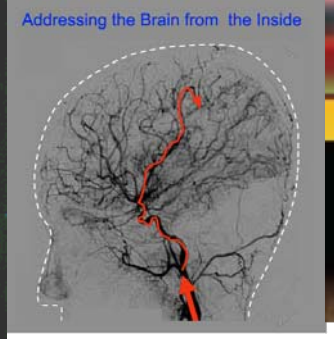
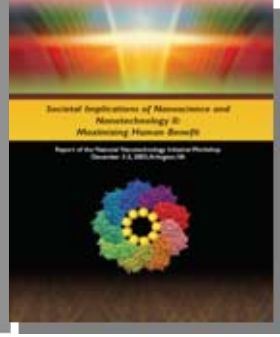










Long View for Nanotechnology R&D at NSF and NNI

M.C. Roco

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

INC3, Brussels, April 16, 2007

Benchmark with experts in over 20 countries

"Nanostructure Science and Technology"

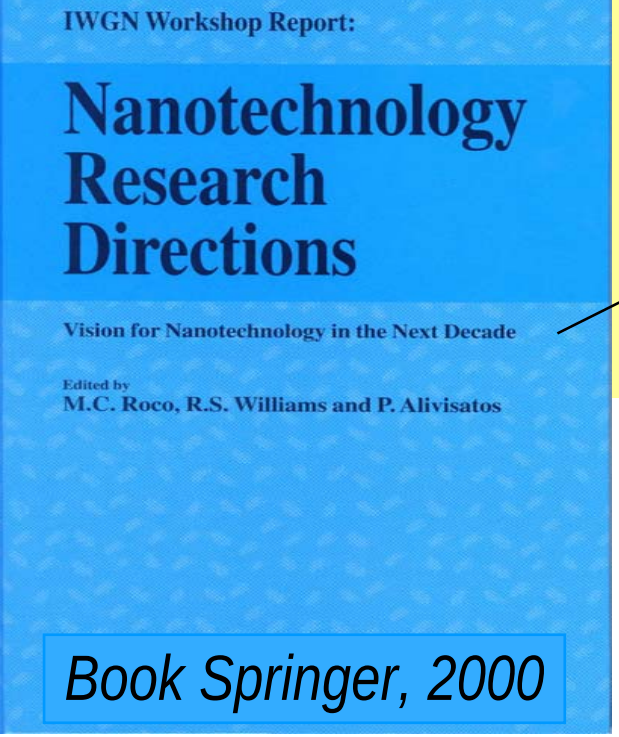
Book Springer, 1999

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.



Book Springer, 2000

Nanotechnology discovery

"Vision for nanotechnology in the next decade" (2001-2010)

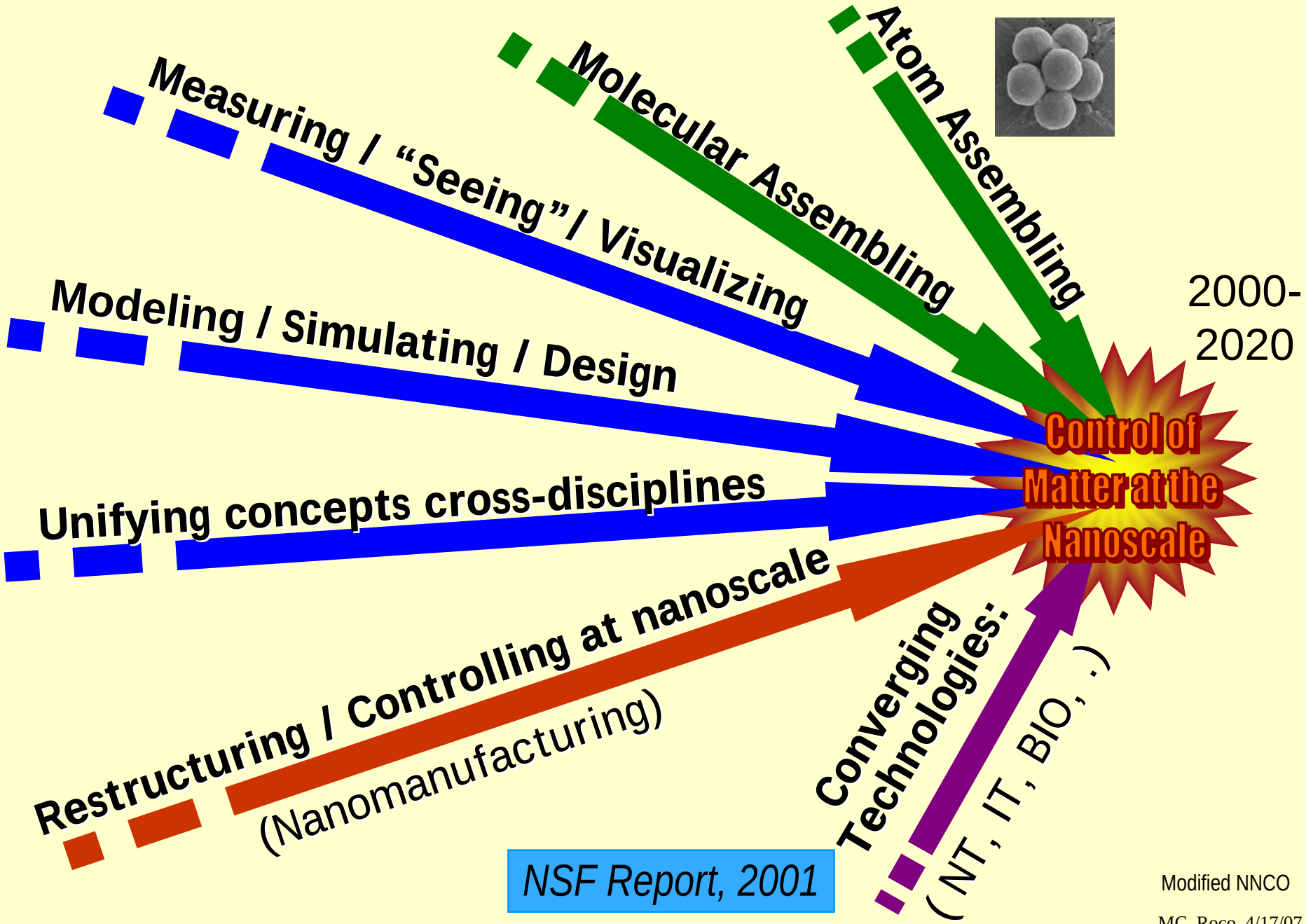
While miniaturization is of interest

Less space, faster, less material, less energy

More important:

- Novel properties/ phenomena/ processes
- Unity and generality of principles
- Most efficient length scale for manufacturing
- Show transition from basic phenomena and nanocomponents to system applications in 10 areas

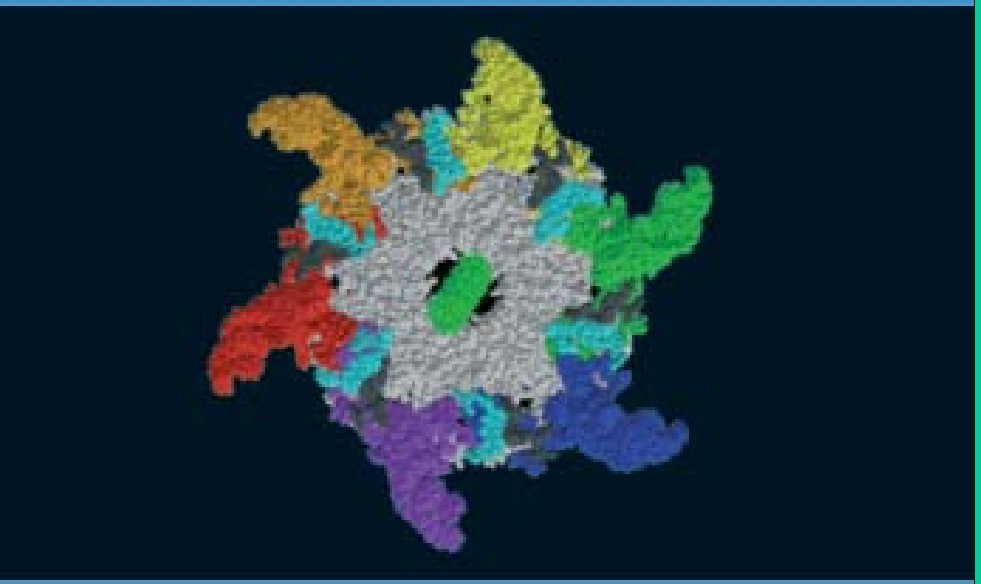
Nanotechnology innovation: *concurrence of capabilities*



MANAGING NANO-BIO-INFO-COGNO INNOVATIONS

CONVERGING TECHNOLOGIES IN SOCIETY

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



Springer

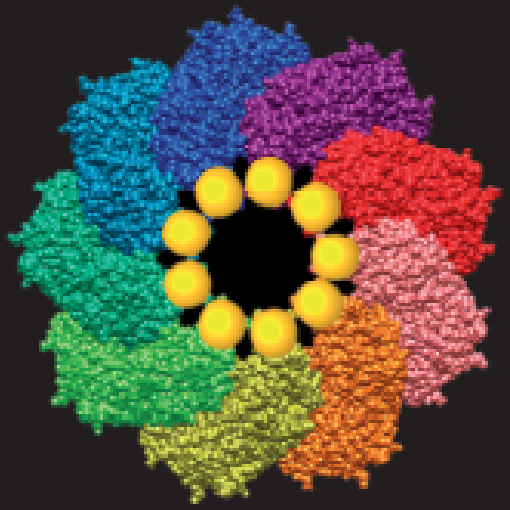
August 2006

Nanotechnology: Societal Implications I

Maximizing Benefits for Humanity

Edited by

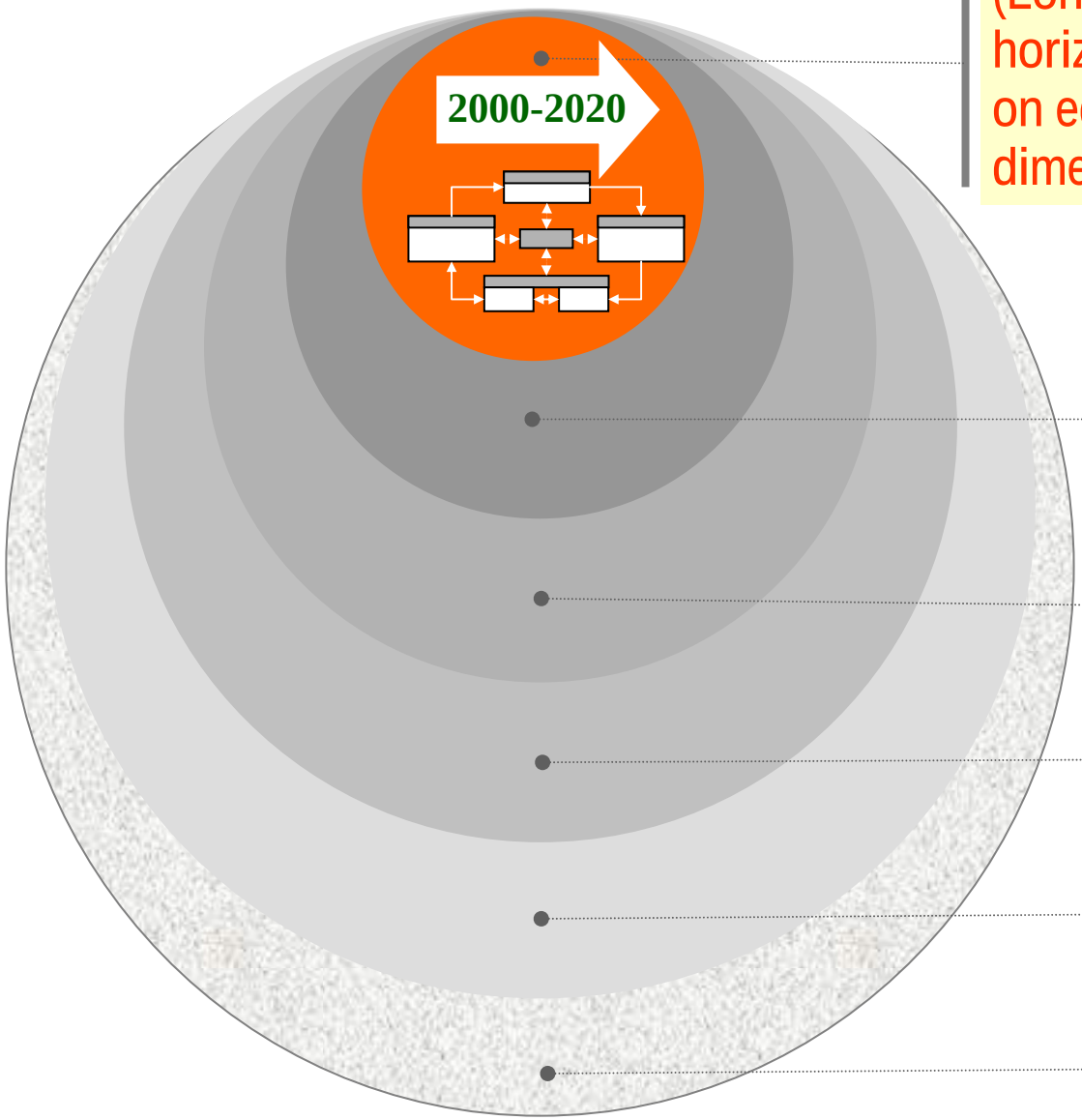
Mihail C. Roco and William Sims Bainbridge



Springer

November 2006

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

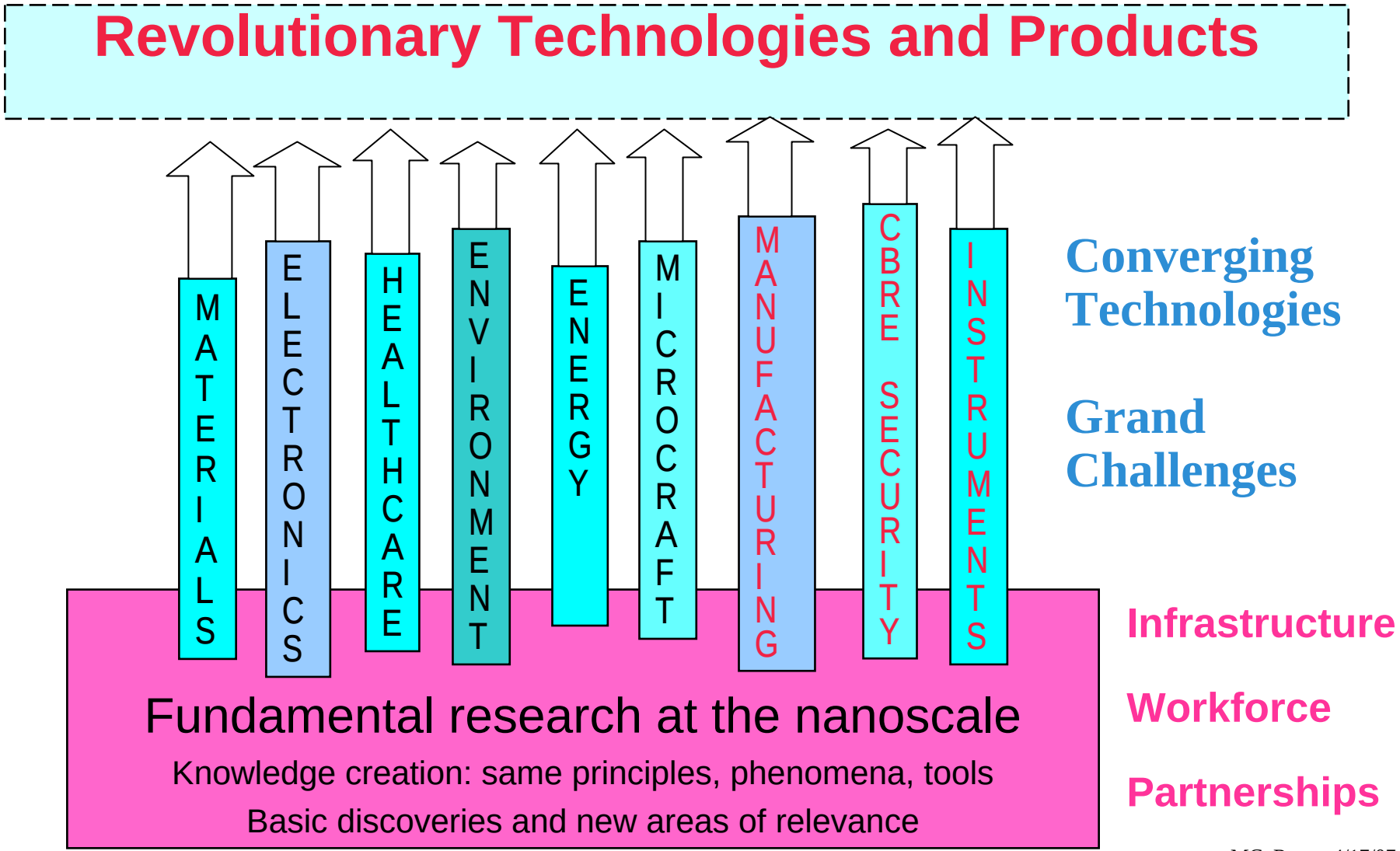
Governance of nanotechnology development: four roles

- **Transformative**
  investment policy, S&T policy, education, transformative tools
- **Responsible development**
  EHS, ELSI+, Methods for risk governance, communication and participation
- **Visionary**
  Long-term and global view, human development/progress
- **Inclusive**
  Building national capacity, international capacity and leveraging

Reference: "Governance of Converging Technologies Integrated from the Nanoscale", MC Roco, Annals NYAS (2006)

Transformative: Stimulate innovation

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

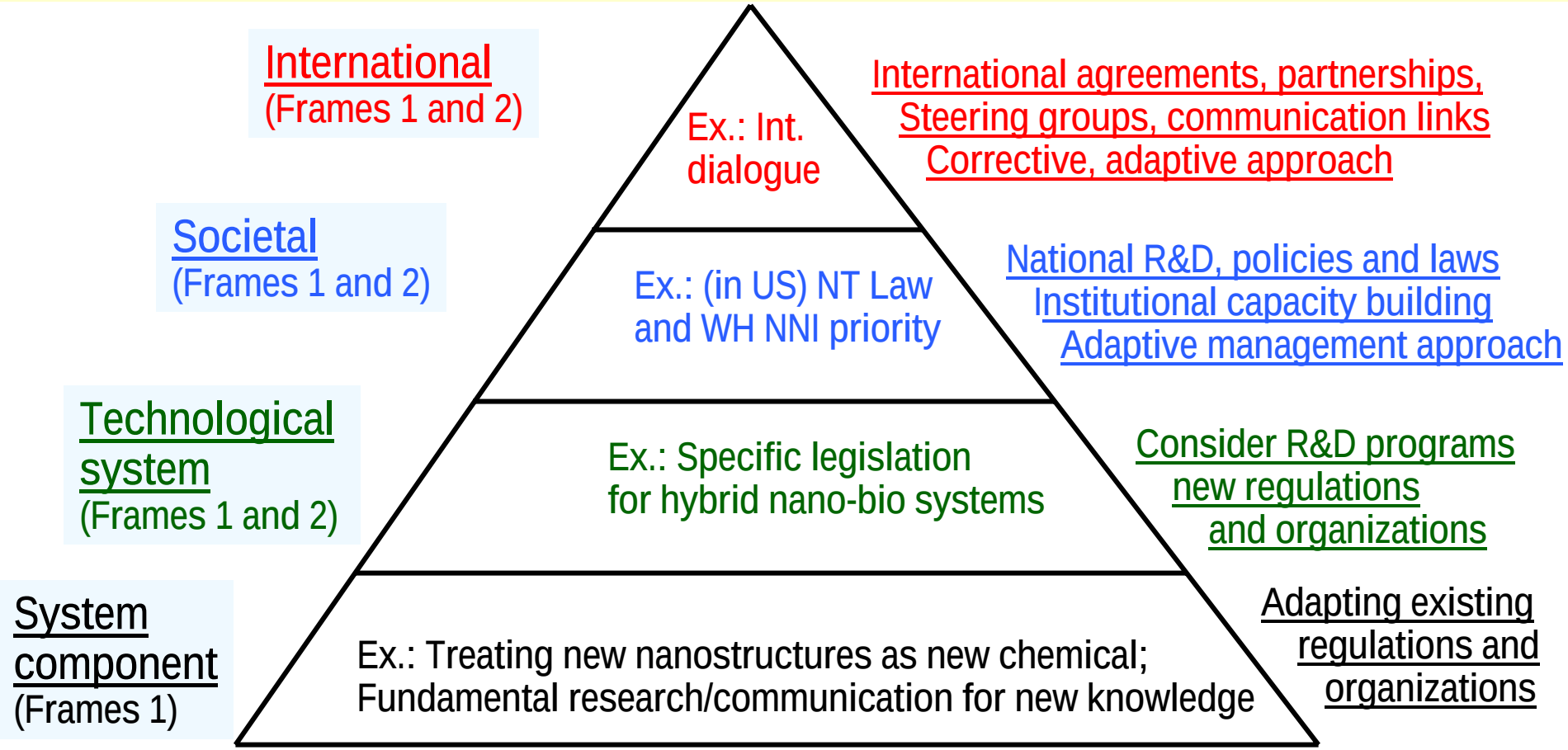


MC. Roco, 4/17/07

Responsible development

Multi-level structure of NT risk governance

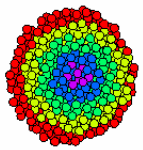
Implication Domain / Examples of RG activities / Implementation approach



Reference: International Risk Governance Council, http://www.irgc.org/irgc/projects/nanotechnology/

Visionary

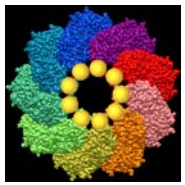
Timeline for beginning of industrial prototyping and nanotechnology commercialization: Four Generations



1st: Passive nanostructures (1st generation products)

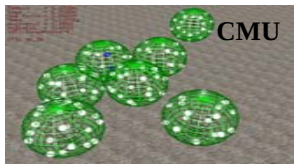
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2000



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

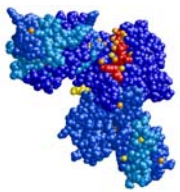
~ 2005



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

New R&D challenges

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

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

The long-term view drives NNI
2000-2020

- NNI was designed as a science project after two years of planning without dedicated funding in 1997-1999:

  Long-term view ("Nanotechnology Research Directions")

  Definitions and international benchmarking ("Nanostructure S&T")

  Science and Engineering Priorities and Grand Challenges ("NNI")

  Societal implications ("NSF Report", 2000)

  Plan for government agencies ("National plans and budgets")

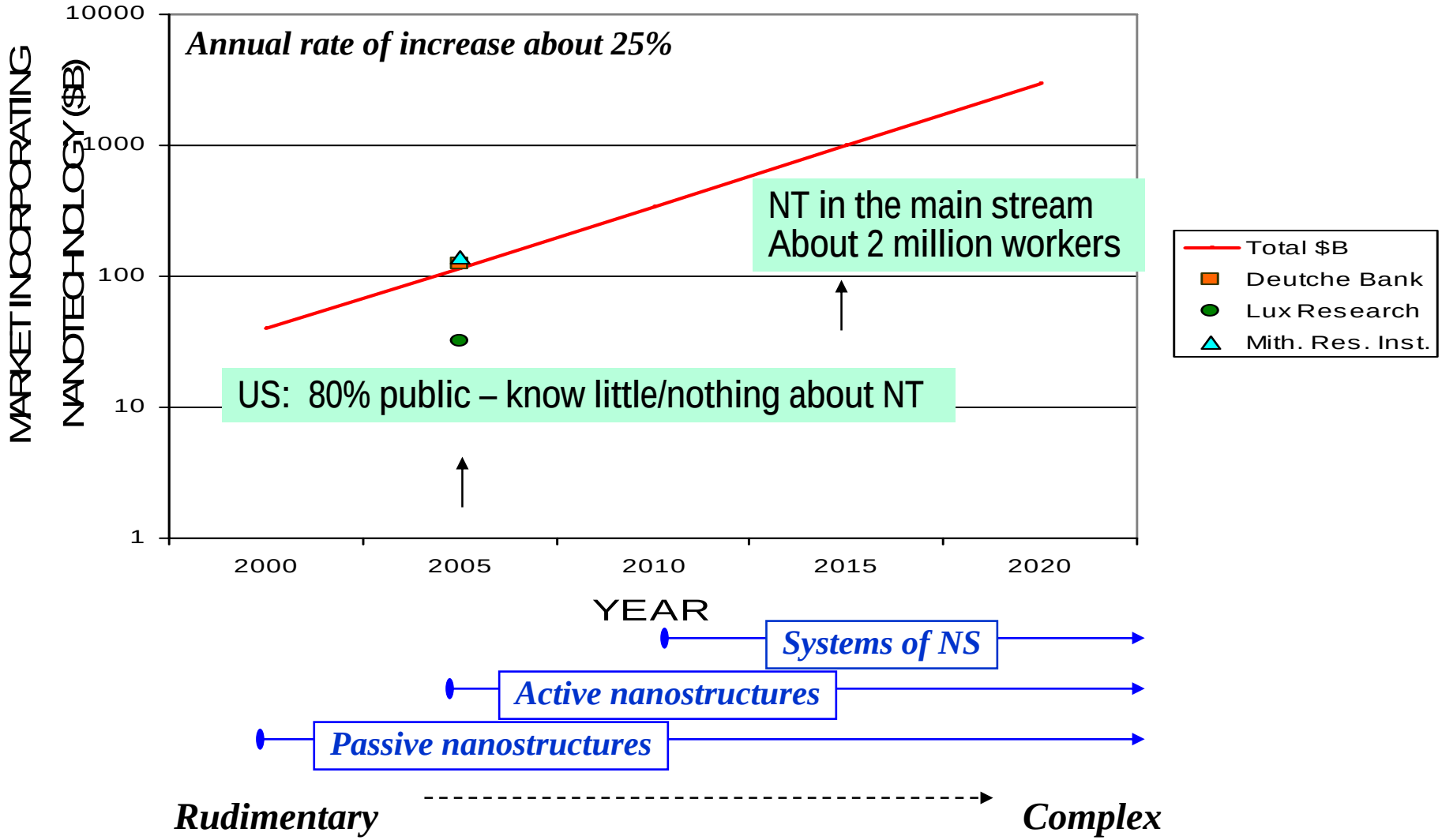
  Public engagement brochure ("Reshaping the word", 1999)

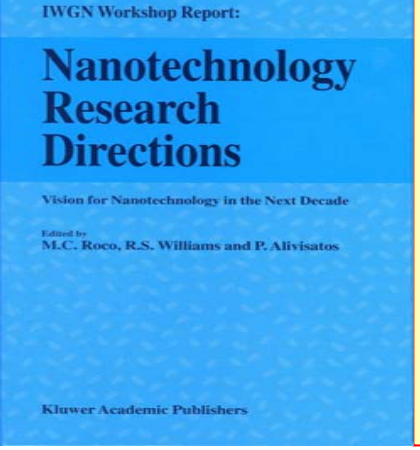
- Combine four time scales in planning:

  Vision - 10-20yrs, Strategic plan - 3-5yrs, Annual budget - 1yr, and Management decisions - 1 month

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

(NSF estimation made in 2000 after international study in > 20 countries)





Inclusive: industry, academe, government

Participants in the National Nanotechnology Initiative

2001: Six Agencies

- NIH
- NIST
- NASA
- DOD
- DOE
- NSF

2002: Seven New Agencies

- DOTr
- DOT
- EPA
- DOS
- IC
- USDA
- DOJ

2003-4: Four New Agencies

- FDA
- NRC
- DHS
- DOC TA

2005: Six New Agencies

- USDA FS
- DOC BIS
- USPTO
- ITC
- CPSC
- NIOSH

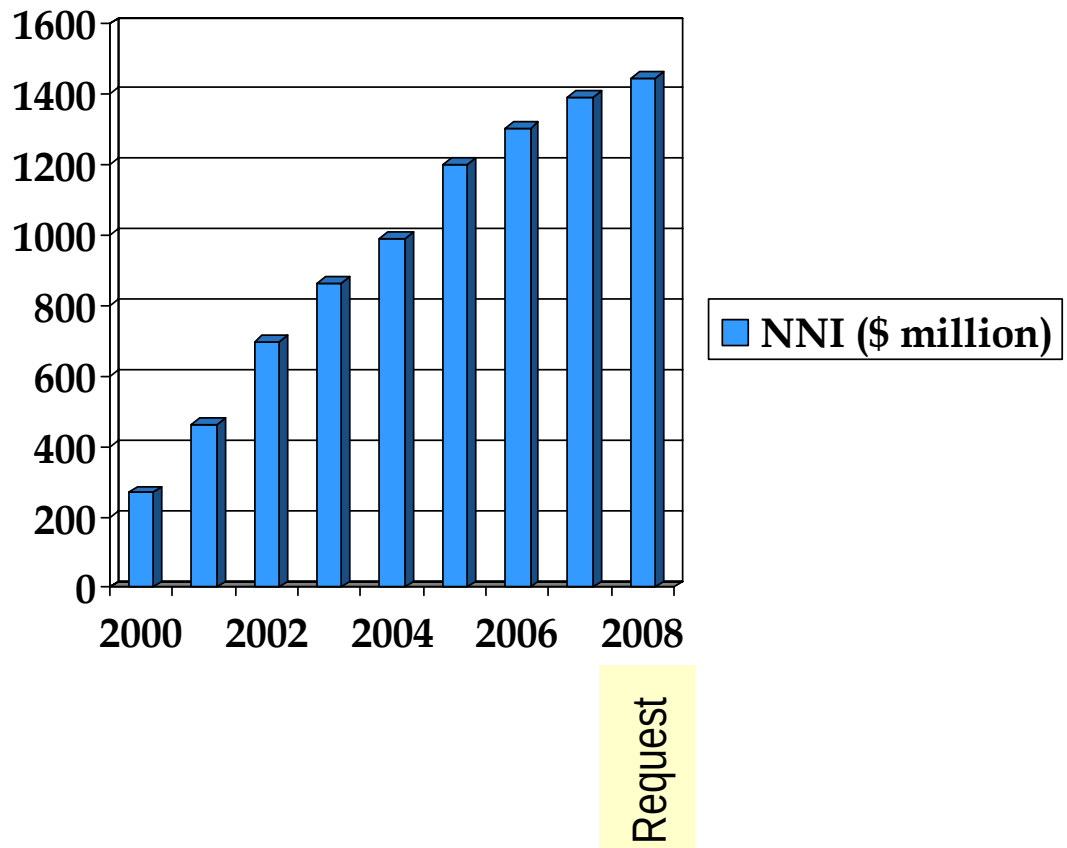
2006: Three New Agencies

- USGS
- DOL
- DOEd

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

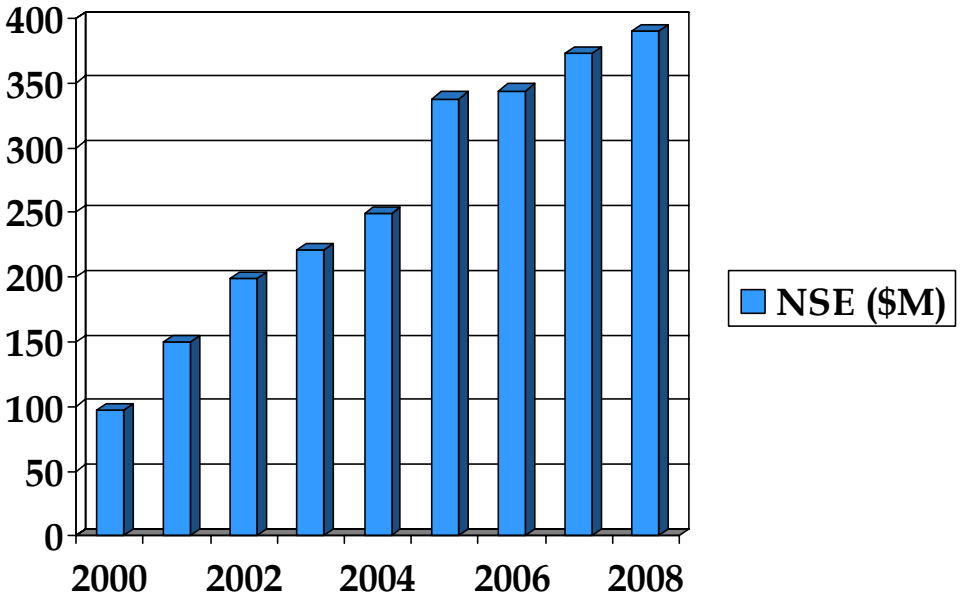
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

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 3,000 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**



NNI Accomplishments (1)

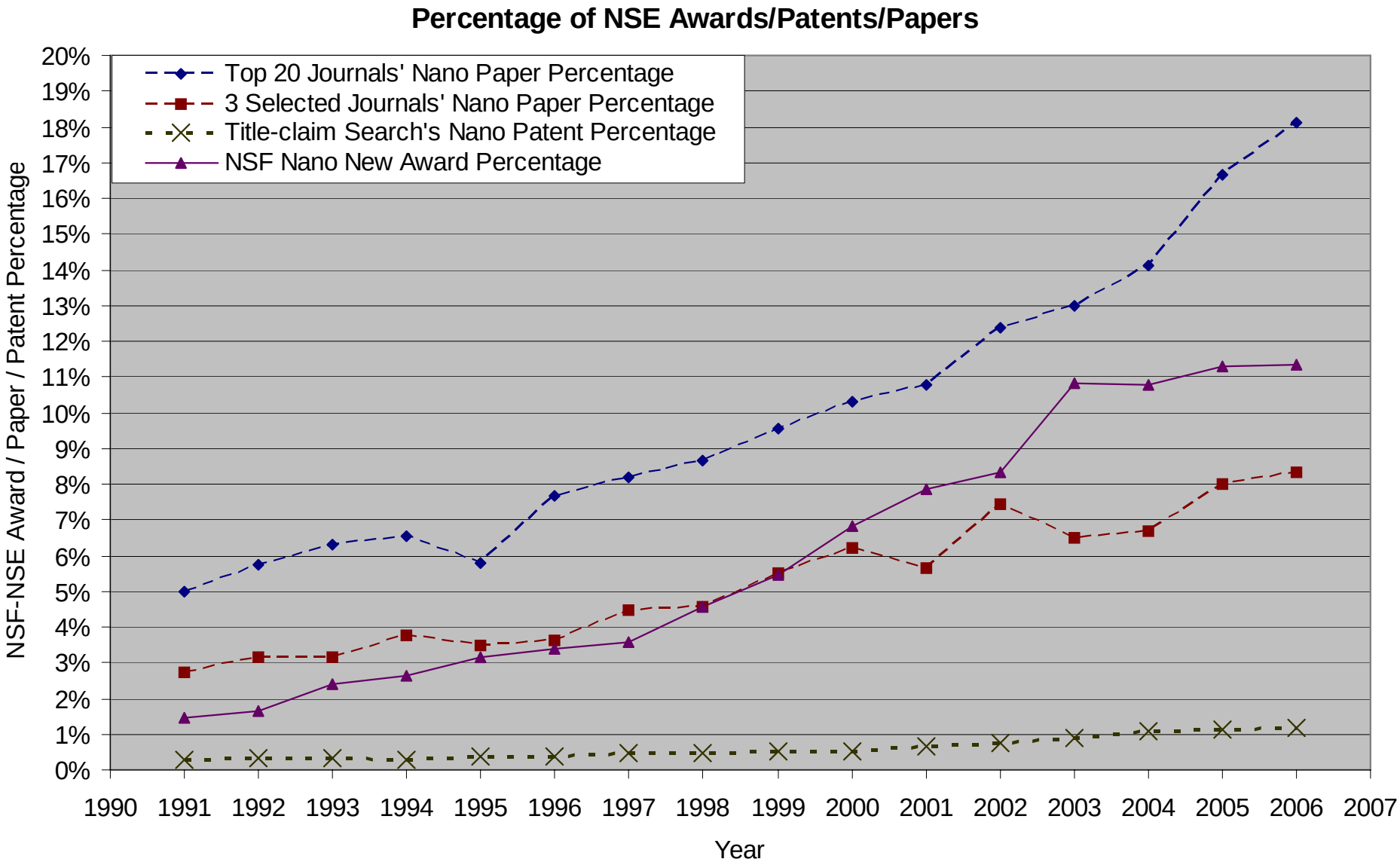
- Developed foundational knowledge for control of matter at the nanoscale:
  about 4000 active projects in > 500 universities, private sector institutions and gov. labs in all 50 states
- "Created an interdisciplinary nanotechnology community" [1]
- R&D / Innovation Results: With ~25% of global government 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 2000 U.S. nanotech companies in 2006
- Infrastructure:
  over 60 new large nanotechnology research centers, networks and user facilities; about 16,000 users in 2 academic-based networks

([1]) NSF Committee of Visitors, 2004; ([2]) Journal of Nanoparticle Research, 2004; ([3]) NanoBusiness Alliance, 2004

NNI Accomplishments (2)

- Partnerships: with industry (Consultative Boards for Advancing Nanotechnology - CBAN), regional alliances (22), international (over 25 countries), numerous professional societies
- Societal implications and applications - since 2000, over 10% of NSF/ NNI with relevance to environmental health, and safety, and other societal and educational concerns; NNI coordinates thru NEHI WG
- Nanotechnology education and outreach - impacting over 10,000 graduate students and teachers in 2006; 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.

Keyword search for nanotechnology contents: NSF awards, USPTO patents and ISO papers



Ex.: NNI Networks and User Facilities

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

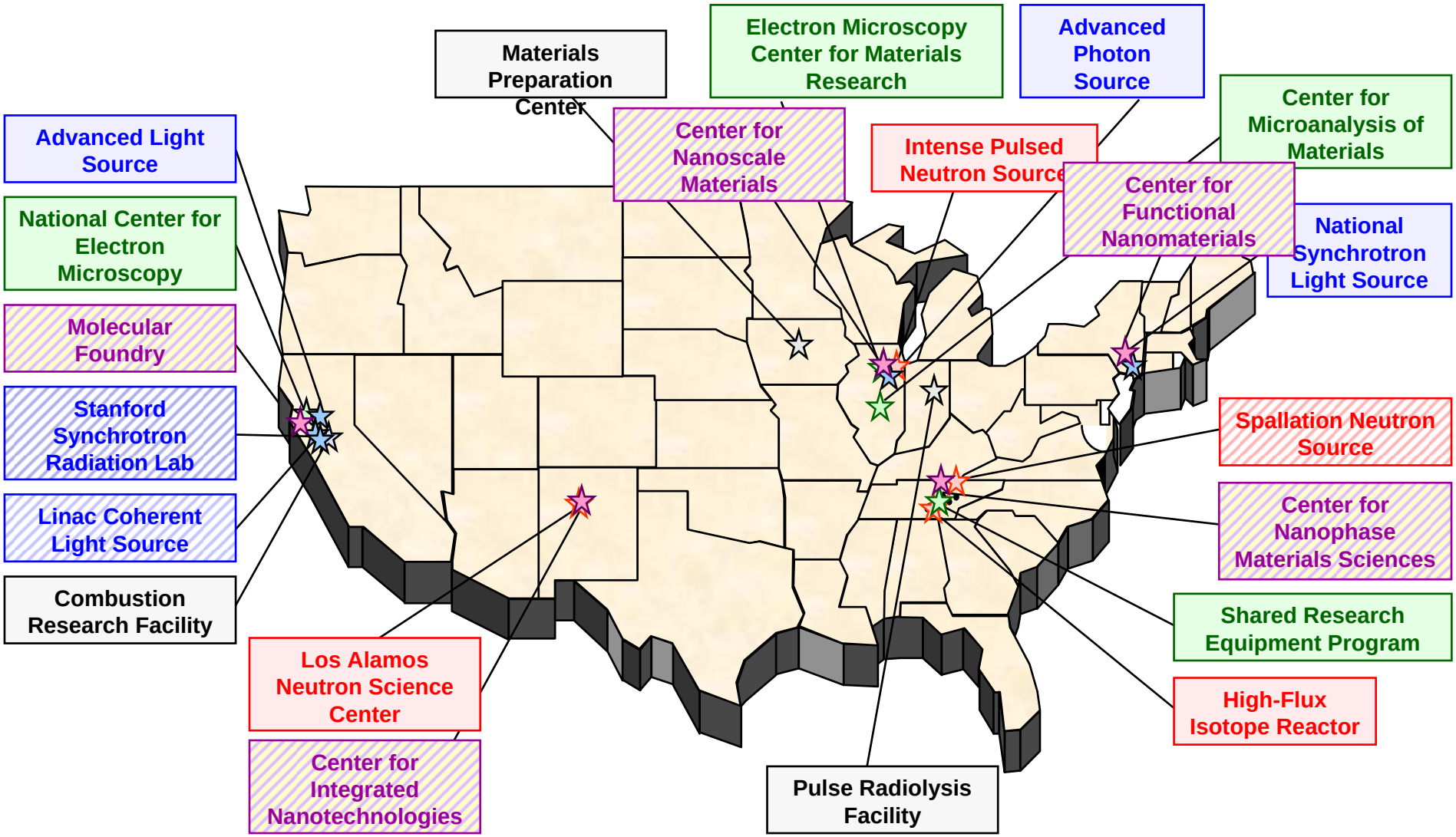
Eight Nanoscale Science and Engineering networks with national outreach

Network for Computational Nanotechnology (2002-) *12,000 users/ 2006*
National Nanotechnology Infrastructure Network (2003-) *4,000 users/ 2006*

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

NSEC Network (2001-) *16 research & education centers*
MRSEC Network (2001-) *6 new research & education centers since 2000*

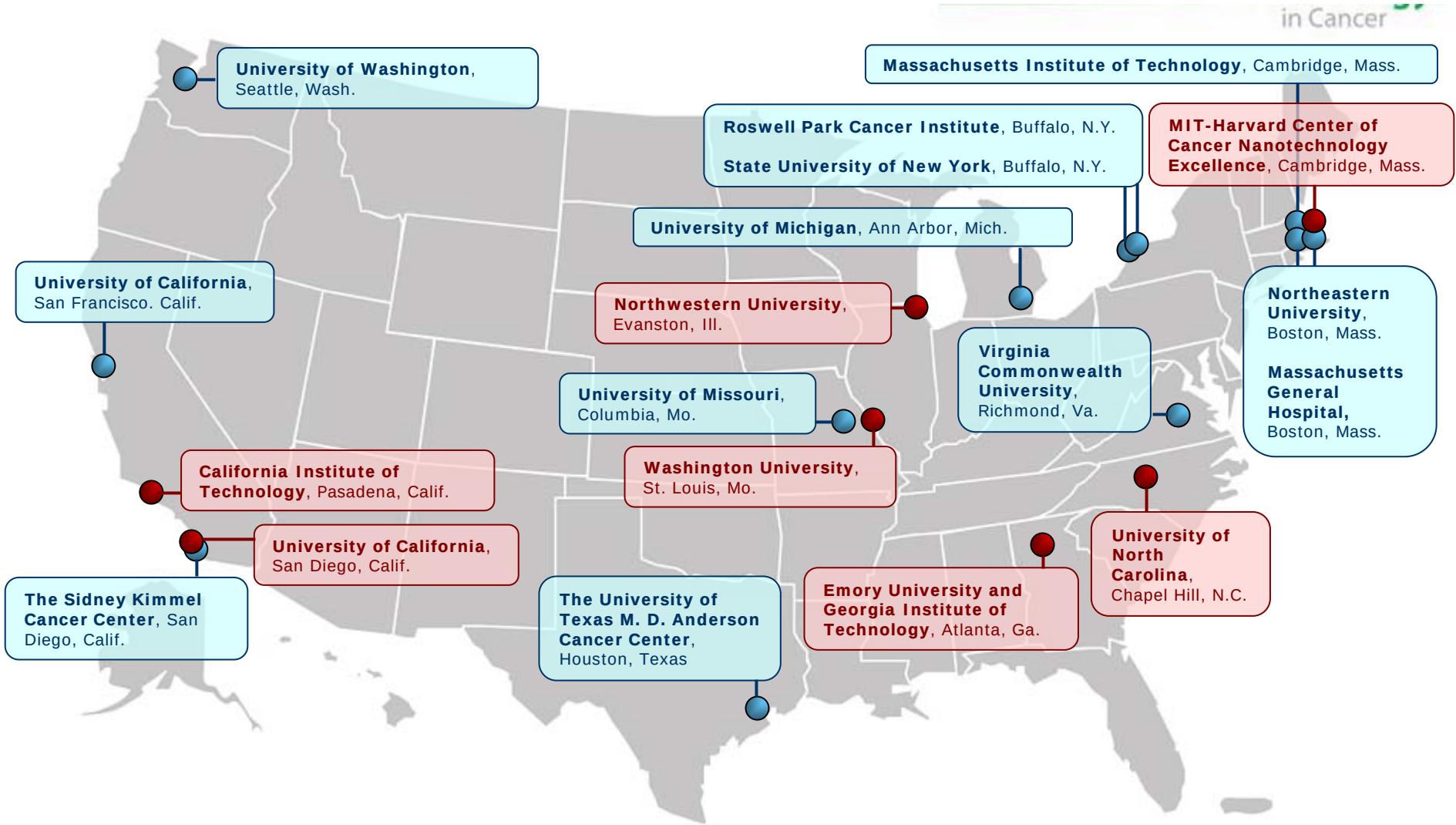
Department of Energy Scientific User Facilities



MC Roco, 04/17/07

NCI Alliance Program Awards

NANOTECHNOLOGY CHARACTERIZATION LABORATORY



Centers of Cancer Nanotechnology Excellence (8)

Cancer Nanotechnology Platform Partnerships (12)

MC Roco, 04/17/07

After 5 years of NNI:
New R&D potential targets for 2015 (ex.)

2005 from COMPONENT to SYSTEM NANOTECHNOLOGY **2015**

Nanoscale visualization and simulation of 3D/m domains

On micro domains with atomic size and chemistry 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

After 5 years of NNI:

New R&D potential targets for 2015 (2)

2005 **2015**

Advanced materials and manu.: ½ from molecular level

Including: adaptive materials, aeronautics, paper products, robotics, etc.

Pharmaceuticals synthesis and delivery: ½ based on nano

Converging technologies from the nanoscale

Including: hybrid structures, manufacturing multidisciplinary platforms, etc.

Life-cycle biocompatible/sustainable development

Education: nanoscale instead of microscale-based

After 5 years of NNI:
New R&D potential targets for 2015 (3)

2005 **2015**

Energy conversion using new principles

(heat gradient in nanomaterials, nanoscale piezoelectric effects, .)

Water filtration and desalinization based on nano

Nano-shop: 3d building at the nanoscale

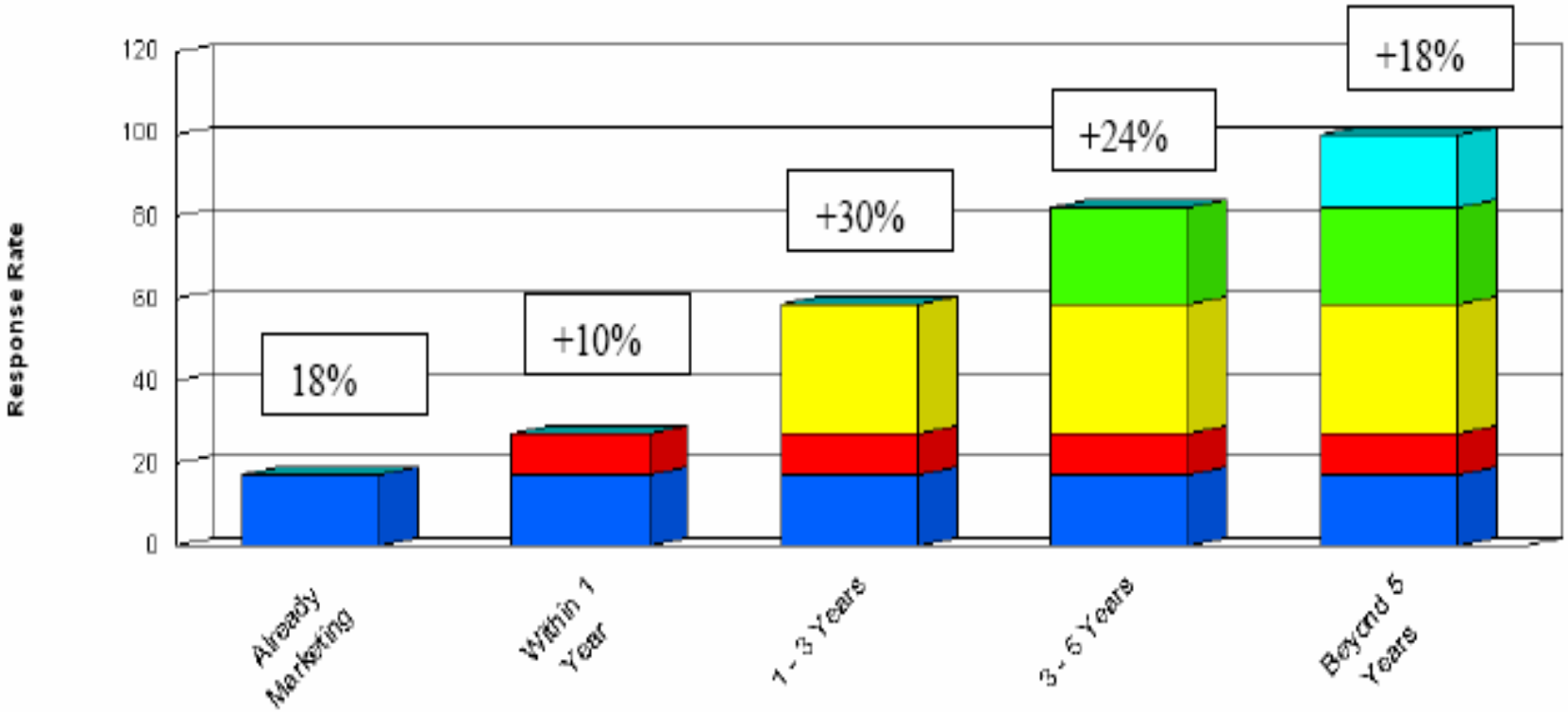
Nano-biomedicine: in vivo control of biology for med.

Nano-informatics: libraries for integrating databases

Four generations of nanoproducts for nanoelectronics

- First generation. Scaling down "masked-lithography of thin-films" - Nanoscale components (ex: passive nanoscale layers) with new physics
- Second generation (with state change of devices during operation)
  - Improving manufacturing: "directed self-assembly" leading to CMOS scaled to its ultimate limits (5-10 nm)
  - Improvement in energy and standby power: "post-CMOS" (still "charge-based") with carbon-nanotubes, single-electron "transistors", etc.
- Third generation. Reducing limitations by most of the interconnect charge-transport issues and near-equilibrium thermodynamic constraints that afflict CMOS: Nanosystem solutions based on state variables other than electric charge (e.g., electron-spin, nuclear-spin or photonic states).
- Fourth generation. Molecular and supramolecular components of nanoelectronic systems "by design"

2005 NCMS Survey on nanotechnology in manufacturing industry (594 companies)



Commercialization timelines indicate many new nanoproducts introductions in 2007-2011, and the high level of expectation in long-term

Reference: National Center for Manufacturing Systems, 2006

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

NNI- Electronic Industry CBAN

Five consultative working groups (CWG), 2003 -

I - Post CMOS information processing technologies

II - Novel materials and assembly methods for extending charge-based technology to its ultimate limit

III - Multi-scale, multi-phenomena modeling and simulation

IV - Novel nano-architectures

V - Nano – Environmental, Health and Safety

Six priorities:

Computational state other than electron charge
Non-equilibrium systems
Novel short range IT mechanisms
Nano architecture
Nanoscale thermal management
Directed selfassembling

NNI contribution to partnership in 2006

- New ideas: about 4000 awards (11 funding agencies), of which 3000 by NSF, of which 400 exploratory (2nd–4th generation)
- People: education and training reaching 10,000 students and teachers per year by NSF alone; Broad spectrum - NIH, DOD, DOE, . .
- Infrastructure: laboratories, experts, centers, publications, patents
  60 centers, networks, user facilities – all NNI of which 24 by NSF
- Funding in electronics, photonics, magnetics. Ex - NSF
  NSF ~ $100M relevant to NSE in FY 2006
  NSF ~ $20M joint NSF-SRC review NSE solicitation in FY 2006
  NSF - $1M for joint NSF- SIA fellowships in FY 2006
  Promote partnerships academe - SIA, through NSECs, NNIN, NCN, MRSECs, ERCs, GOALI, PFI
  Support joint workshops: about 4 per year

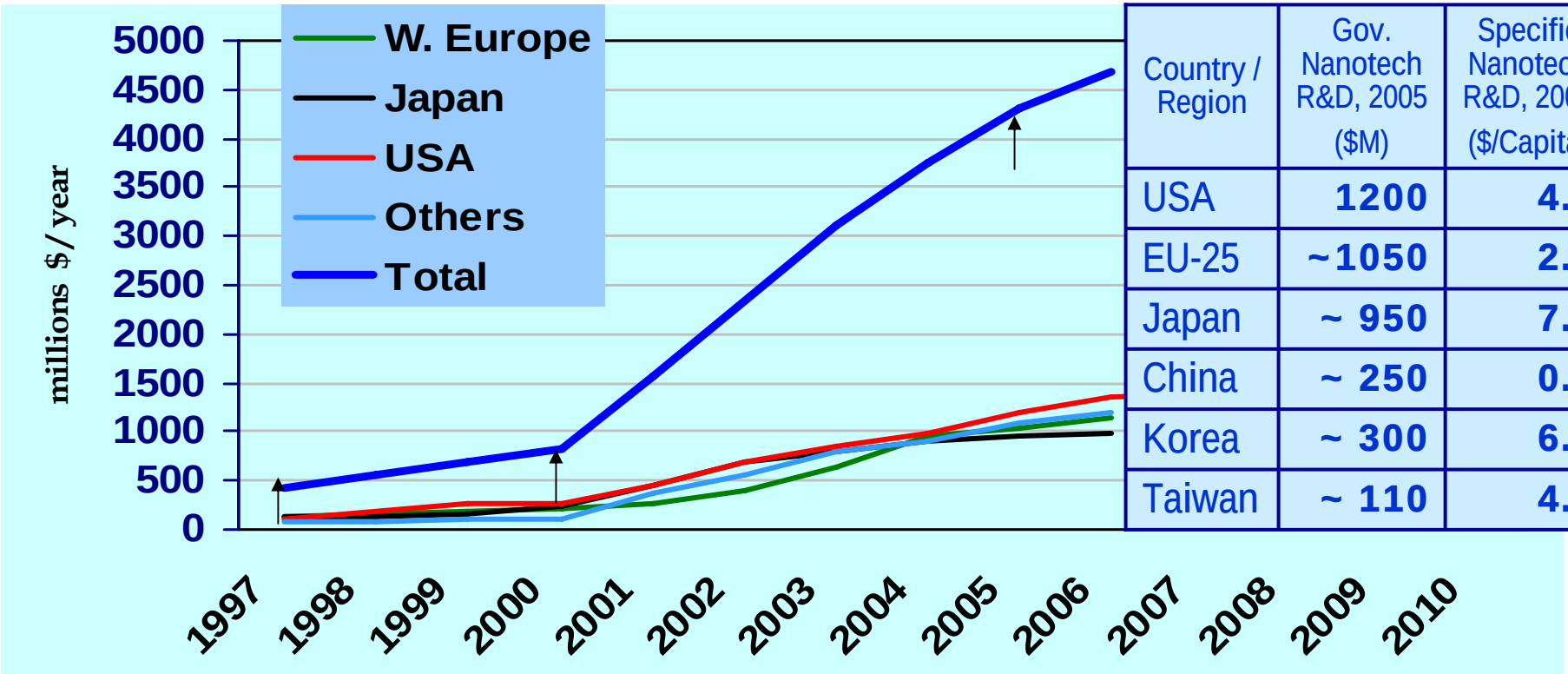
Several NSF awards of relevance to NSF - SIA collaboration in nanoelectronics (2005-2006)

- Nanoscale Science and Engineering Centers NSEC ~ 10
- Networks (NNIN, NCN, NNN) - 3
- Materials Research S&E Centers MRSECs ~ 5
- Nanoscale Interdisciplinary Research Teams NIRT – 30
- Nanoscale Exploratory Research NER – 50
- Engineering Research Centers, ERCs – 2

2006: Nanoelectonics Research Initiative established
3 new research centers on complementary R&D topics
in the New York state, California and Texas

Context – Nanotechnology in the World

National government investments 1997-2006 (est. NSF)



Country / Region	Gov. Nanotech R&D, 2005 ($M)	Specific Nanotech R&D, 2005 ($/Capita)
USA	1200	4.0
EU-25	~1050	2.3
Japan	~ 950	7.4
China	~ 250	0.2
Korea	~ 300	6.2
Taiwan	~ 110	4.7

Seed funding (1991 -)

NNI Preparation (vision / benchmark)

1st Strategic Plan (passive nanostructures)

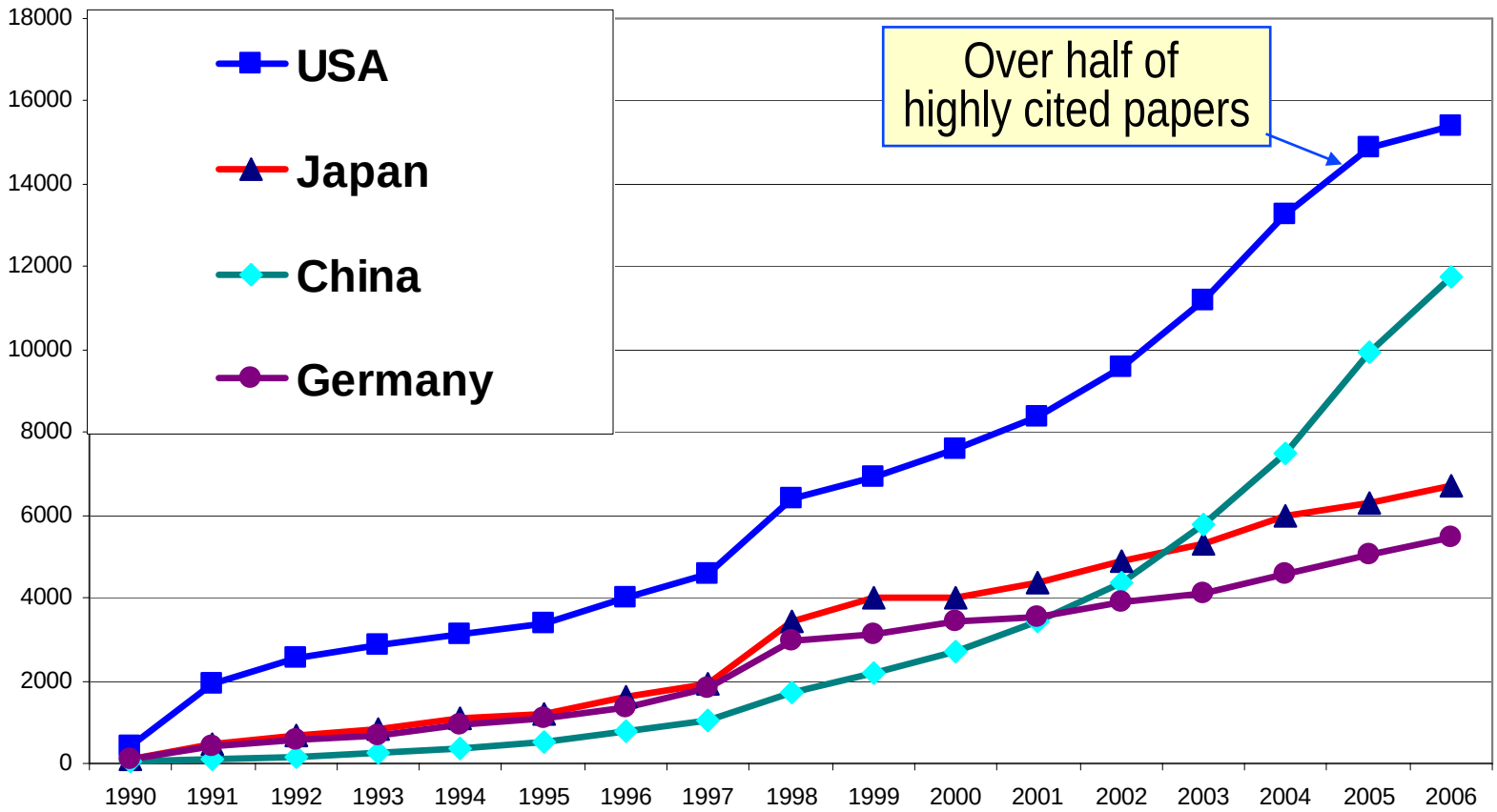
2nd Strategic Plan (active ns. & systems)

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

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

Nano publications per year

1990 - 2006



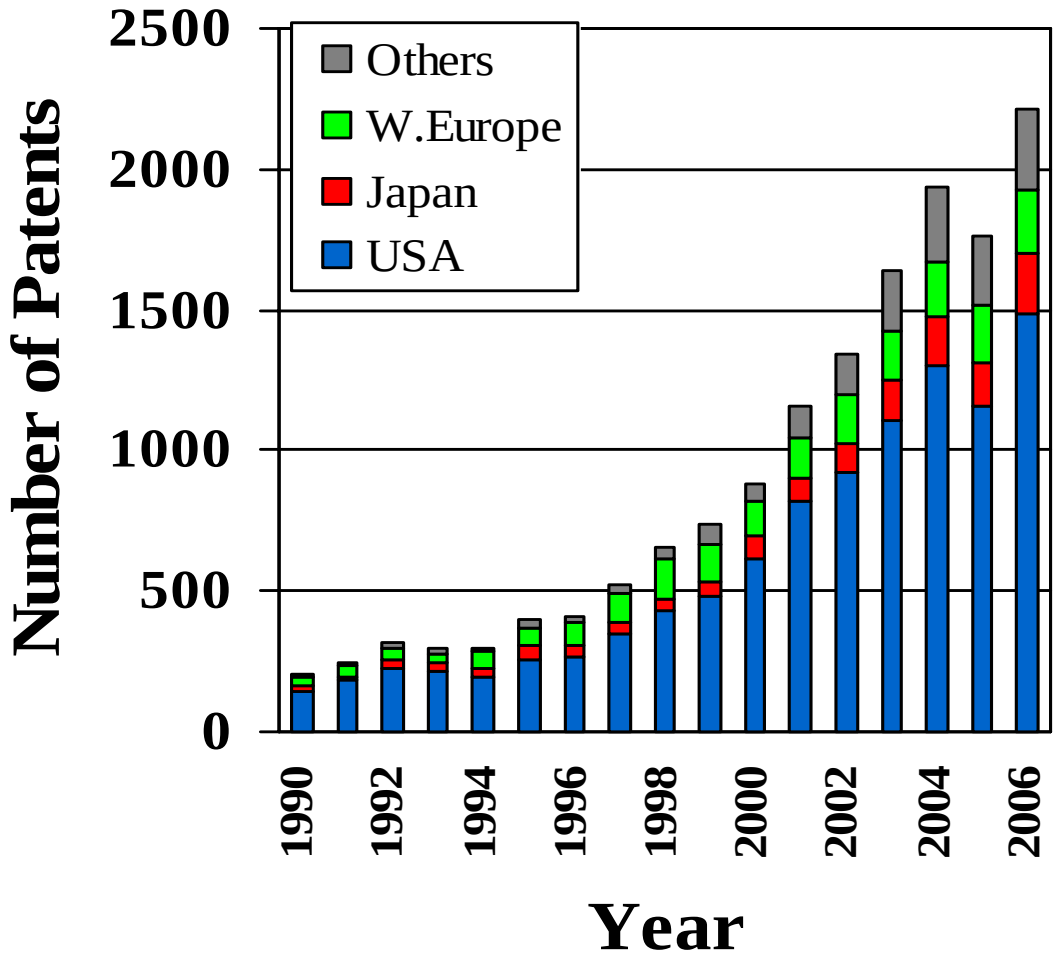
Courtesy: Georgia Tech TPAC / CNS-ASU Analysis of SCI Publication (August 2006)

US has about 60% of world NT Patents (USPTO database)

using "Title-claims" search for nanotechnology by keywords

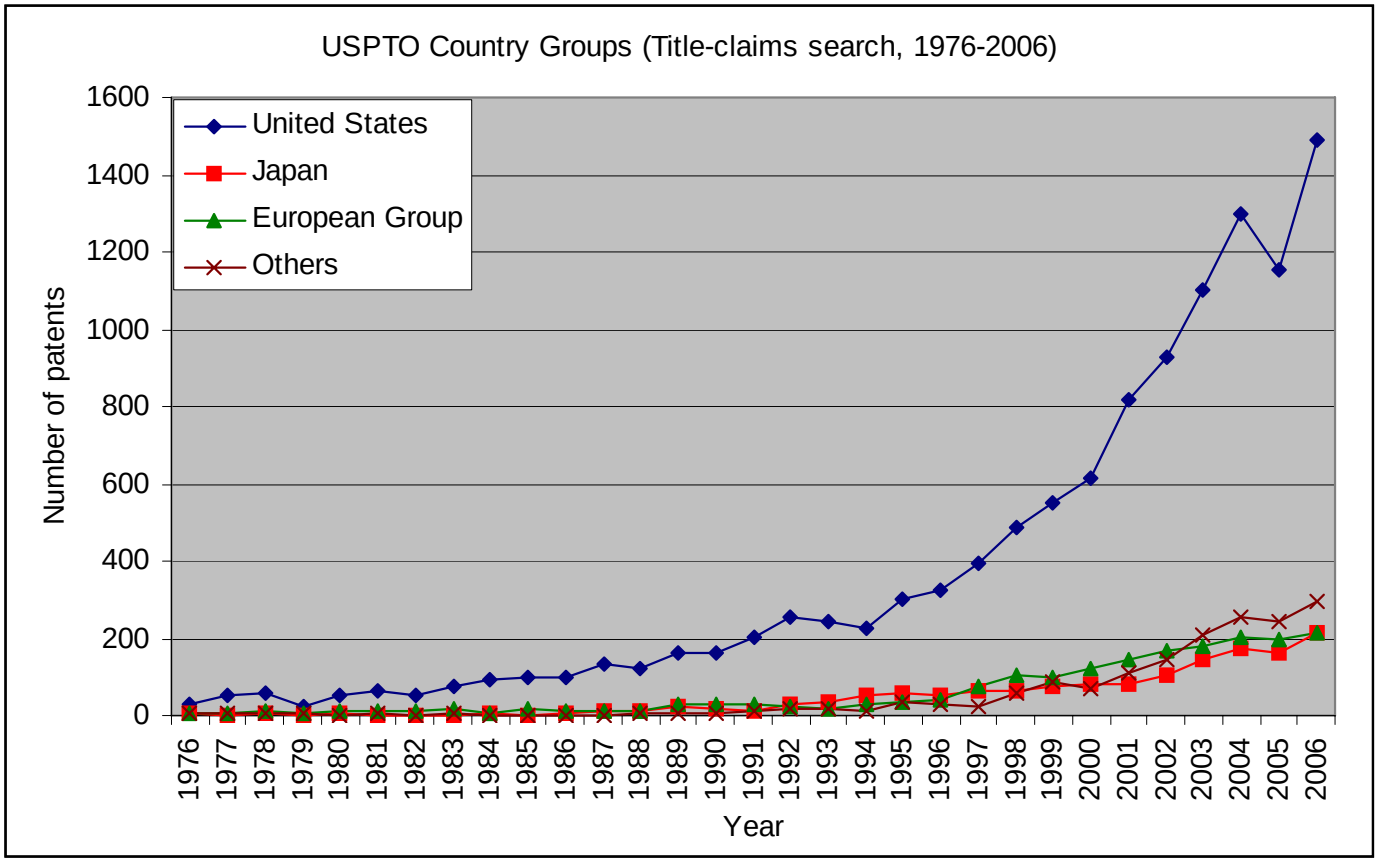
(using intelligent search engine, update J. Nanoparticle Research, 2004, Vol. 6, Issue 4)

Using "Title-claims" keyword search:
<u>nanotechnology claims</u>



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

Technological Comparison

Europe; Japan; U.S.

This is an extension in 2004 survey of the WTEC Nanotechnology Workshop's first evaluation in 1999

	Level 1 (Highest)	Level 2	Level 3	
Synthesis & Assembly	U.S.	Europe	Japan	BASIC APPROACHES
Biological Approaches & Applications	U.S.	Europe	Japan	
Dispersions and Coatings	U.S./Eur	Japan		R&D for PRODUCTS 1st Generation
High Surface Area Materials	U.S.	Europe	Japan	
Consolidated Materials	Japan	U.S./Eur		
Nanodevices	Japan	U.S./Eur		2nd Generation
Nanosystems/ Molecular systems	U.S.	Jap/Eur		3rd and 4th Generation
Instrumentation	Japan	U.S./Eur		TOOLS
Simulations	U.S.	Eur/Jap		

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

International Grand Challenges
(suggestions)

- Focus on single molecules and single cell
- Nanoscale instrumentation and metrology
- Theory, modeling and simulation at nanoscale
- Tools for manufacturing at the nanoscale
- Improving common resources: water, energy, food
- Improving human potential and education programs
- Enhancing societal implications, environment & health

References:
"International Strategy for Nanotechnology R&D", MC Roco, J. Nanoparticle Research, 2001
"International Perspective of Nanotechnology R&D", MC Roco, J. Nanoparticle Research, 2005

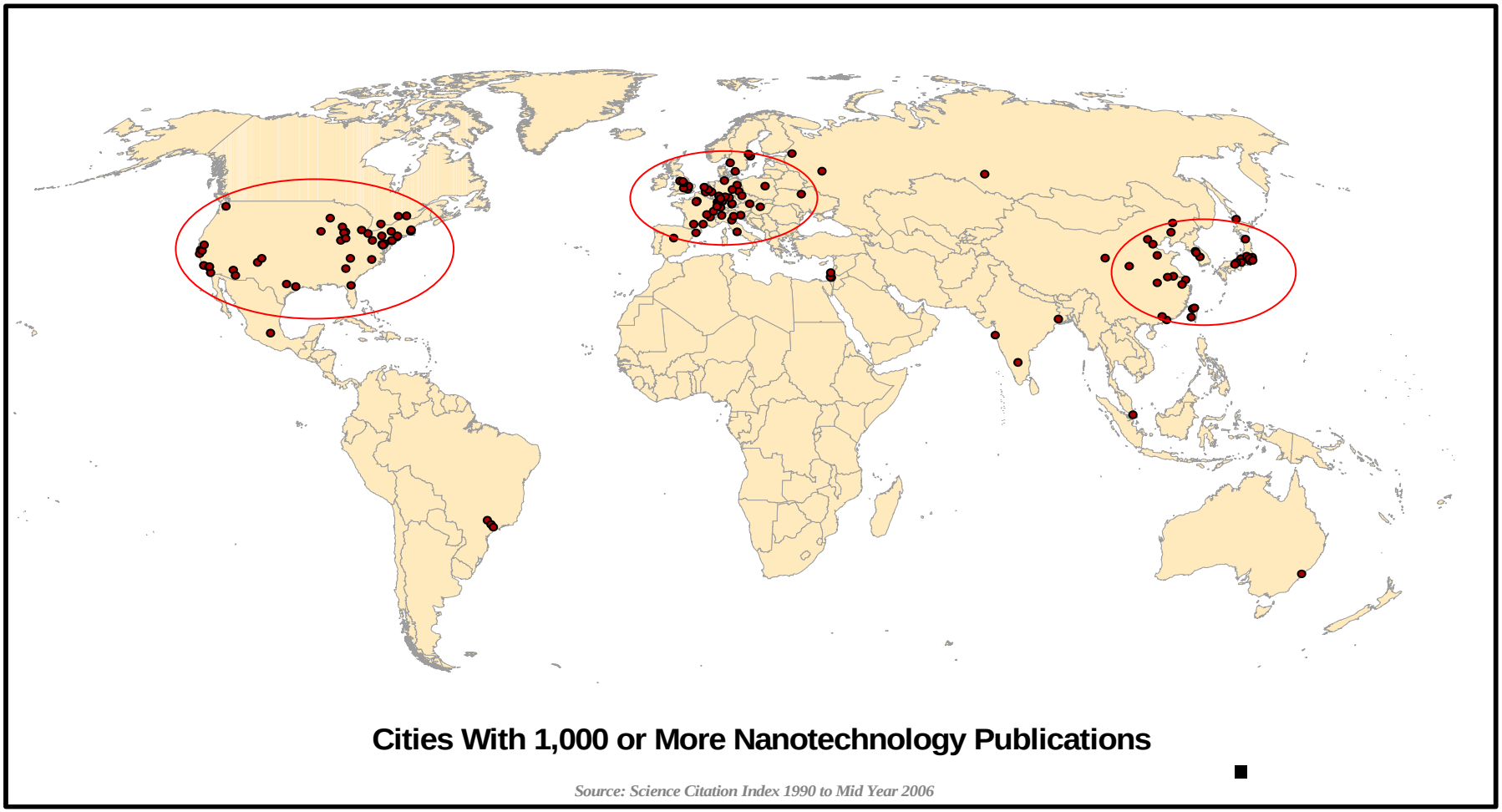
Several Priorities at NSF / NNI (2007)

- System Nanotechnology
- Nanoinformatics
- Measuring tools of systems with atomic resolution
- “On-site” nanomanufacturing
- Use of nanotechnology for common use resources: water, food, energy, environment
- Basic research on Beyond CMOS, partner with SIA/SRC
- Networking development for EHS, Education, ELSI

Opportunities for international industry- government-academe collaboration to be discussed at this meeting

R&D for keeping with the Moore’s law: Challenges that cannot be solved by one company, country or region

Collaboration and competition: Leading nanodistricts in America, Europe and Asia



2007 “Nanotechnology in Society” survey based on Citation Index