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Overview and Implications of Nanotechnology

Mike Roco

National Science Foundation, National Nanotechnology Initiative, International Risk Governance Council

- Five generations of nanotechnology products (2000-2030)
- International perspective
- Contribution of National Nanotechnology Initiative

Nanotechnology in Food and Agriculture, Washington, D.C., June 18, 2008

Benchmark with experts in over 20 countries

“Nanotechnology Science and Technology”

Book Springer, 1999



Nanotechnology

is the ***control and restructuring of matter*** at dimensions of roughly 1 (size small molecule) to 100 nanometers,

where new phenomena
enable new applications.

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

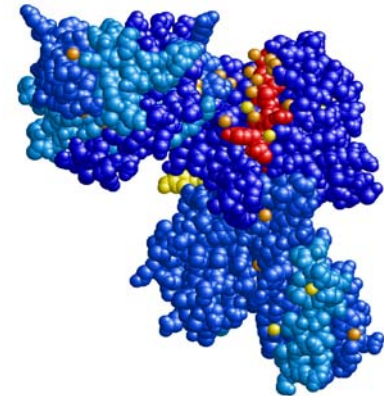
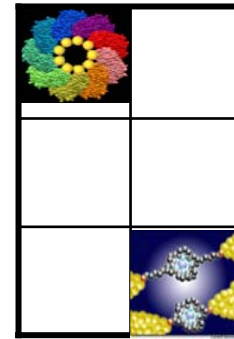
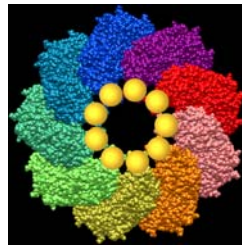
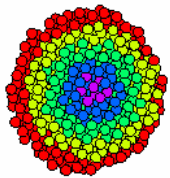
Defining Nanoproducts and Nanomanufacturing

- Fragmentation
- Patterning
- Restructuring of bulk
- Lithography, ..

- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration..



Assembling



- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

- Eng. molecules as devices,
- Quantum control,
- Synthetic biology..

PASSIVE NANOSTRUCTURES

ACTIVE NANOSTR.

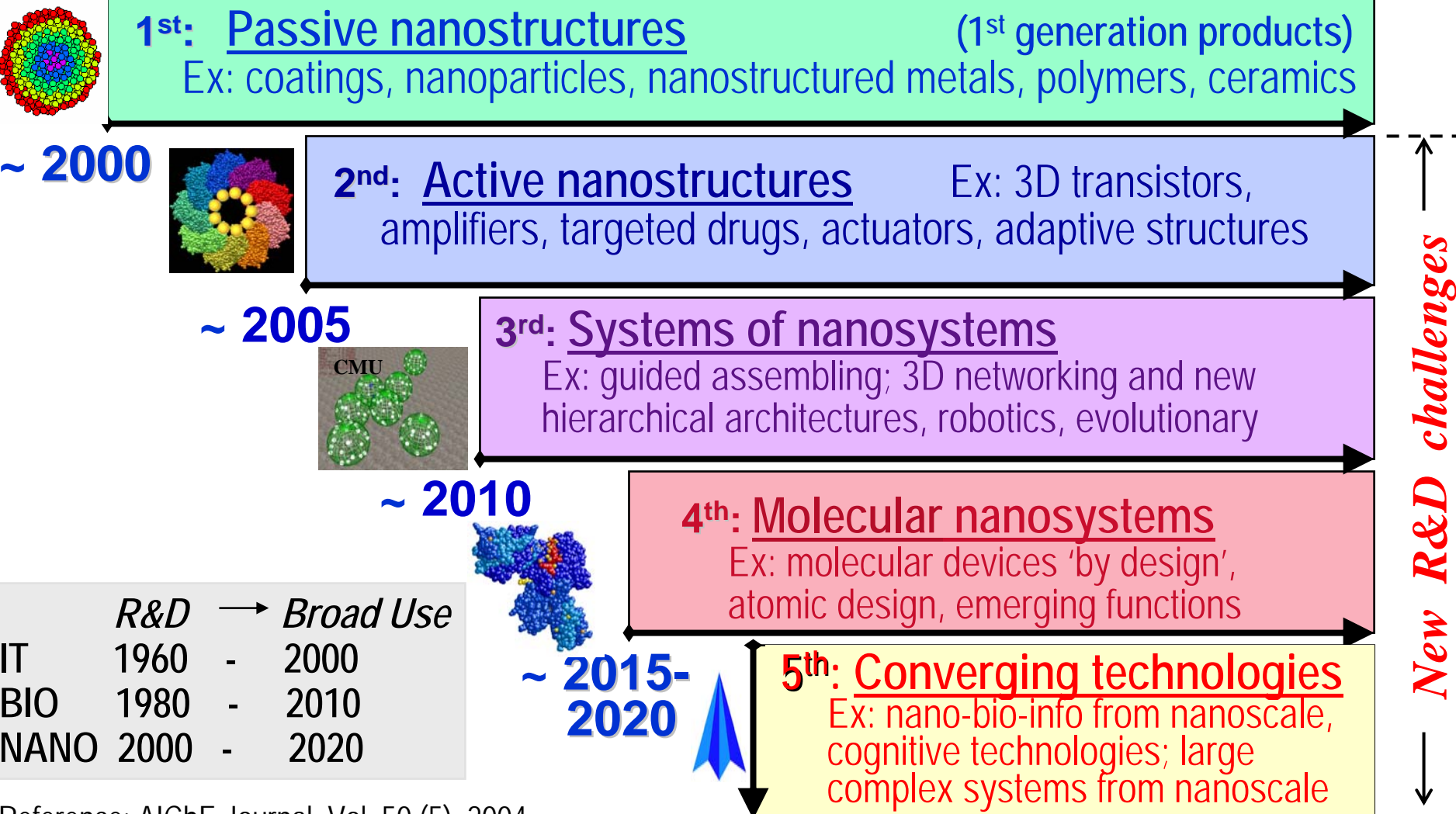
- SYSTEMS OF NANOSYSTEMS

- MOLECULAR NANOSYSTEMS

NANOPRODUCTS

Five Generations of Products and Productive Processes

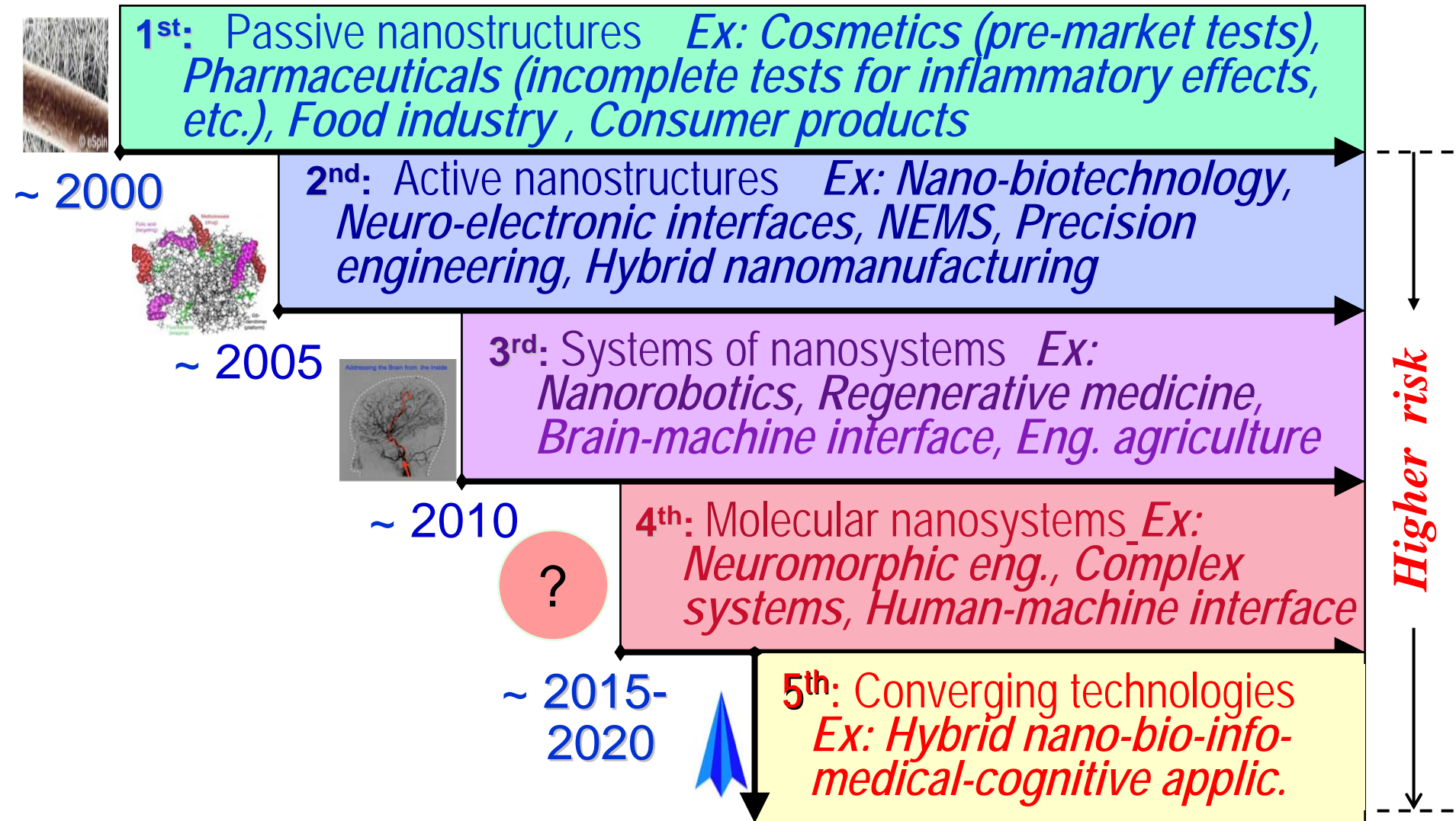
Timeline for beginning of industrial prototyping and nanotechnology commercialization (2000-2020; 2020-)



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

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

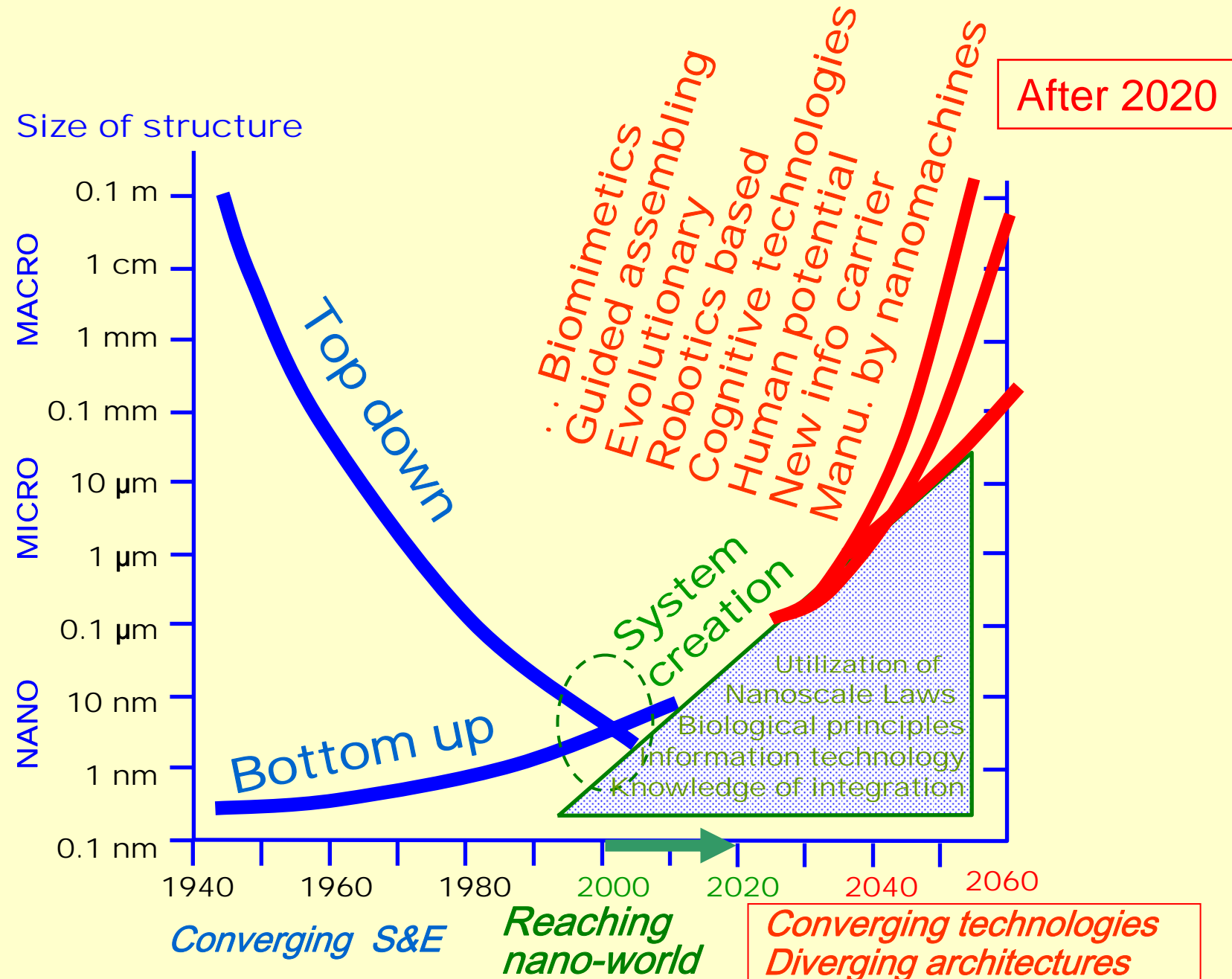
as a function of the generation of products



Examples of 3rd and 4th generation

- Artificial organs using nanoscale control of growth
- Subcellular intervention for treatment of cancer
- Bioassembly (ex. use of viruses) of engineered nanomaterials and systems
- Evolutionary systems for biochemical processing
- Sensor systems with reactive mechanisms
- Nanoscale robotics on surfaces and 3-D domains
- Simulation based experiments and design of engineered nanosystems from basic principles
- New molecules designed as devices
- Hierarchical selfassembling for micro or macro products

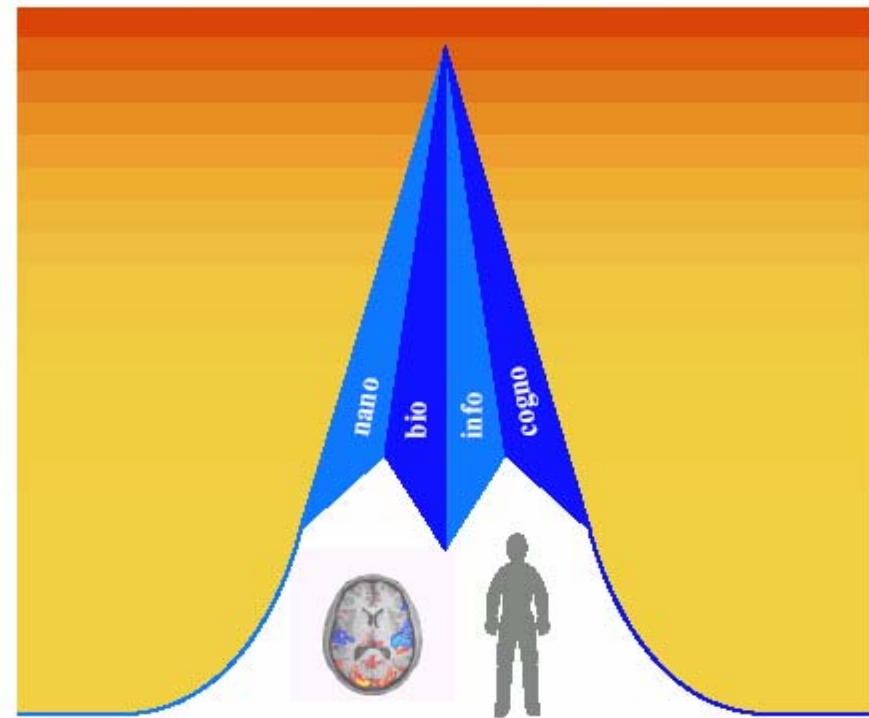
Fifth generation of products: Diverging architectures (>2020)



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

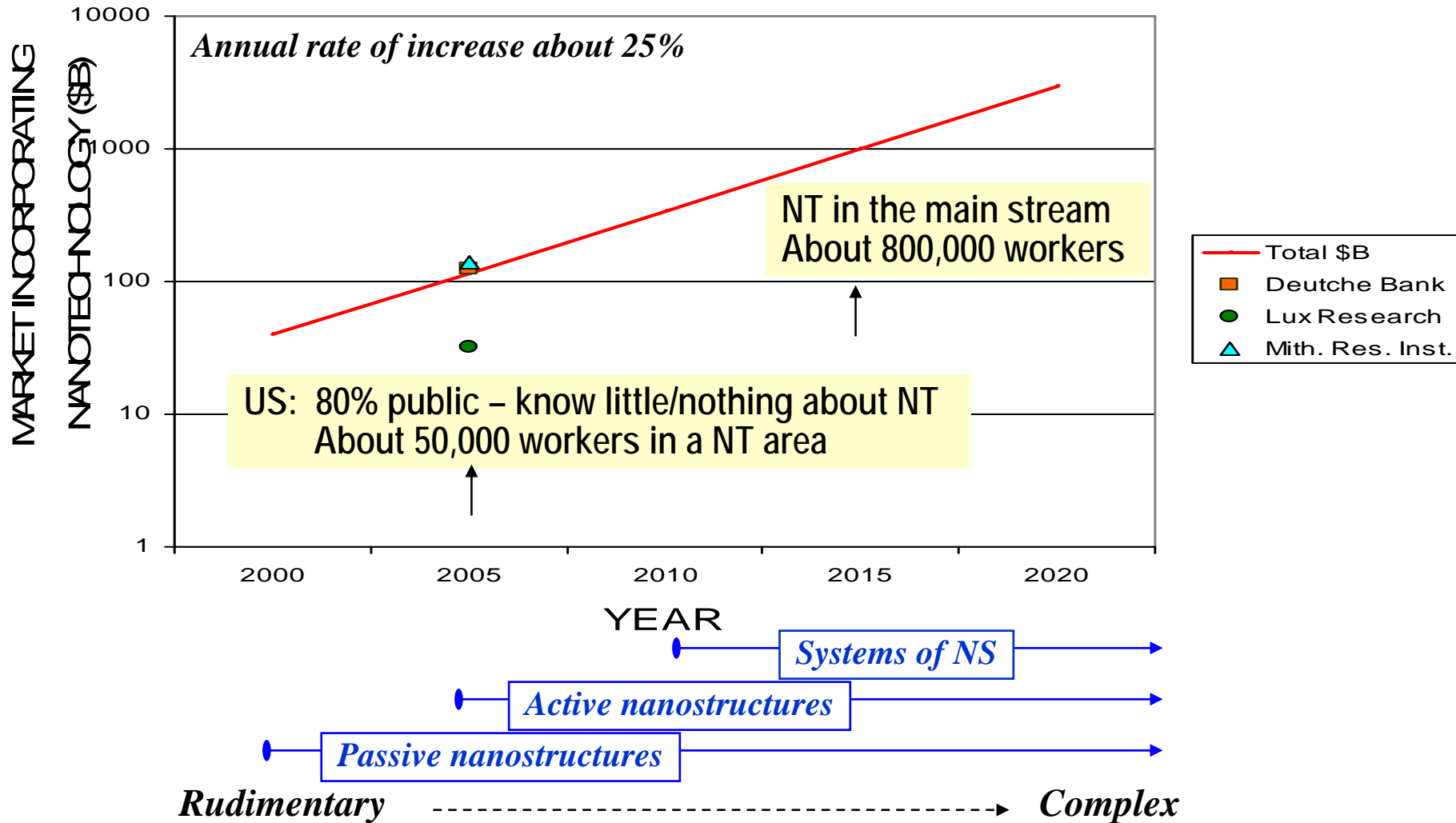
MIHAIL C. ROGO AND WILLIAM SIMS BAINBRIDGE (Eds.)



 Springer

November 2006

Worldwide market incorporating nanotechnology. Estimation made in 2000 (NSF)



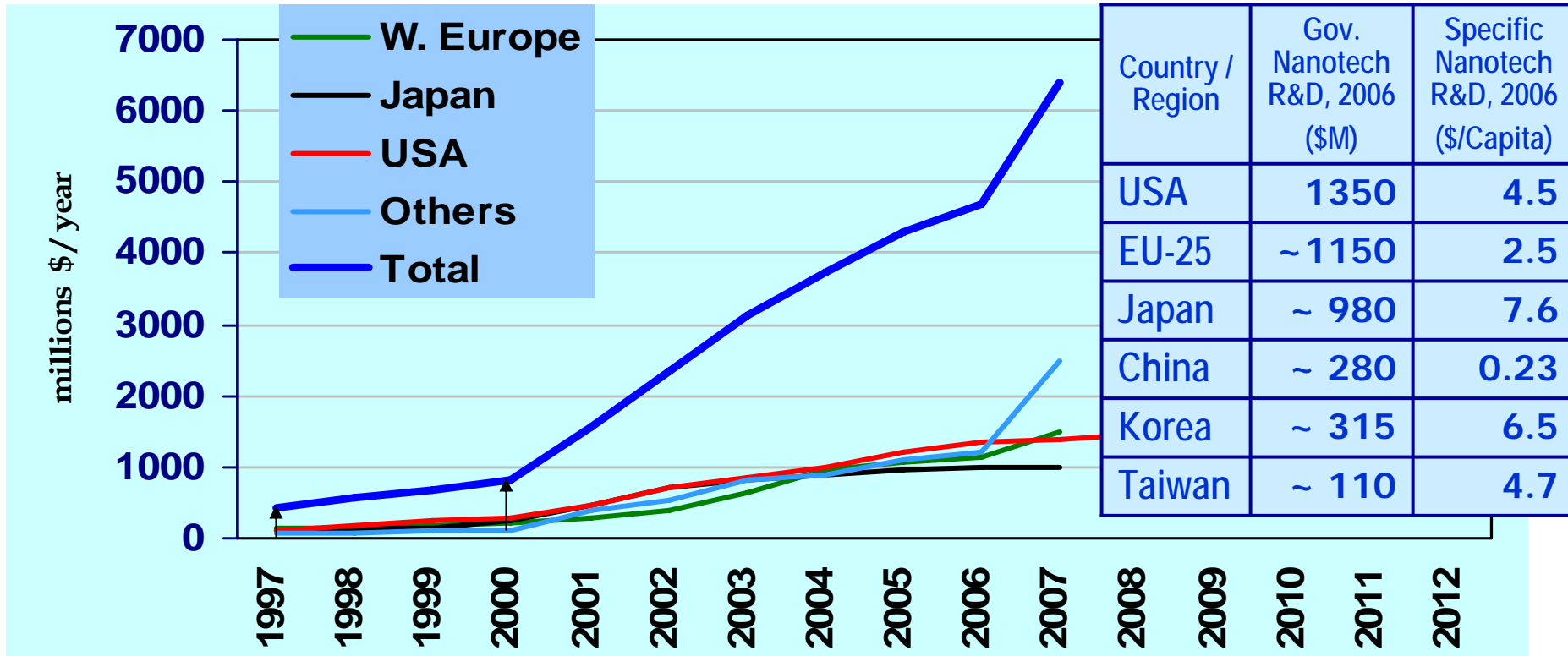
Changes in the international context since 2000:

Expanding nanotechnology domains

- 2000-2001:* nano expanding in almost all disciplines (NNI begins)
- 2002-2003:* industry moves behind nano development
- 2003-2004:* medical field sets up new goals
All developed countries and many countries in development invest in R&D (over 60 countries)
- 2004-2005:* media, NGOs, public, international organizations get involved
- 2006-2007:* new focus on common Earth resources - water, food, environment, energy, materials
- 2007-2008:* Nano seen as a technological, economical and strategic advantage for nations and large businesses

Context – Nanotechnology in the World

National government investments 1997-2007 (estimation NSF)



Seed funding
(1991 -)

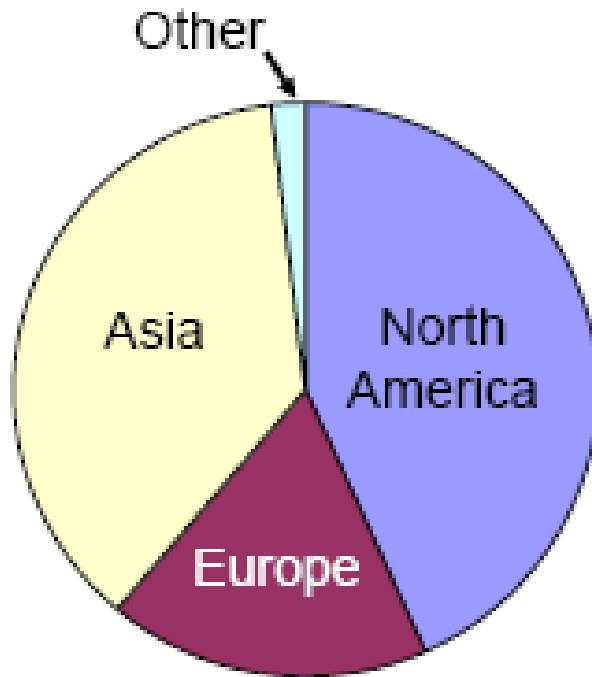
NNI Preparation
(vision / benchmark)

1st Strategic Plan
(passive nanostructures)

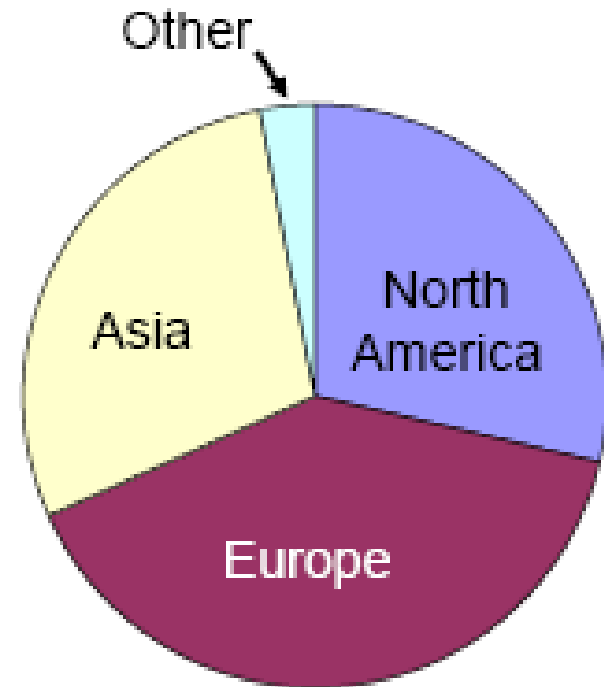
2nd Strategic Plan
(active ns. & systems)

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

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



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



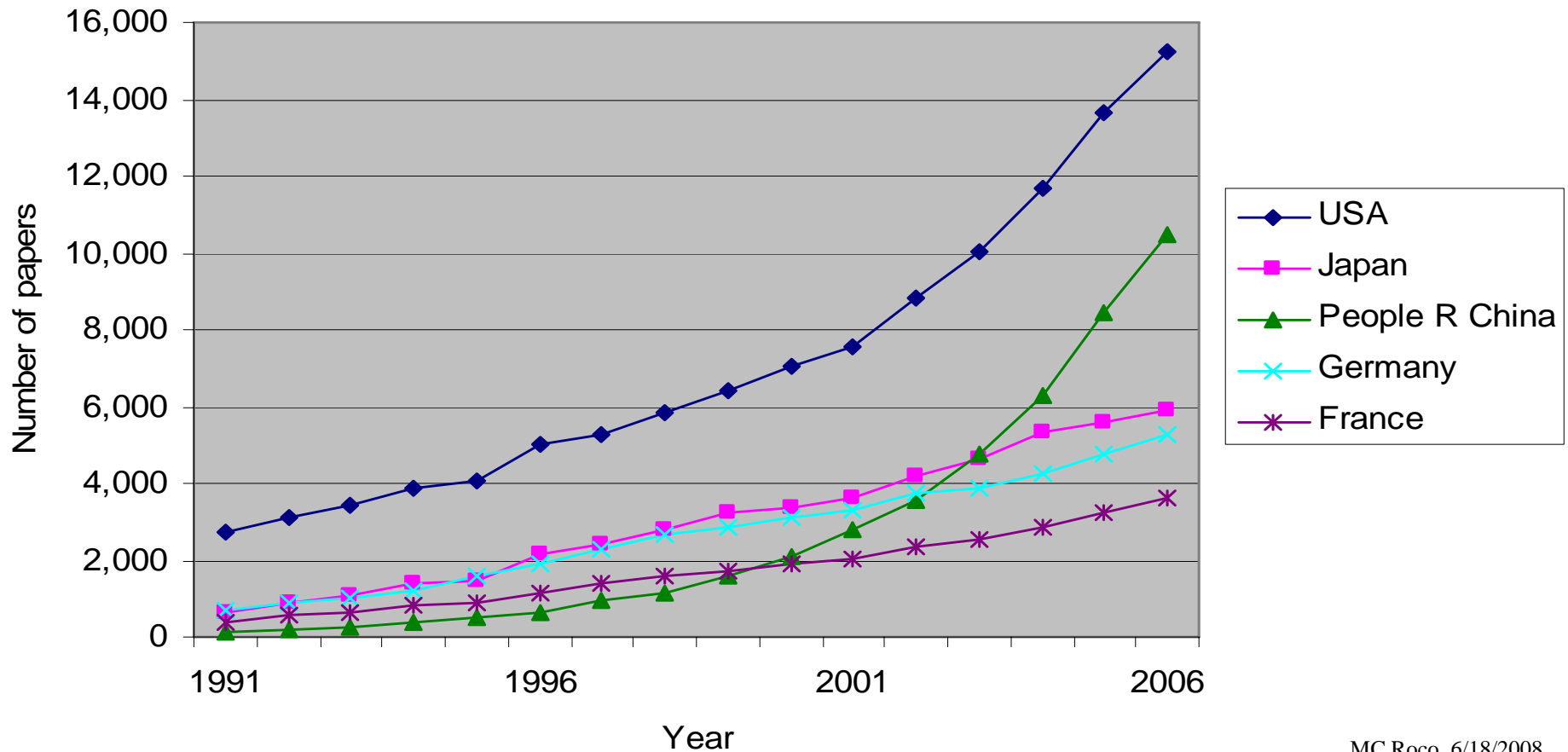
Public (National, regional, state)
Total = \$6.4 billion

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

Source: Lux Research

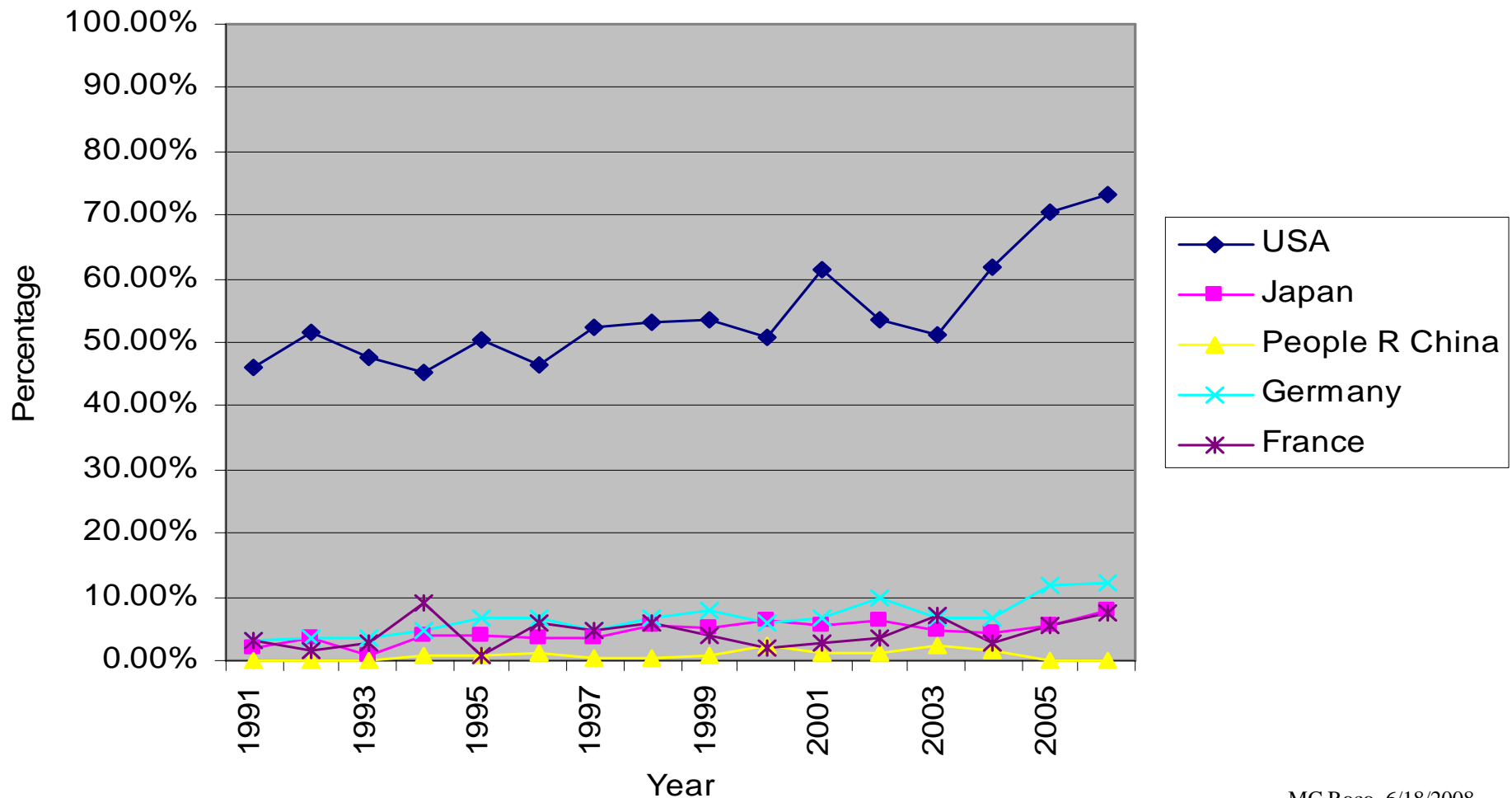
Nanotechnology research publications

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))



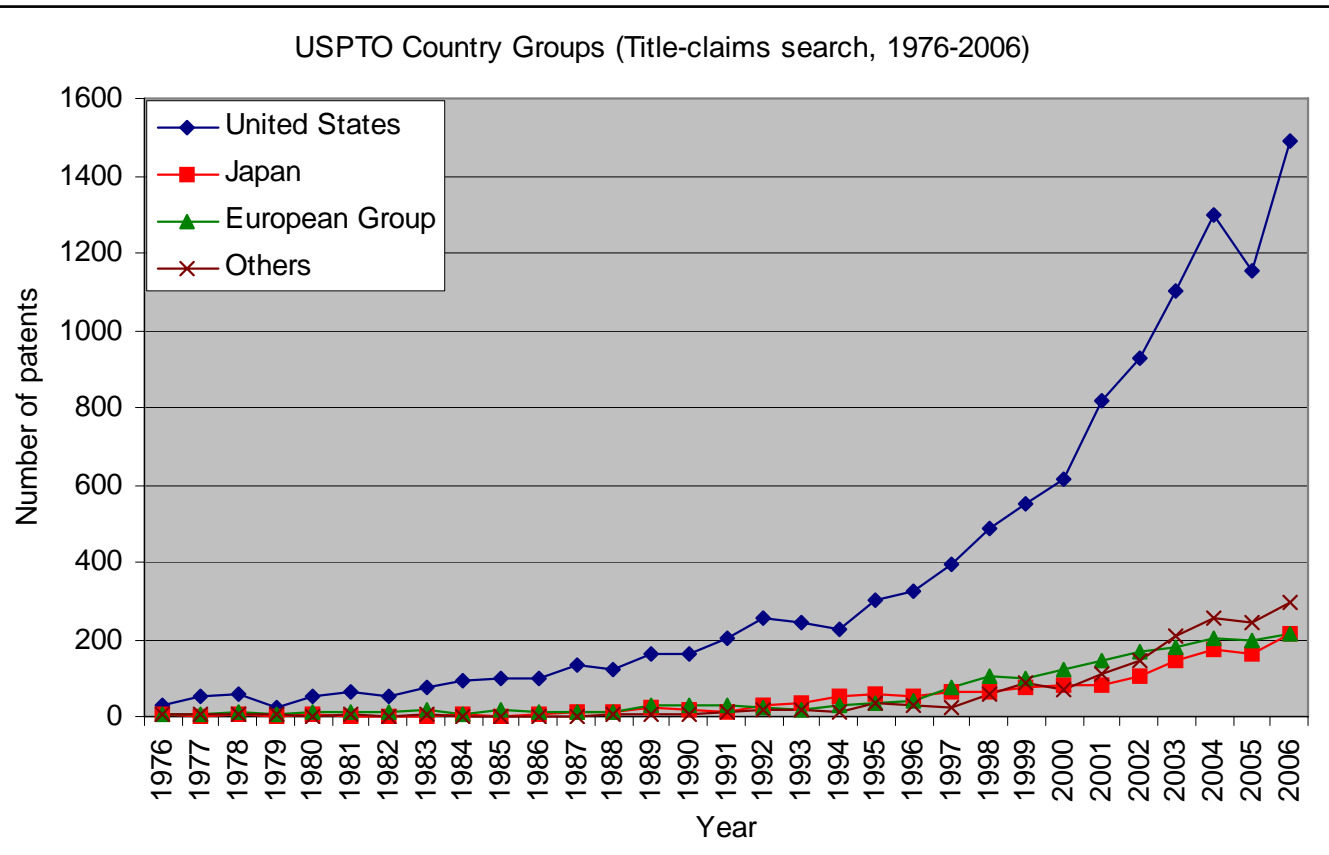
Highly cited nanotechnology related papers published in Science, Nature and PNAS

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



NSE patents at USPTO by country group

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



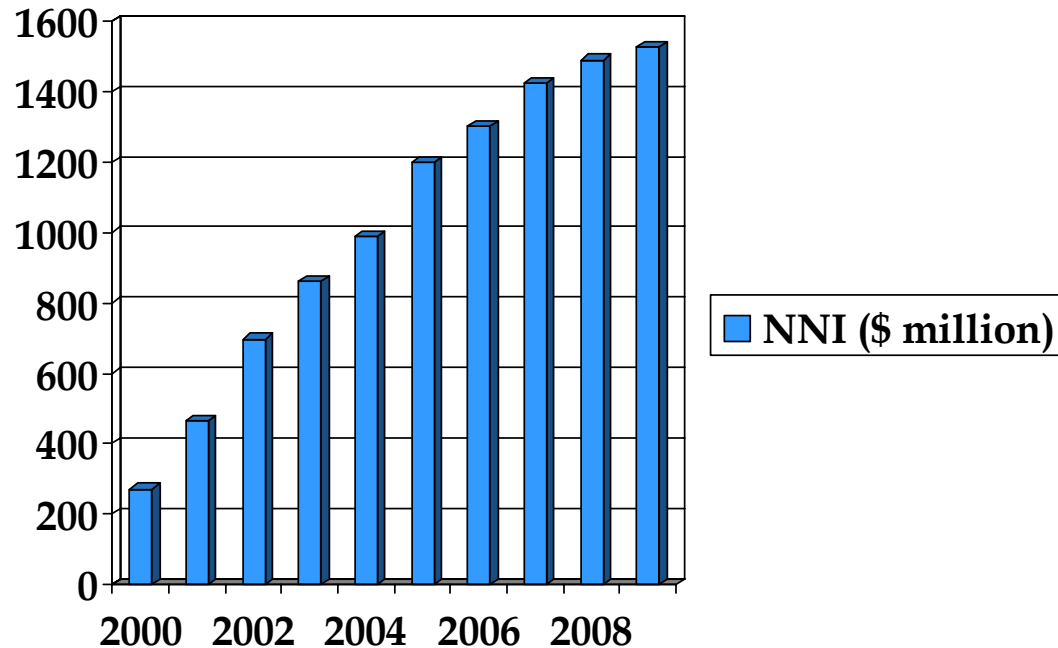
	United States	Japan	European Group	Others
1976	30	3	3	6
1977	53	2	3	3
1978	58	3	9	3
1979	26	2	7	3
1980	50	3	9	0
1981	61	1	10	3
1982	51	1	13	1
1983	73	1	15	4
1984	93	4	8	0
1985	97	2	16	1
1986	100	6	11	1
1987	132	12	11	0
1988	124	10	10	6
1989	162	21	28	4
1990	164	17	28	7
1991	204	14	28	9
1992	256	31	26	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

Changing national investment

FY 2009 NNI Budget Request - \$1,527 million

MC Roco, 01/10/2009

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

Building balanced and flexible R&D infrastructure

Ex: US - NNI Infrastructure since 2000

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

Centers & Networks

◆ DOD

◆ NASA

◆ NIH

◆ NIOSH

◆ NSF Centers

User Facilities

◆ DOE NSRCS

◆ NIH User Facility

◆ NIST

◆ NNI

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



Nationwide Impact

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

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

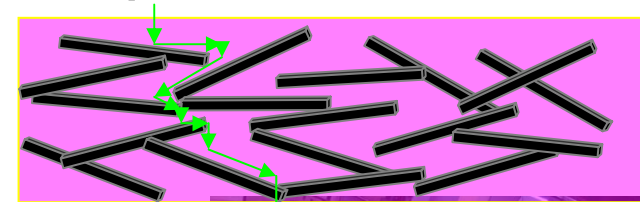
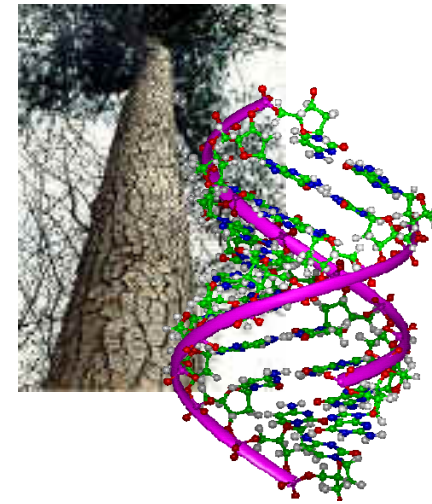


Nanotechnology holds major implications in agriculture and food systems

- **NT offers the tools to understand and transform biosystems**
Strong impact on sub-cellular dynamics; Regeneration mechanisms; Genome description; Food characterization
- **Solutions to agriculture and food industry**
Diagnostics and treatment; Synthesis of chemical for agriculture; More effective chemicals and biodegradable; Food preparation and conservation; Sensors and control
- **A new platform for new developments**
Nanoscale-based chemical treatment; Bio-engineering and bio-processing, bio-nanomechanical systems, biochips, filtration, fluidics, green manufacturing (waste treatment, biocompatibility and biocomplexity aspect); New nanoscale materials and processes; Automation using nanoelectronics and nanosensors
- **Promise of sustainable development in long term**

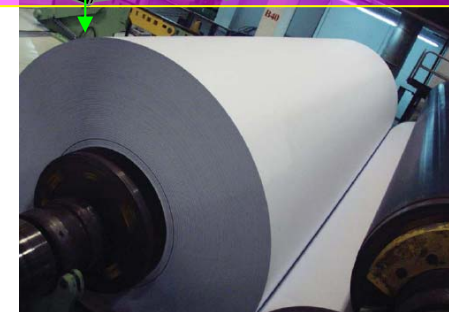
Research Directions Reports related to agriculture and food systems

- *Nanotechnology Research Directions*
Springer (former Kluwer), 1999
- *Nanoscale Science and Engineering for Agriculture and Food Systems*. Report from the National Planning Workshop, Washington, DC, Nov. 18-19, 2002.
www.nseafs.cornell.edu/web.roadmap.pdf
- Forestry and paper products *Road Map and Workshops*



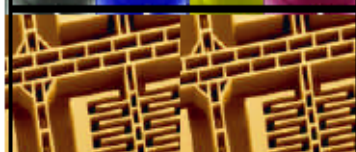
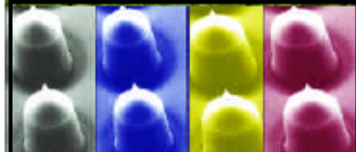
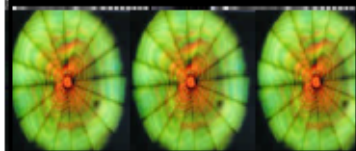
NNI contributes through the general S&E foundation and via specific programs at USDA, DOE, NSF, others.

NNI-Forestry Industry CBAN (informal work, to be signed)



"We do not want science floating in the skies. We want to bring it down and hitch it to our plows."

(Anonymous Wisconsin farmer, from "One Hundred Years of Agricultural Research at Cornell University," 1997)



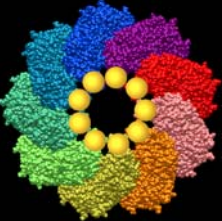
NANOSCALE SCIENCE AND ENGINEERING FOR AGRICULTURE AND FOOD SYSTEMS

A Report Submitted to
Cooperative State Research, Education and Extension Service
THE UNITED STATES DEPARTMENT OF AGRICULTURE

NATIONAL PLANNING WORKSHOP
November 18-19, 2002
Washington, DC

Co-Chairs:
Dr. Norman Scott, Cornell University
Dr. Hongda Chen, CSREES/USDA

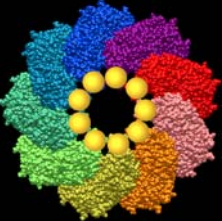
September 2003



NNI Accomplishments (1)

- Developed foundational knowledge for control of matter at the nanoscale:
over 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 patents², and
 - ~70% of startups³ in nanotech.Over 2,500 companies with nanotechnology products in 2007 (U.S.)
- Infrastructure:
70 new large nanotechnology research centers, networks and user facilities in 2007; about 30,000 users/yr in 2 academic-based networks

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

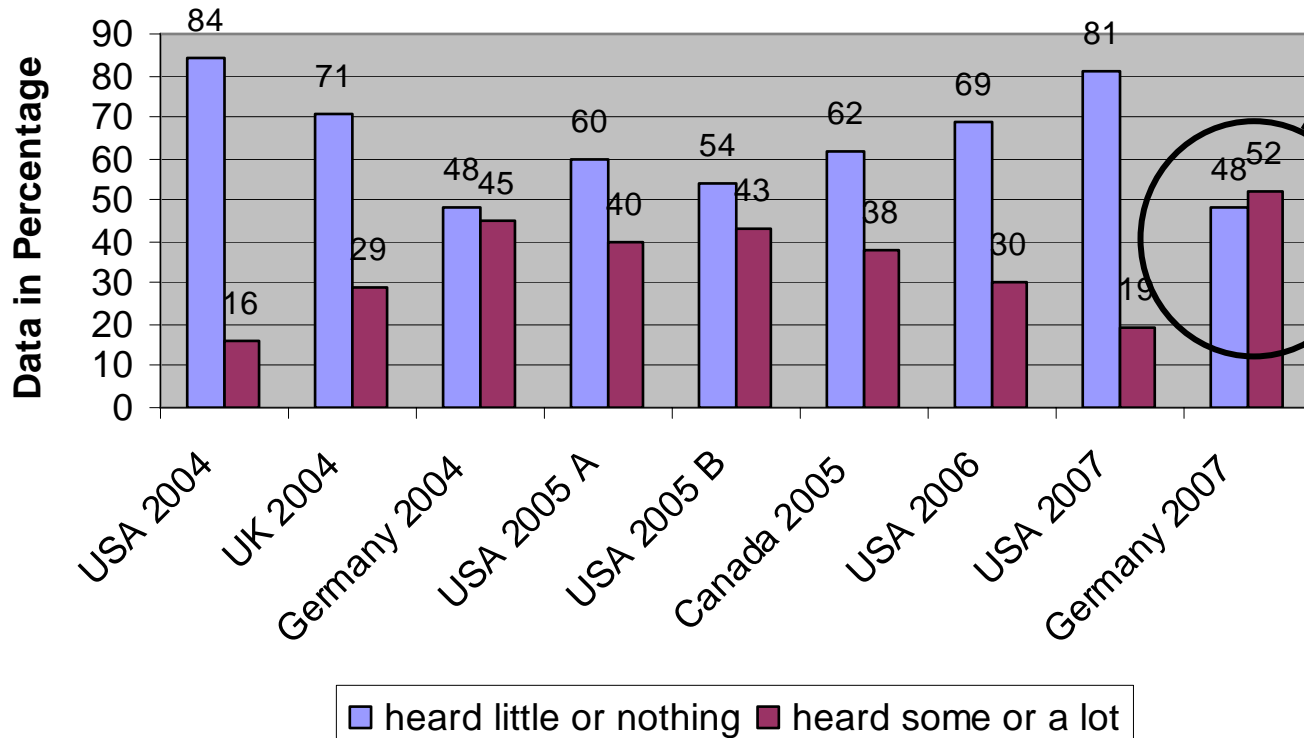


NNI Accomplishments (2)

- **Partnerships**: with industry (Consultative Boards for Advancing Nanotechnology - CBAN), regional alliances (22), international (over 25 countries), numerous professional societies
- **Societal implications and applications** -
from the beginning, about 10% of 2004 NNI; addresses environmental and health, safety, and other societal and educational concerns; NSET SC leadership thru NEHI WG
- **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
- **Leadership**:
The U.S. NNI has catalyzed global activities in nanotechnology and served as a model for other programs.

International Surveys On Public Perception: Public Knowledge

Public Knowledge Base on Nanotechnologies in International Surveys



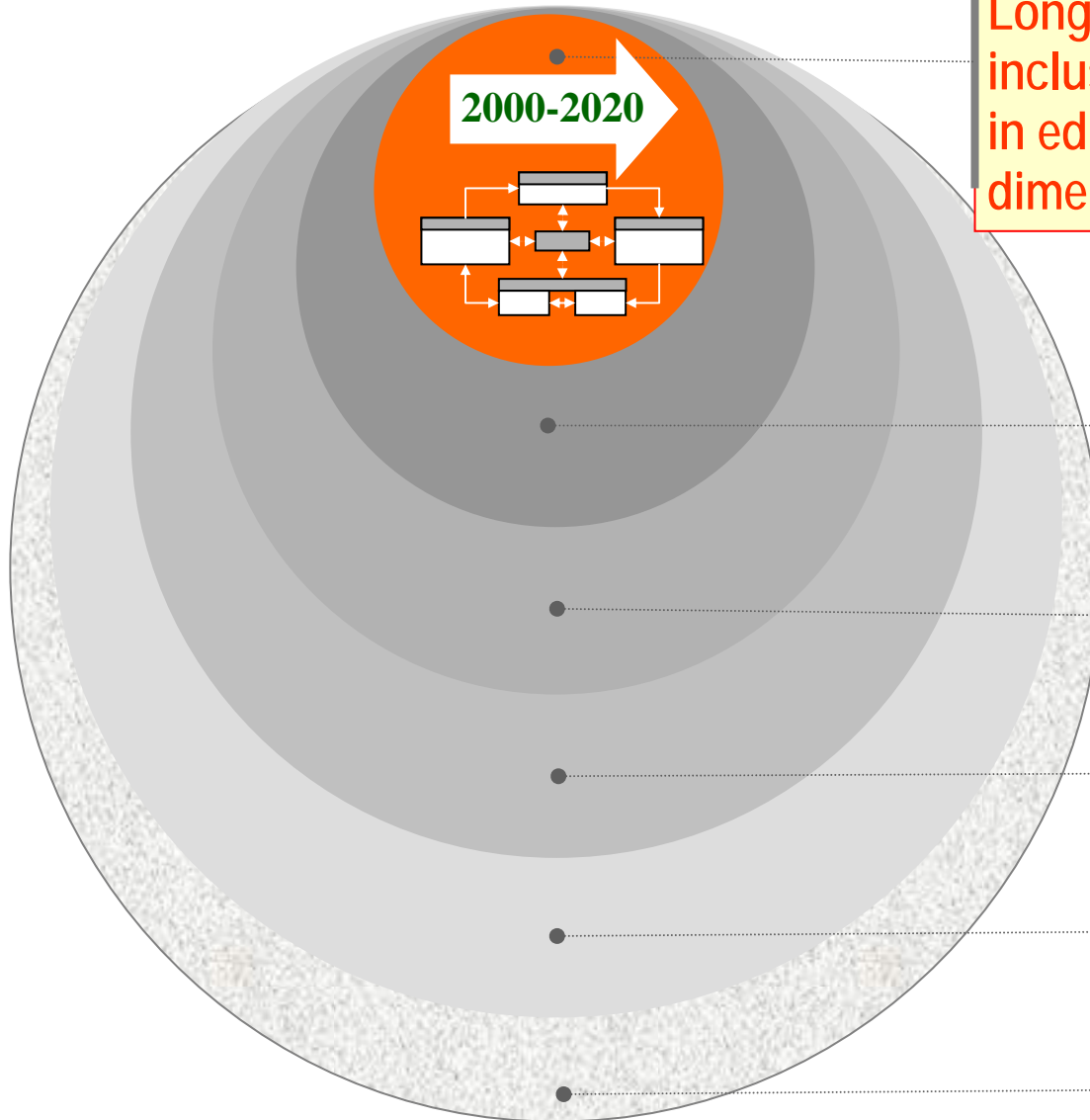
Consumers know applications mainly from Science Shows on TV and advertising

(IRGC, A. Grobe et al., 2008)

USA 2004 Cobb & Macoubrie; UK 2004 Royal Society; Germany 2004 komm.passion; USA 2005 A Einsiedel; USA 2005 B Macoubrie; Canada 2005 Einsiedel; USA 2006 Hart; USA 2007 Kahan et al.; Germany 2007 BfR

NANOTECHNOLOGY GOVERNANCE OVERVIEW

Core Governance Process:
Long-term view, transforming,
inclusive, horizontal/vertical, priority
in education, addressing societal
dimensions, NT risk governance



Main Actors:

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

IRGC workshop “risk governance of nanotechnology applications in food and cosmetics”

Linkov et al. 2008
J. Nanopart. Res.

Comparison of different nanotechnology risk framework documents

Document	Focus	Science and Risk Research				Regulation and Law				Stakeholder Engagement, Society				Leadership and Governance				Extent of criteria addressed by document
		Metology: detection, characterisation, data collection	Assessment: environmental impact & transport	Assessment: tox. effects, human health	Assessment: environmental effects & toxicity	Voluntary Codes: Best Practice	Regulation by information: (eg labelling)	Regulation by economics: (eg tax of testing fee)	Liability: penalty for pollution	Risk communication: education and information	Stakeholder engagement: tools	Partnership: Academia, industry, public org., intl. regulators	Emphasis on ethics	Transparent: decision making	Consideration of benefits	Legislation: adaptive modification or new development	Consideration of Precautionary Principle	
US EPA White Paper	. current scientific knowledge and gaps . environmental risks and benefits	2	2	2	2	2	1	1	1	2	1	2	1	1	2	1	0	23
US FDA	. recommendations to FDA Commissioner . adequacy and application of FDA authority	2	0	2	0	0	2	2	0	2	1	1	0	1	0	0	0	13
Woodrow Wilson Center	. outlines possibilities for govt action to deal with adverse effects	1	1	2	1	2	2	2	1	2	2	2	0	0	1	2	1	22
ED-Du Pont	. self regulation framework . whole life cycle	2	2	2	2	2	1	0	0	1	1	0	0	2	1	2	1	19
Québec Commission	. scientific, legal and ethical implications . focus societal implications	1	2	2	2	2	2	0	0	2	1	2	2	2	2	1	2	25
Royal Society UK	. current scientific knowledge and applications . EHS risks and uncertainties	2	2	2	2	1	2	2	1	2	2	1	2	1	2	1	1	26
UK DEFRA	. voluntary reporting scheme . goal: help govt to develop appropriate risk control	1	1	1	1	2	0	0	0	1	1	1	0	0	0	0	0	9
Responsible NanoCode	. key issues for development of responsible nano code . workshop paper	0	0	1	0	2	0	0	0	1	1	1	0	0	0	0	0	6
EC SCENIHR	. appropriateness of current RA methodologies . suggestions for methodological improvements	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	8
EC Action Plan	. ensure research with max. impact and responsibility . ensure that products are useful, safe and profitable	1	1	1	1	0	1	0	0	2	2	2	2	0	1	1	0	15
IRGC Policy Brief	. assist policy makers in developing processes and regulations	1	2	2	2	2	1	0	0	2	2	2	2	1	2	1	1	23
IRGC White Paper I	. integrated, holistic and structured investigation of risk . pertaining governance structures and processes	1	1	2	2	1	1	1	1	2	2	2	2	2	2	2	2	26
IRGC White Paper II	. application of WOP I to nanotechnology	1	2	2	2	1	1	1	1	2	2	2	2	2	2	2	2	27
Over all:		17	18	23	19	17	14	9	5	21	18	18	13	12	15	13	10	

≥ 18 met covered criteria (green)
12-17 covered to some extent (yellow)
≤ 12 insufficiently covered criteria (red)

Five possibilities for global nanotechnology governance

1. Establish models for the global self-regulating ecosystem to enhance discovery, education, innovation, informatics, commercialization and broad societal goals
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