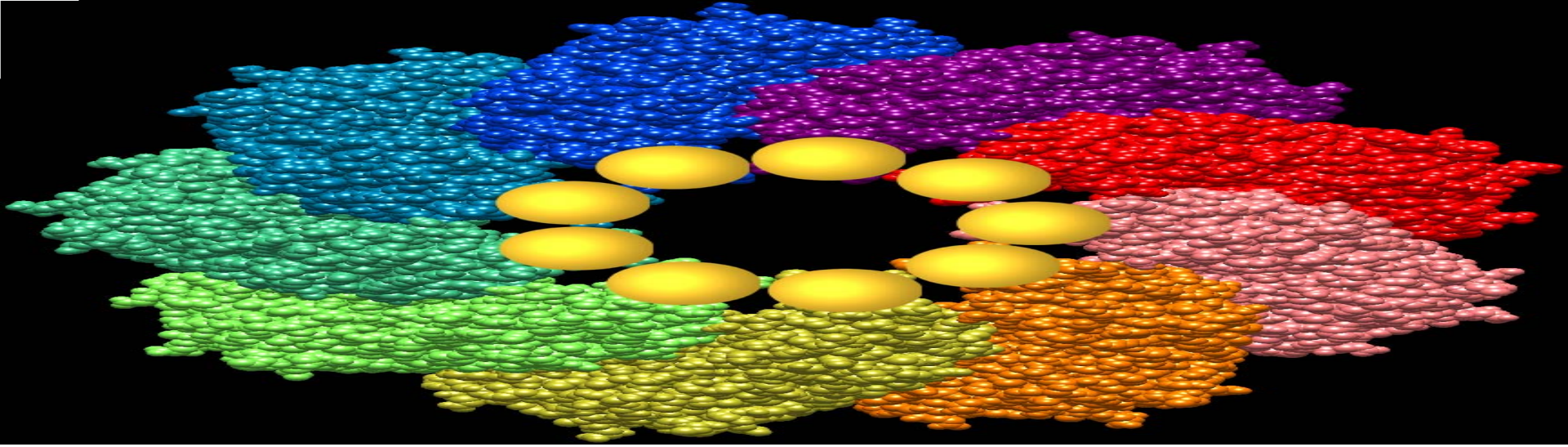


McMillan, 2004

Global Development and Governance of Nanotechnology

Mihail Roco

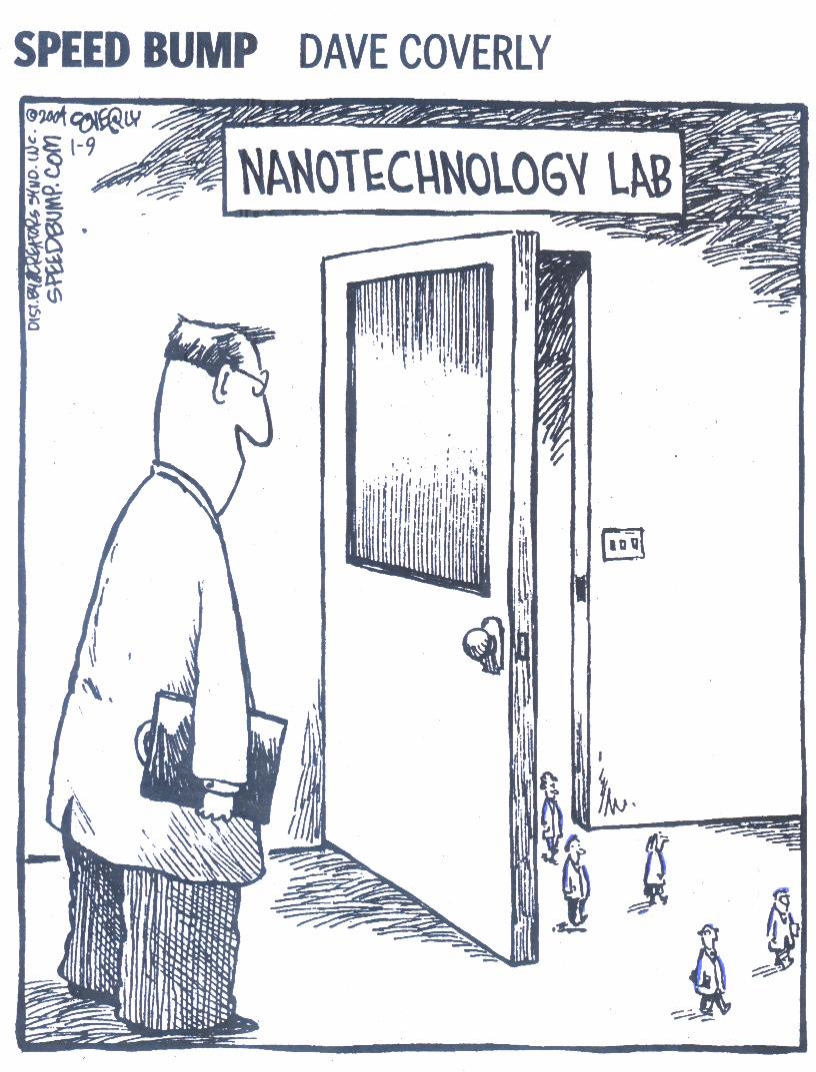
National Science Foundation and National Nanotechnology Initiative

The Frank Howard Distinguished Lecture Series

George Washington University, October 12, 2009

Many perceptions of nanotechnology today

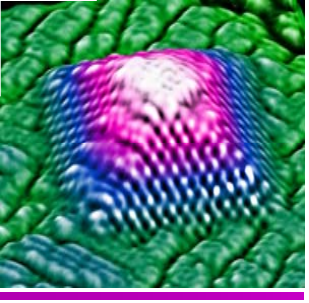
from CAN DO ANYTHING

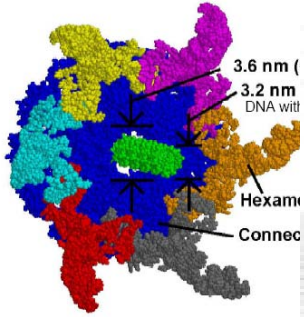


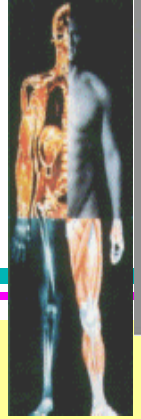
to RISK ANYWHERE

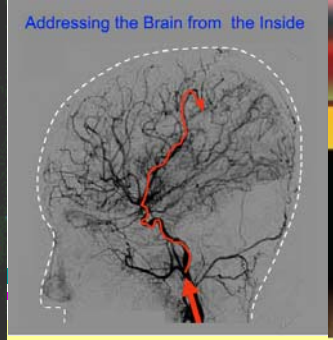
At a nano lunch,
there is a perceived risk

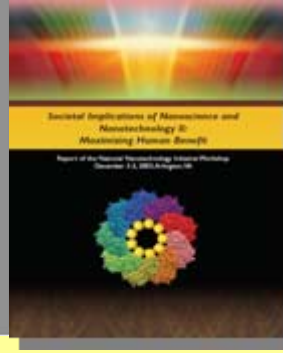
"... nanopizza is taking technology a step too far"











TOPICS

Long-view for nanotechnology development

NNI and the international context

Future opportunities

Global governance of nanotechnology

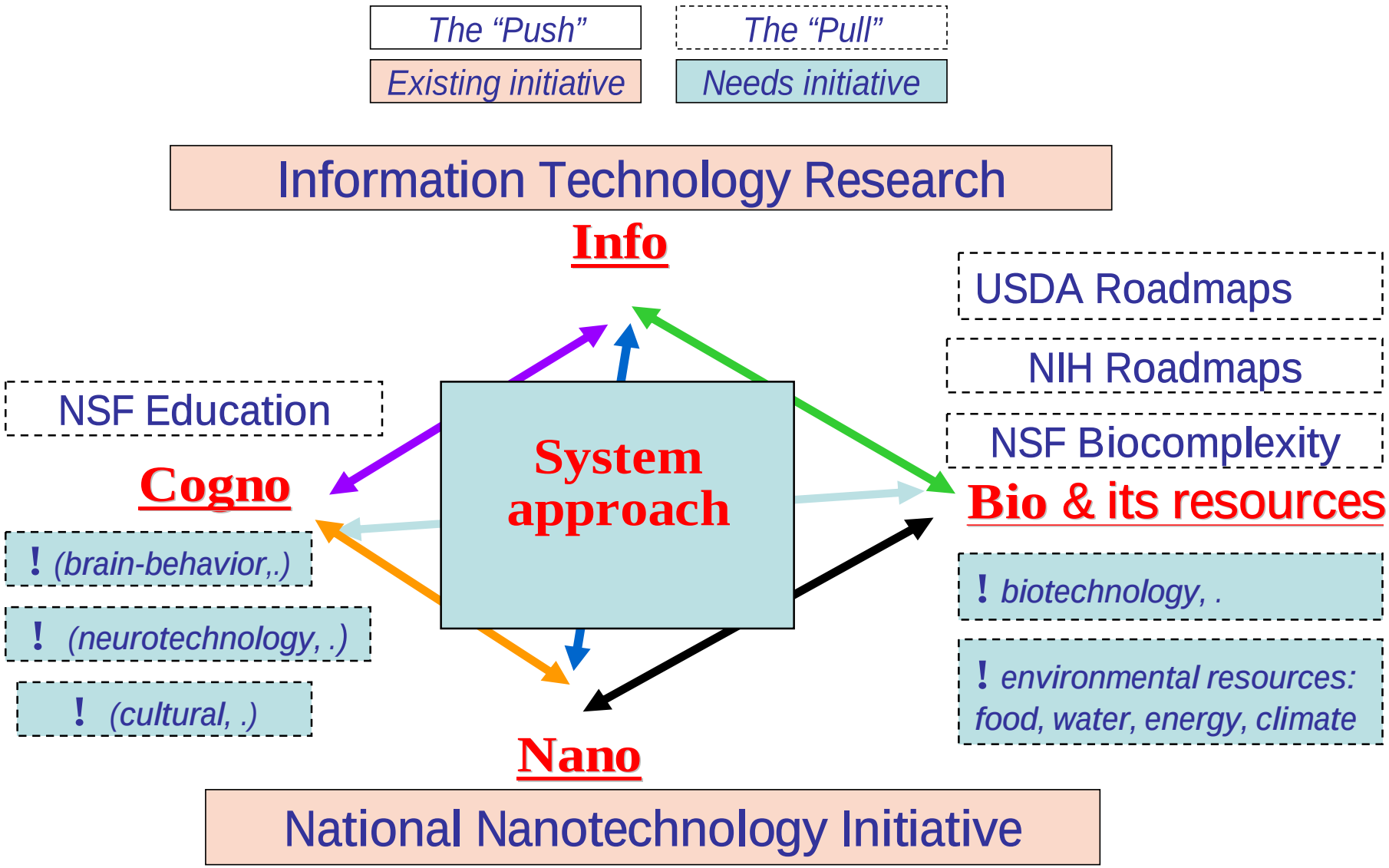
Context: A transforming word underlying the importance of emerging technologies

- Knowledge has exponential growth
- Education, science, technology and economic shift, including transfer of wealth from ”West to East”

- Need of radically new technologies
  Demographics and limited resources
- Need of global governance
  Collaboration and conflict

Converging New Technologies transforming tools

(overview in 2000; convergence better than for large-scale systems)



Benchmark with experts in over 20 countries

"Nanostructure Science and Technology"

NNI preparatory Report, Springer, 1999

Nanotechnology Definition for the R&D program

Working at the atomic, molecular and supramolecular levels, in the length scale of ~ 1 nm (a small molecule) to ~ 100 nm range, in order to understand, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure

- NNI definition encourages new R&D that were not possible before:

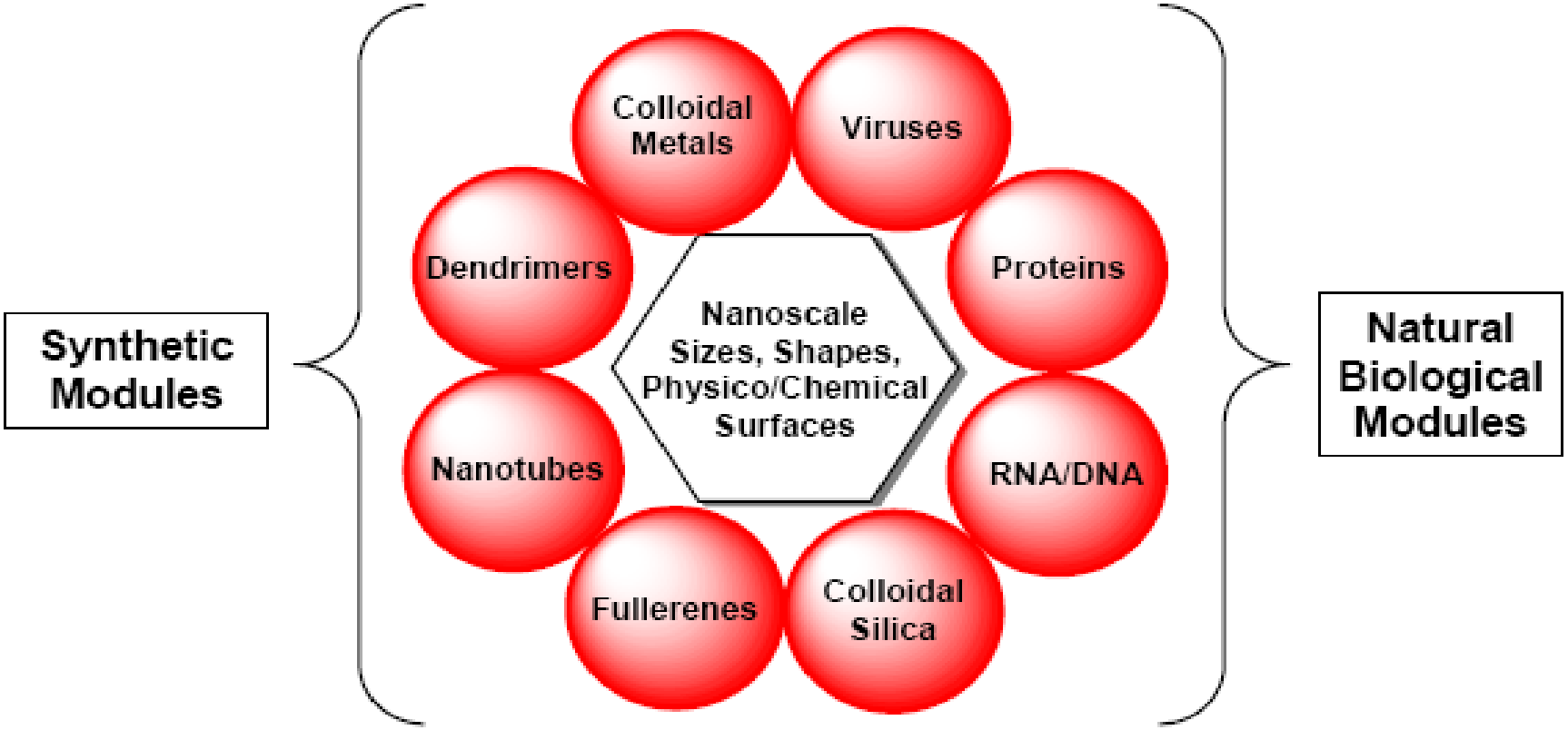
  - ***the ability to control and restructure matter at nanoscale***
  - ***novel phenomena, properties and functions at nanoscale,***
  - ***integration along length scales, systems and applications***

NANOSCALE IS A NATURAL THRESHOLD OF TRANSITION

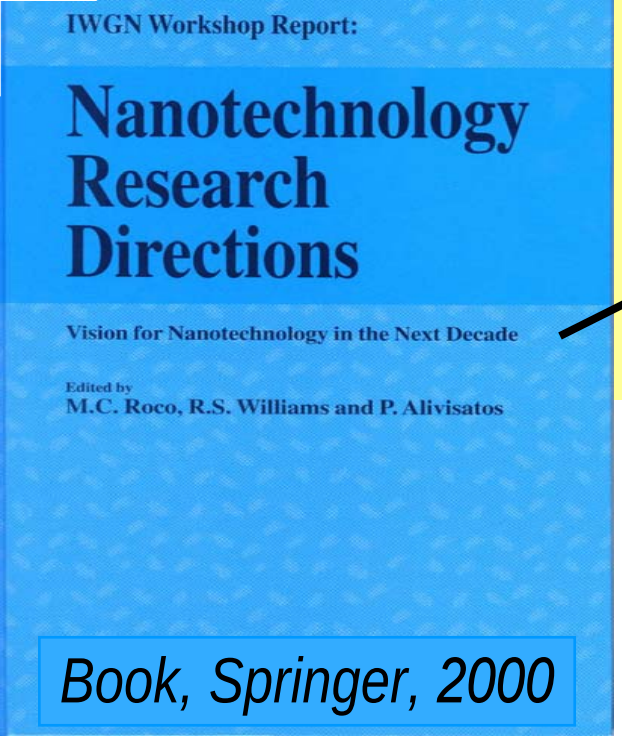
from individual to collective behavior of atoms & molecules,

where nanoscale modules are established

dominated by quantum, selfassembling, etc. effects



Characteristic internal structure



Book, Springer, 2000

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

Systematic control of matter on the nanoscale will lead to a revolution in technology and industry

- *Change the foundations from micro to nano in knowledge, industry, medicine, sustainability, ..*
- *Create a general purpose technology (similar IT)*

More important than miniaturization itself:

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

CREATING AN NEW FIELD AND COMMUNITY IN TWO FOUNDATIONAL STEPS (2000~2020)

Nanotechnology Applications

MATERIAL | ELECTRON | HEALTH | ENVIRON | ENERGY | MICROCR | MANUFACT | SECURITY | INSTRUM

NANO 2

Converge knowledge for general purpose technology

~ 2011 ⟷ ~ 2020

Direct measurements; Science-based design and processes; Collective effects; Create nanosystems by technology integration

New disciplines
New industries
Societal impact

NANO 1

Interdisciplinary research at the nanoscale

~ 2001 ⟷ ~ 2010

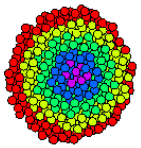
Indirect measurements, Empirical correlations; Single principles, phenomena, tools; Create nanocomponents by empirical design

Infrastructure
Workforce
Partnerships

MC Roco, Oct. 12 2009

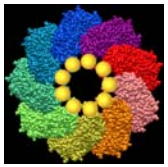
Generations of Products and Productive Processes

Timeline for introduction of industrial prototyping and nanotechnology commercialization (2000~2020)



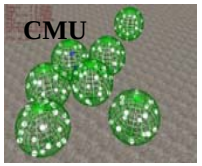
1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 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

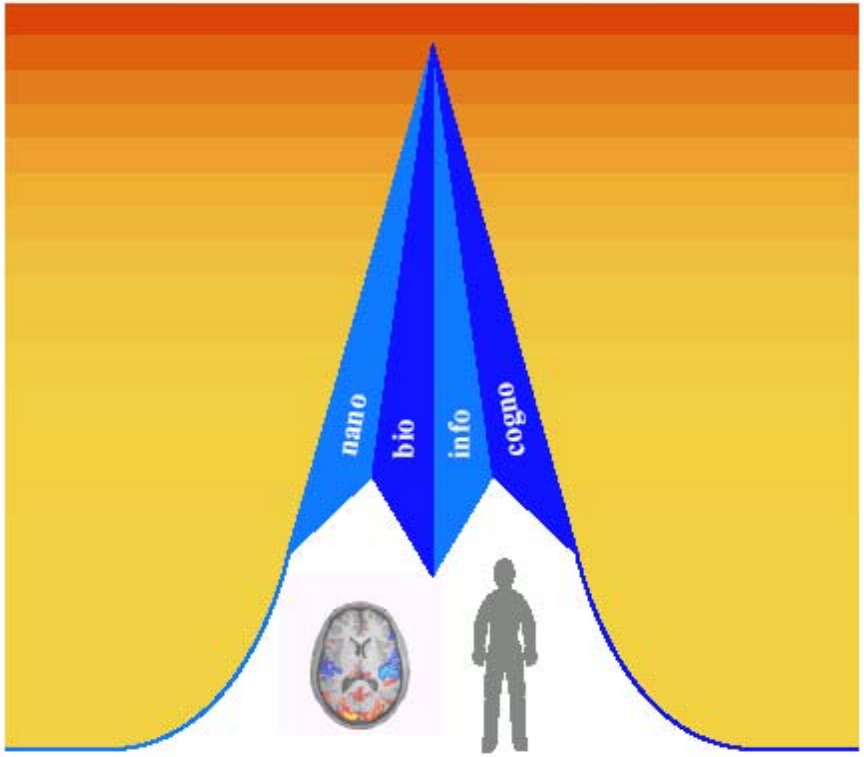
~ 2015-2020

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

Increased Complexity, Dynamics, Transdisciplinarity

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

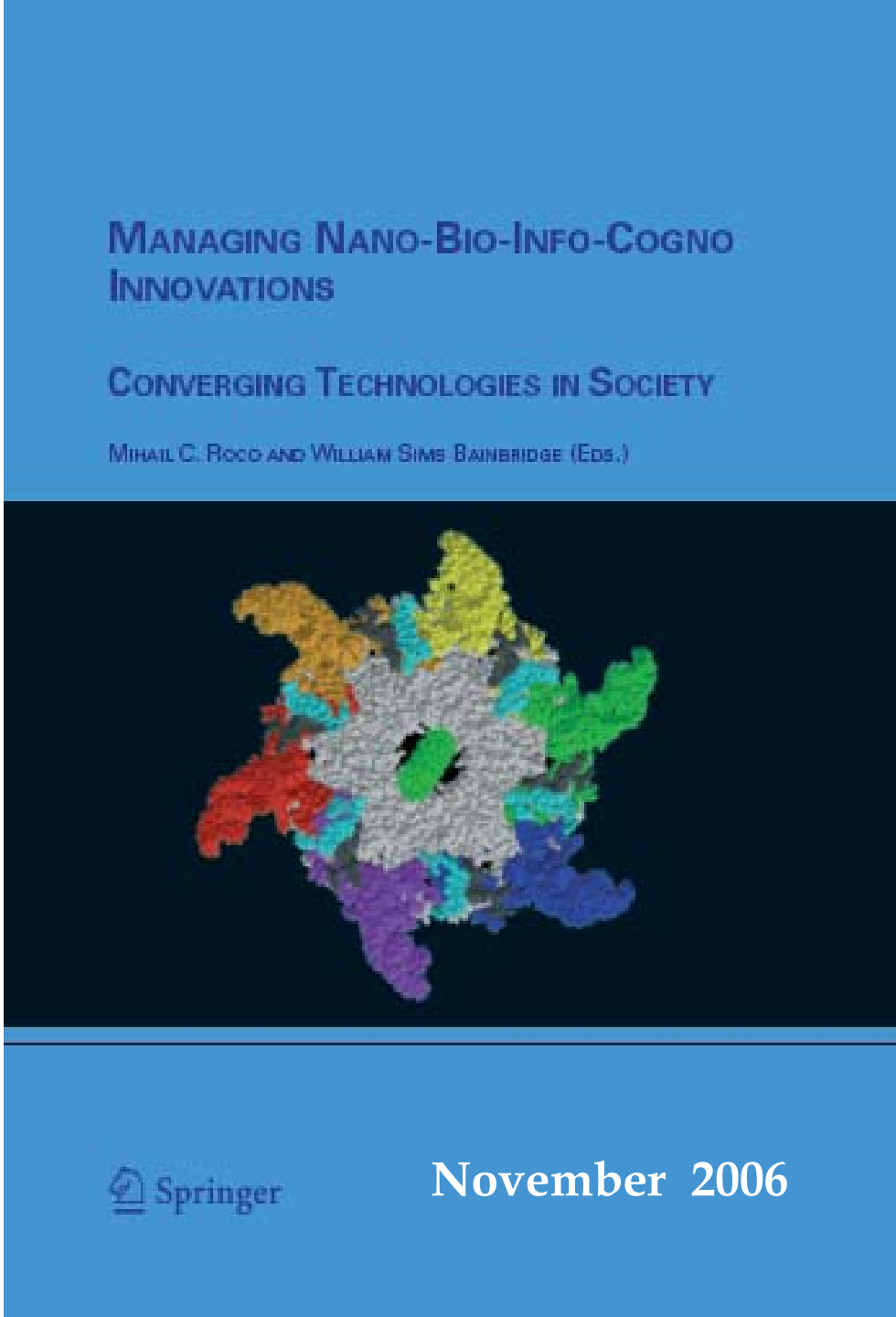
Four volumes on Convergence: 2003, 2006 and 2007 Springer; 2004 NYAS



CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

Workshop, Dec. 2001
www.nsf.gov/nano
Springer, 2003



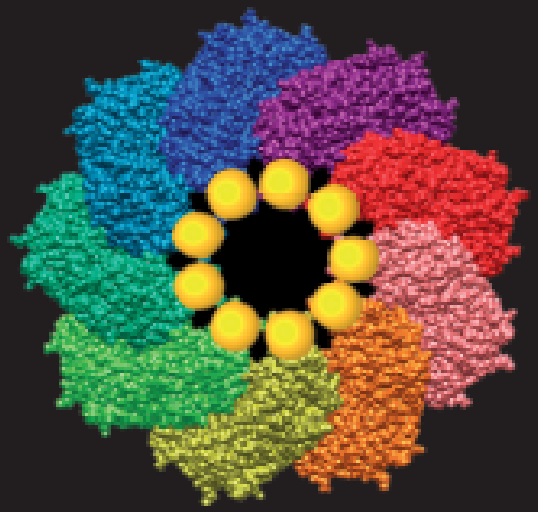
November 2006

Nanotechnology: Societal Implications I

Maximizing Benefits for Humanity

Edited by

Mihail C. Roco and William Sims Bainbridge



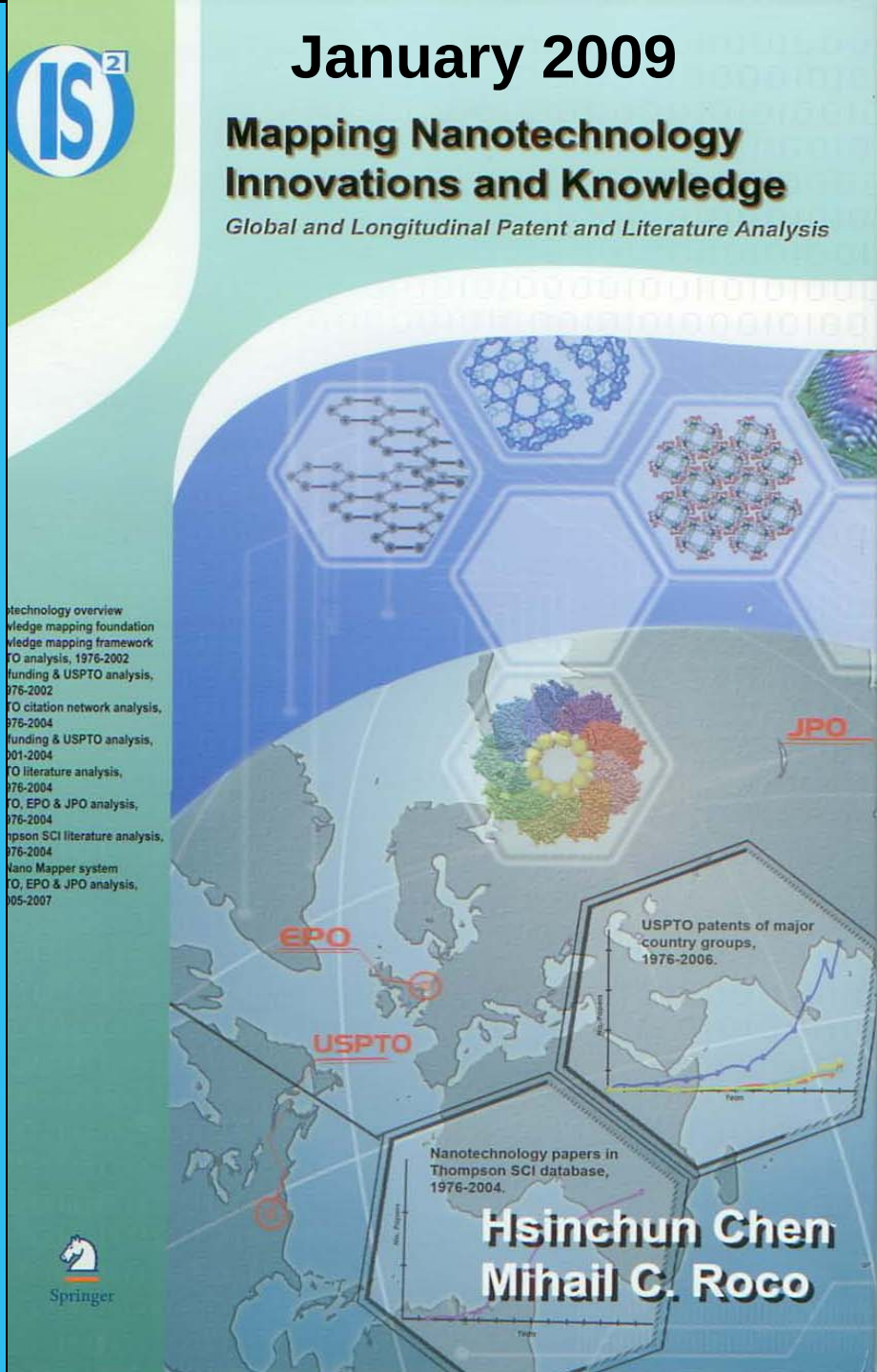
Springer

March 2007

January 2009

Mapping Nanotechnology Innovations and Knowledge

Global and Longitudinal Patent and Literature Analysis



2000-2009

Expanding nanotechnology domains

2000-2001: nano expanding in almost all disciplines;
by 2009: 11% of NSF awards; 5% papers; 1-2% patents

2002-2003: industry moves behind nano development
by 2009: ~ $200B products incorporating nano worldwide

2003-2004: medical field sets up new goals

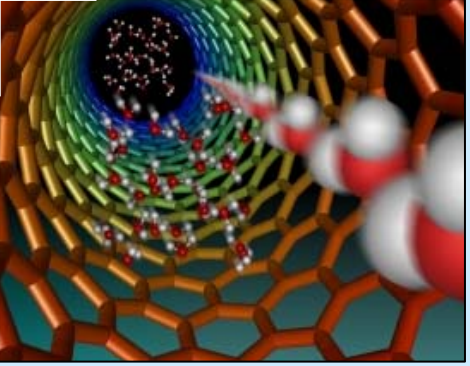
2004-2005: media, NGOs, public, organizations -involved

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

2008-2009: increased relevance to
economy – policies - sustainability

Nanotechnology in 2009 - still in an earlier formative phase of development

- Characterization of nanomodules is using micro parameters and not internal structure
- Measurements and simulations of a domain of biological or engineering relevance cannot be done with atomic precision and time resolution of chemical reactions
- Manufacturing Processes – empirical, synthesis by trial and error, some control only for one chemical component and in steady state
- Nanotechnology products are using only rudimentary nanostructures (dispersions in catalysts, layers in electronics) incorporated in existing products or systems
- Knowledge for risk governance – in formation



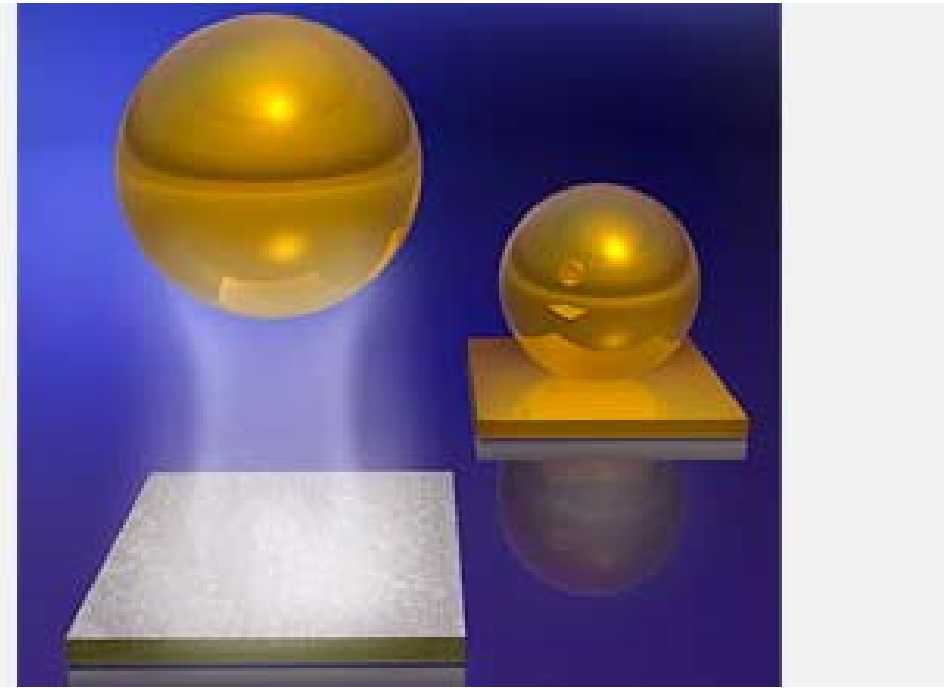
NS&E Priorities Research Areas

A. Scientific challenges for basic phenomena

- 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

Discovery of Nanoscale Repulsion

Federico Capasso, Harvard University



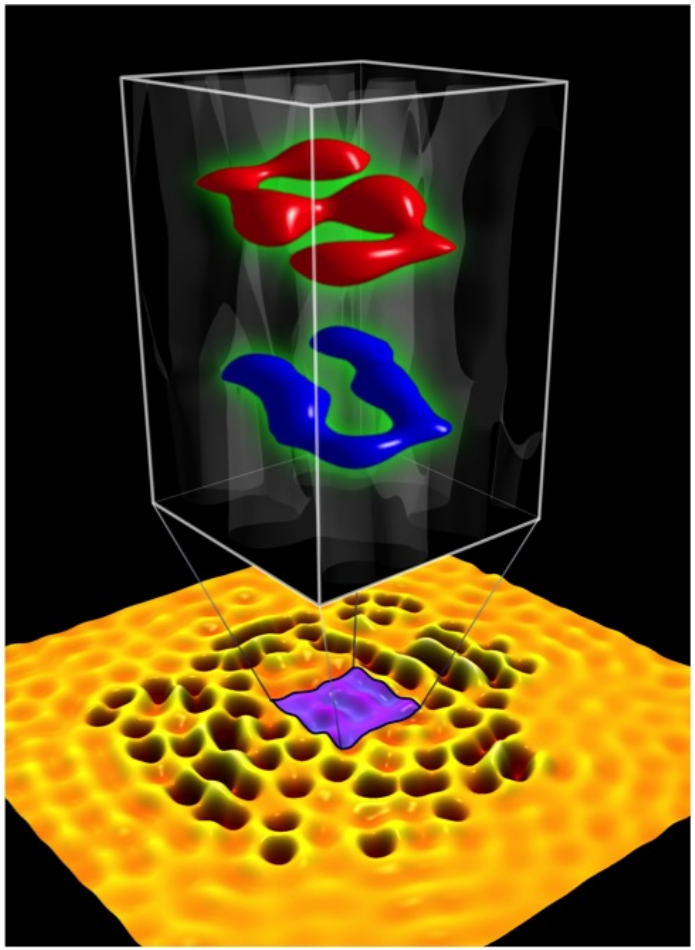
A repulsive force arising at nanoscale was identified similar to attractive repulsive Casimir-Lifshitz forces.

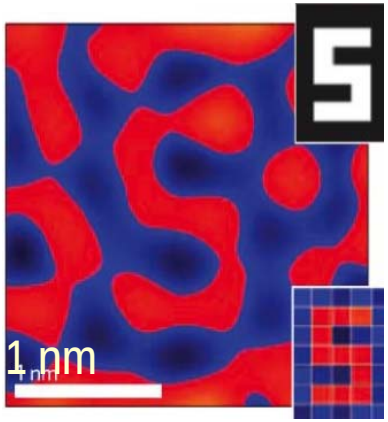
As a gold-coated sphere was brought closer to a silica plate - a repulsive force around one ten-billionth of a newton was measured starting at a separation of about 80 nanometers.

For nanocomponents of the right composition, immersed in a suitable liquid, this repulsive force would amount to a kind of quantum levitation that would keep surfaces slightly apart

Creating the World's Smallest Letters

Hari Manoharan, NSF – 0425897, NSEC Stanford U.





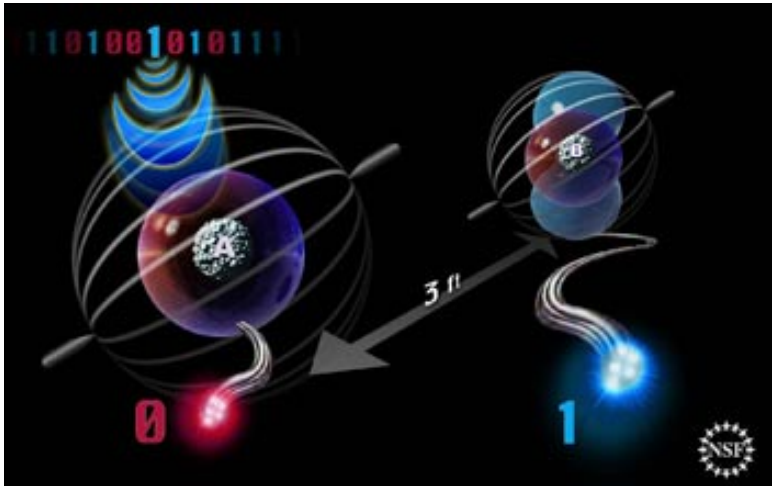
A STM is used to position CO molecules on a copper (111) surface and to read out by 2D illumination the **molecular holographic encoding** spelling the **letters SU of** <u>about 1 nm (0.8 by 1.5 nm) size in 3D</u>

The letters with features as small as 3 A are formed in the interference pattern generated by the 2D surface state electrons from the (111) face of the copper crystal and confined by the CO molecules acting as local gates (quantum holographic encoding)

C. Moon et al., Nature Nanotechnology, 4, (2009)

How to Teleport Quantum Information from One Atom to Another

Chris Monroe, University of Maryland, NSF 0829424



Teleportation carries information between entangled atoms.

Teleportation to transfer a quantum state over a significant distance from one atom to another was achieved.

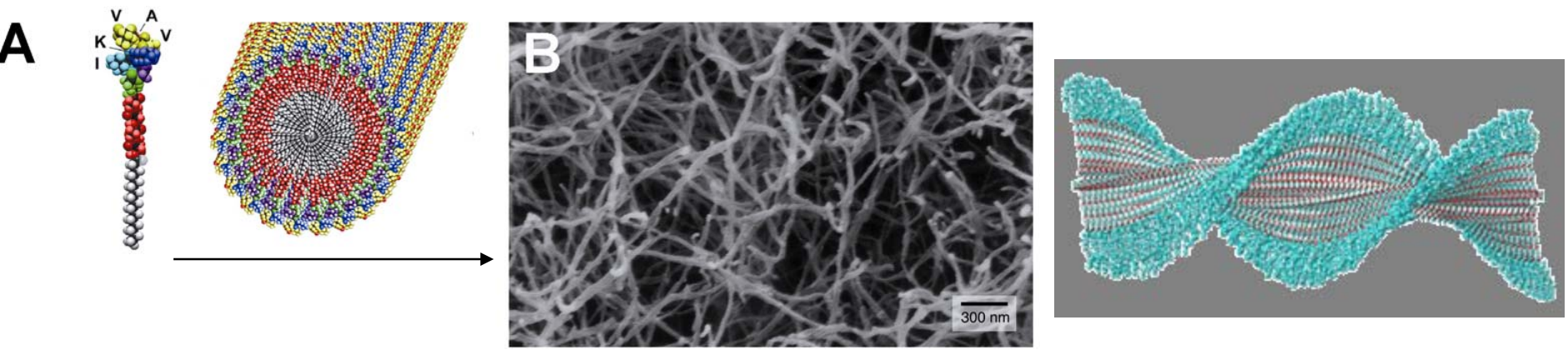
Two ions are entangled in a quantum way in which actions on one can have an instant effect on the other

Experiments have attempted to teleport states tens of thousands of times per second. But only about 5 times in every billion attempts do they get the simultaneous signal at the beam splitter telling them they can proceed to the final step.

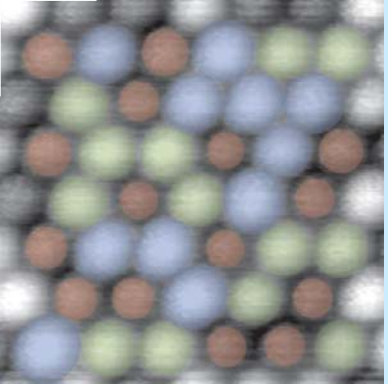
Example 4th generation (in research)

Designing molecules for hierarchical selfassembling

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



- New nanomachines, robotics - 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)



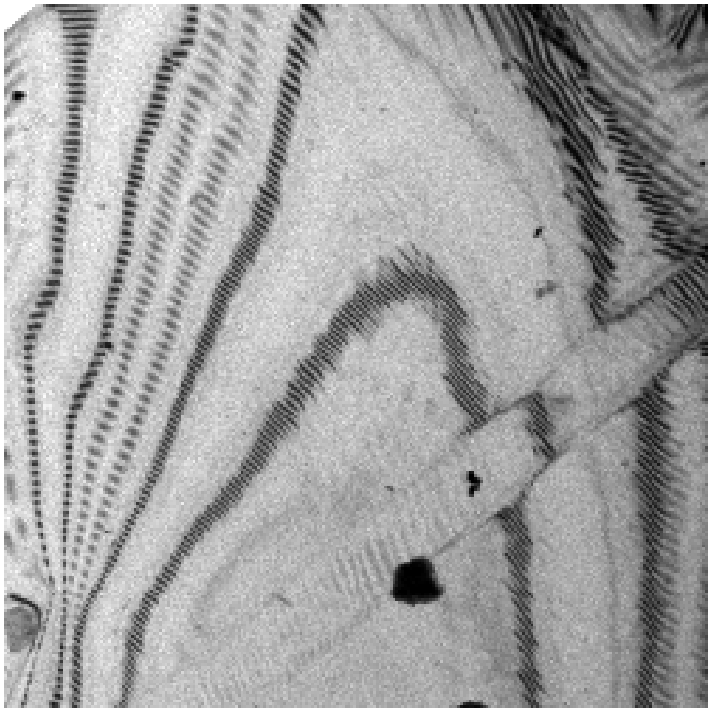
NS&E Priorities Research Areas

B. Development of nanotechnology

- Tools for measuring and restructuring
  with atomic precision, time resolution of reactions
- Understanding and use of quantum phenomena
- Understanding and use of multi-scale selfassembling
- Nanobiotechnology – sub-cellular and systems approach
- Nanomanufacturing hybrid, on site
- Systems nanotechnology

4D Microscope Revolutionizes the Way We Look at the Nano World

A. Zewail, Caltech, and winner of the 1999 Nobel Prize in Chemistry



Nanodrumming of graphite, visualized with 4D microscopy.

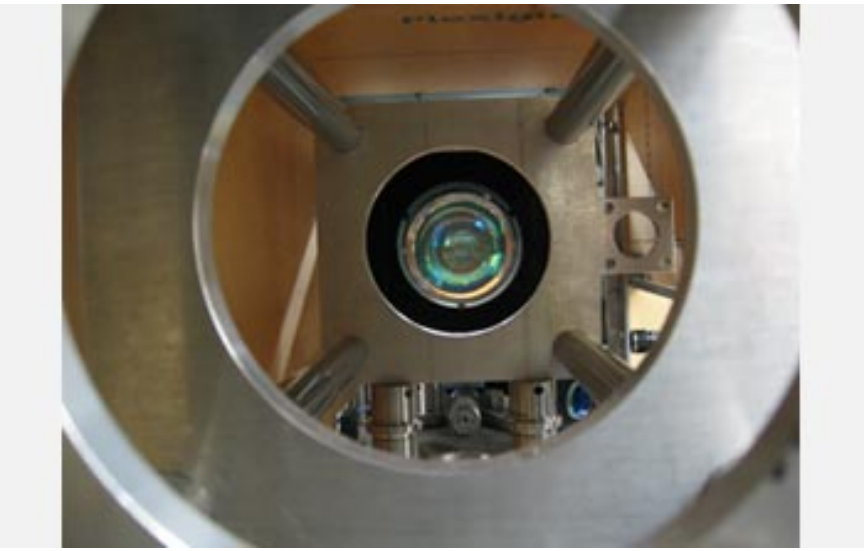
http://ust.caltech.edu/movie_gallery/

Use of ultra short laser flashes to observe fundamental motion and chemical reactions in real-time (timescale of a femtosecond, 10^{-15}s), with 3D real-space atomic resolution.

Allows for visualization of complex structural changes (dynamics, chemical reactions) in real space and real time. Such visualization may lead to fundamentally new ways of thinking about matter

Excited Atoms to Advance Quantum Computing

Mark Saffman, University of Wisconsin-Madison



End-on view of high numerical aperture custom lens system used to trap and image single atoms.

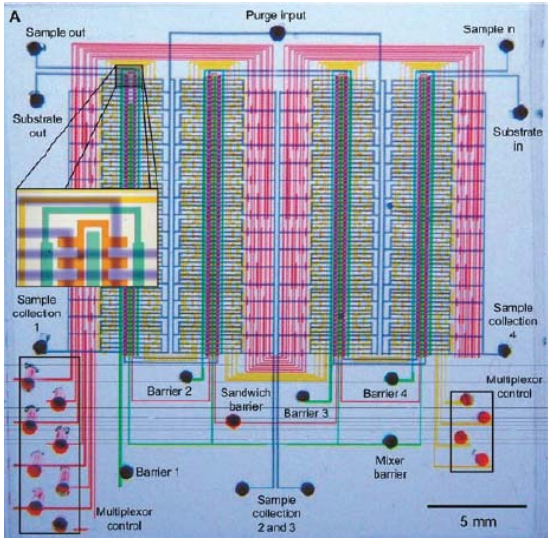
Use a single atom to control another atom: potential to create working logic devices, similar to transistors in an electronic circuit, which could eventually be used in a quantum computer.

Experiment performed to prove Rydberg blockade effect for quantum logic gates.

Nature Physics, 2009

Challenges in Systems Nanotechnology

- Create controllable systems built from nanoscale components: unifying principles that enable control of emergent behavior in complex nanosystems
- Wide application: revolutionary new products, petascale computing, organ regeneration, sensors for health monitoring
- Enable other goals for: nanomanufacturing, efficient use of energy; and sensor capabilities
- Development of a new framework for risk assessment

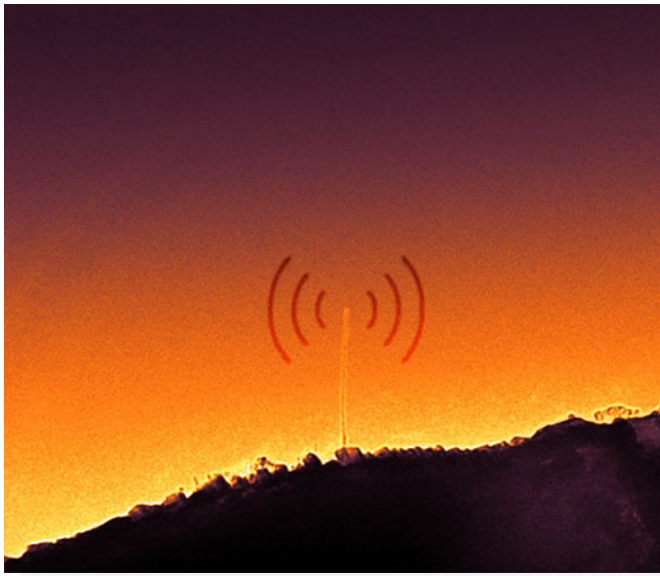


Microfluidics systems built from or incorporating nanocomponents. *Ferreira, UIUC*

Examples new topics in 2008

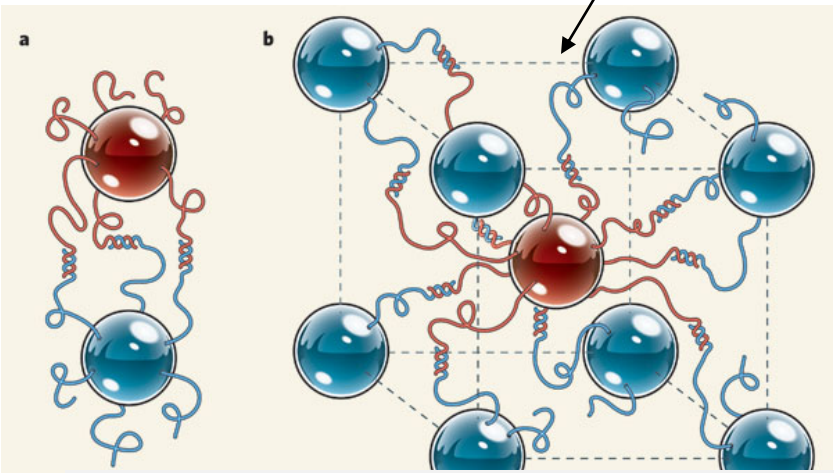
Nanodevices and components of nanosystems

- A. Zettl (UCB), J. Rogers (U Illinois):
  nano radio = antenna, filter, amplifier



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

- C. Mirkin (NU), O. Gang (BNL)
  Architectures for new, designed crystals



Selfassembling of atoms through DNA strands

Screen-printed Solar Cells

NS&E Priorities Research Areas

C. Integration of nanotechnology in application areas

- Replacing electron charge as the information carrier
- Energy and water resources using new principles
- Efficient nanomanufacturing and sustainable environment
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for better communication and nanosystem design

Nanoelectronics Research Initiative (NRI)

NRI Mission: Demonstrate novel computing devices capable of replacing the CMOS FET as a logic switch in the 2020 timeframe.

To meet these goals, NRI pursues five research vectors:

- **NEW DEVICE:** Device with alternative state vector
- **NEW WAYS TO CONNECT DEVICES:** Non-charge data transfer
- **NEW METHODS FOR COMPUTATION:** Non-equilibrium systems
- **NEW METHODS TO MANAGE HEAT:** Nanoscale phonon engineering
- **NEW METHODS OF FABRICATION:** Directed self-assembly of devices

Platform of NNI's Nanomedicine Initiative at NIH

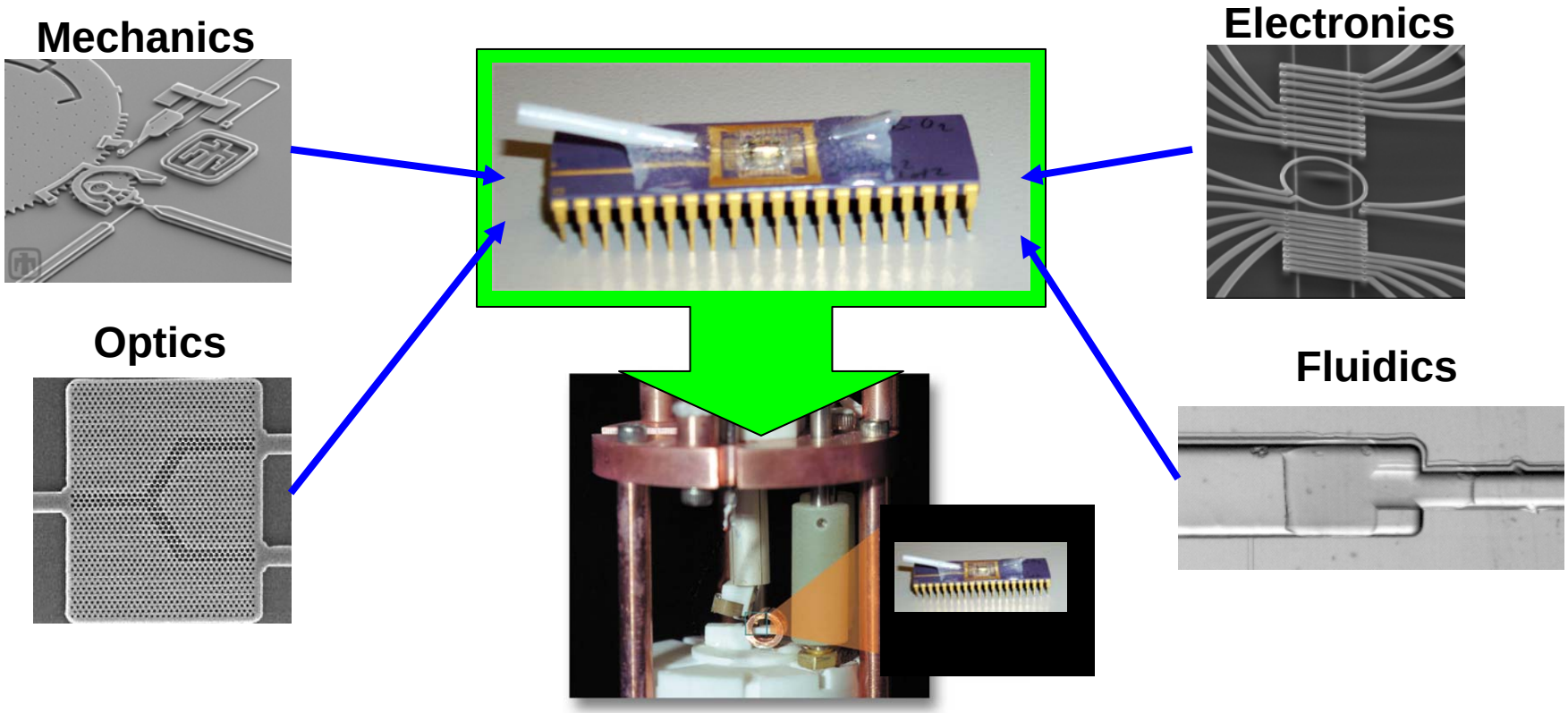
Steps to achieve the goal:

- Characterize quantitatively the physical and chemical properties of molecules and nanomachinery in cells;
- Gain an understanding of the engineering principles used in living cells to "build" molecules, molecular complexes, organelles, cells, and tissues; and
- Use this knowledge of properties and design principles to develop new technologies, engineer devices and hybrid structures for repairing tissues and for preventing and curing disease.

CONTROL AND MANIPULATE BIOLOGY AT THE NANOSCALE IN VIVO FOR MEDICAL USES

Center for Integrated Nanotechnologies: Discovery Platforms™:

Modular micro/nano-labs for measuring nanoscale processes



- Multiple in/out signals for stimulation, interrogation
- Standardized, rugged and robust
- "Pop-In" design for instrument compatibility, rapid exchange.
- Parallel architecture for statistics

MC Roco, Oct. 12 2009

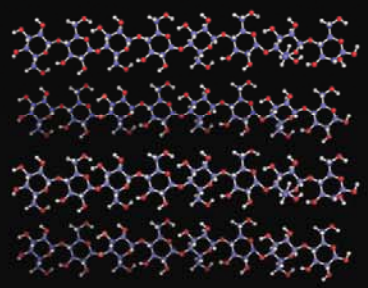
Los Alamos NATIONAL LABORATORY

http://CINT.sandia.gov or http://CINT.lanl.gov

Sandia National Laboratories

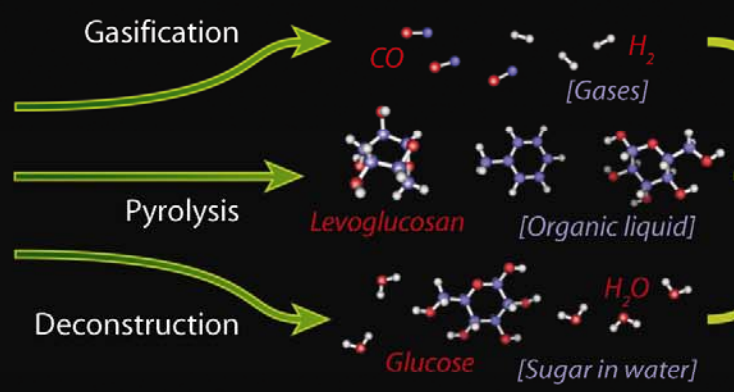
Green Gasoline: A Renewable Petroleum Alt

Source

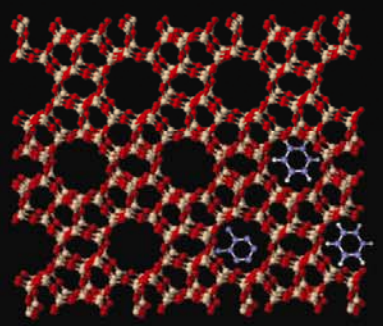


Plants are composed of carbohydrates such as cellulose & other molecules

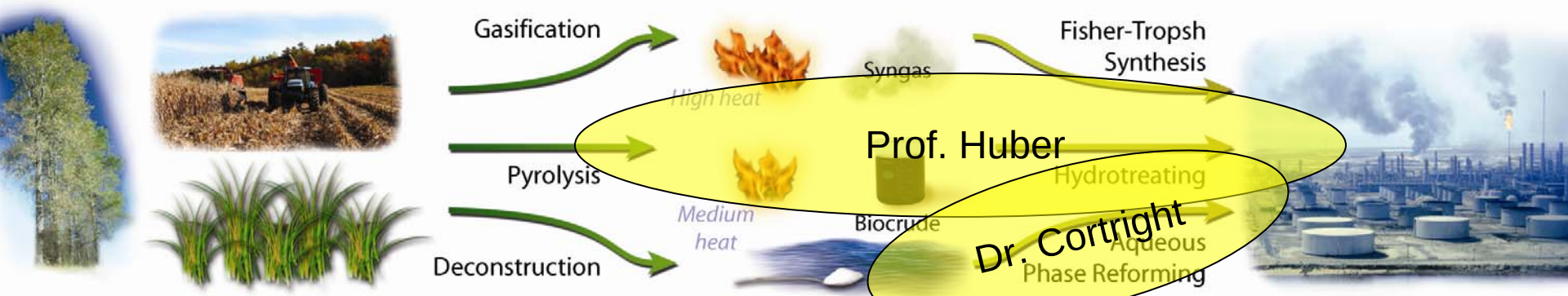
Breakdown



Catalysis



Catalysts help recombine molecular components



Plant biomass: poplar, switchgrass, corn stover, and others

Converging technologies from the nanoscale - examples of new transdisciplinary domains

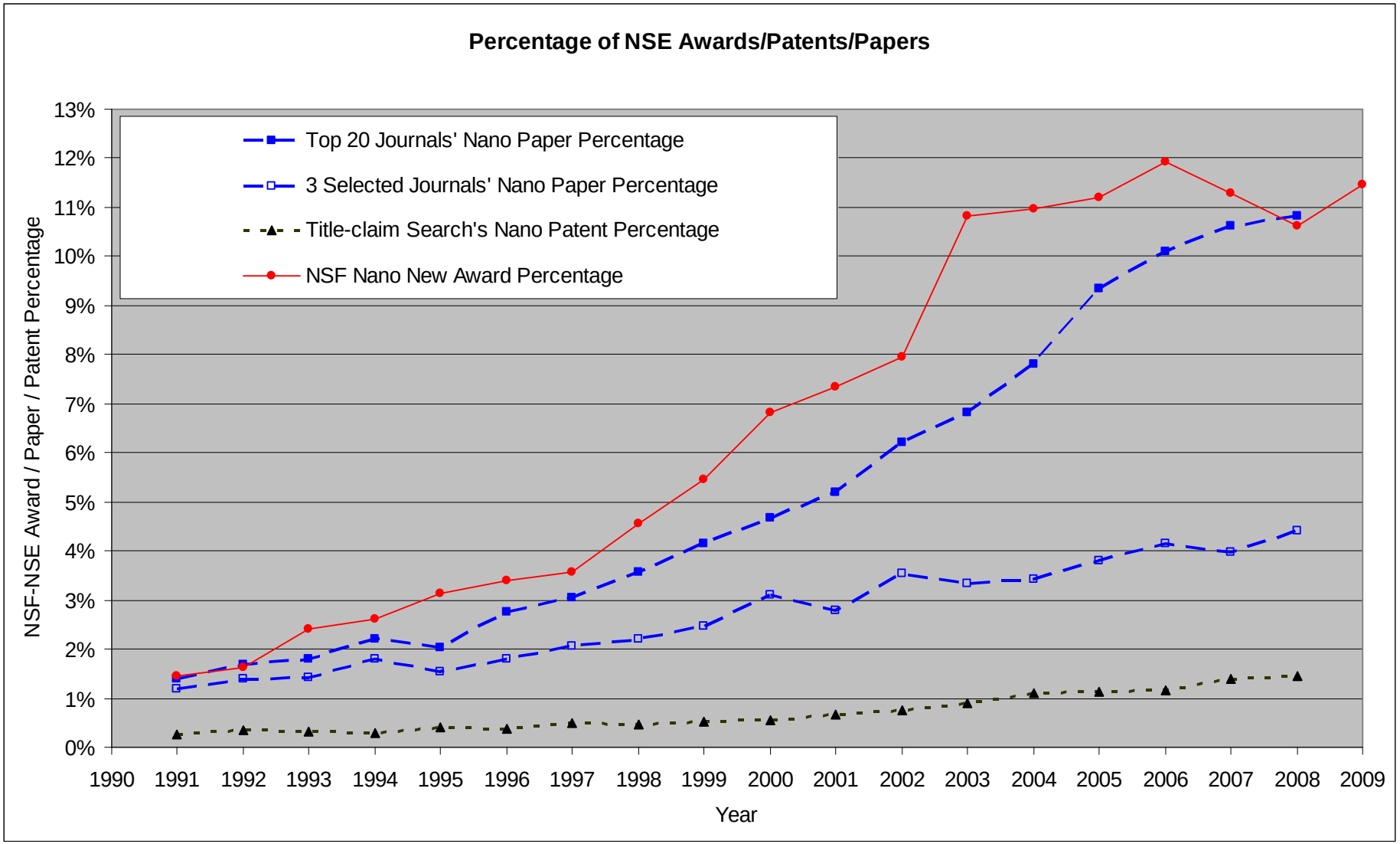
- **Quantum information science** (Nano and subatomic physics; IT, System approach for dynamic/ probabilistic processes, entanglement and measurement)
- **Eco-bio-complexity** (Bio; Nano; System approach for understanding how macroscopic ecological patterns and processes are maintained based on molecular mechanisms, evolutionary mechanisms; interface between ecology and economics; epidemiological dynamics)
- **Neuromorphic engineering** (Nano, Bio, IT, neurosc.)
- **Cyber-physical systems** (IT, NT, BIO, others)
- **Synthetic biology** (Bio, Nano, IT, neuroscience)

NS&E Priority research areas

D. Societal dimensions of nanotechnology

- Understanding and sustainable ENV, including research for natural/ incidental/ manufactured nanomaterials
- Earlier formal and informal education
- Prepare methods and organizations for governance
- Social issues and public engagement and participation

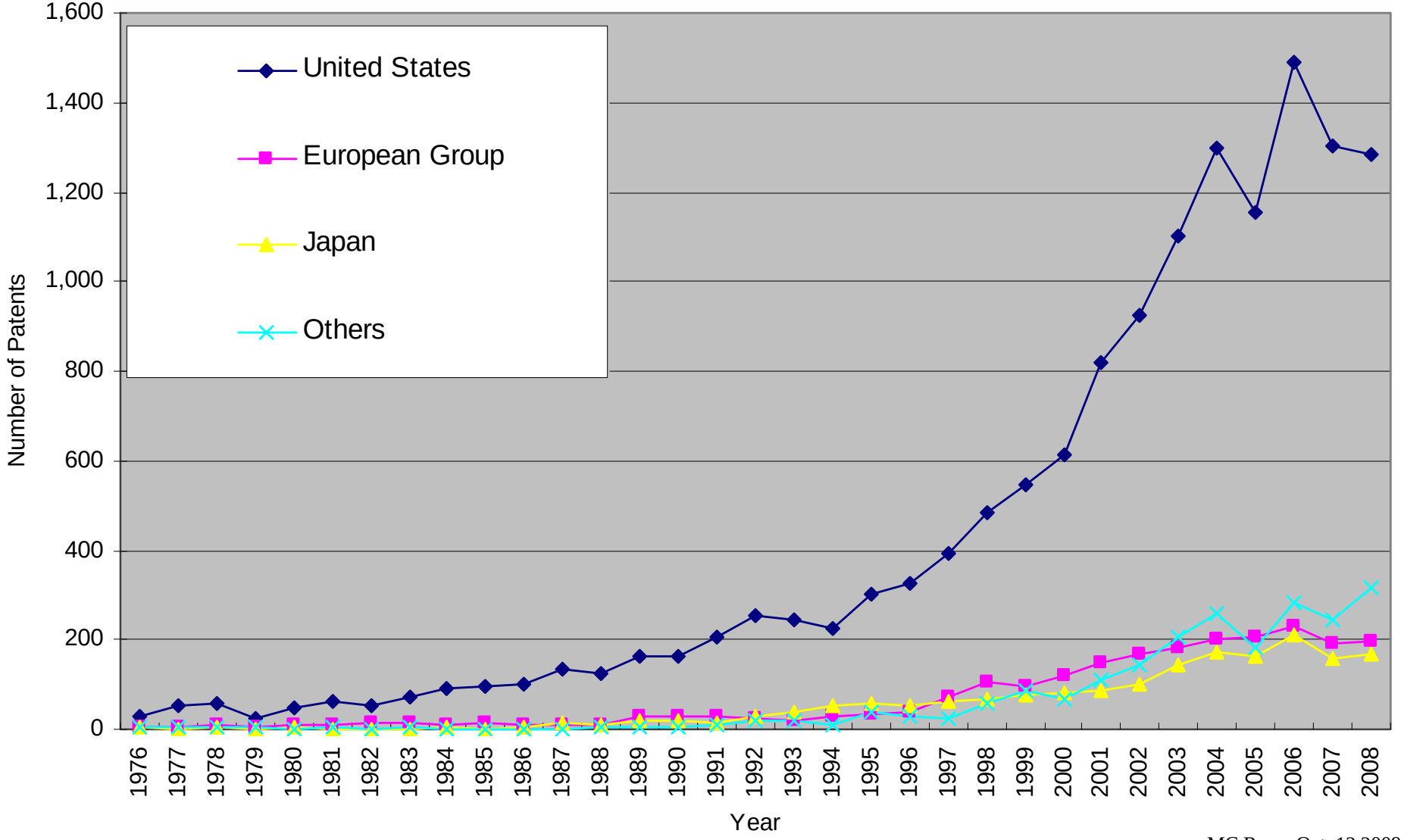
Proportion of nanotechnology contents in NSF awards, ISO papers and USPTO patents (1991-2008)



Searched by keywords in title and abstract/claims

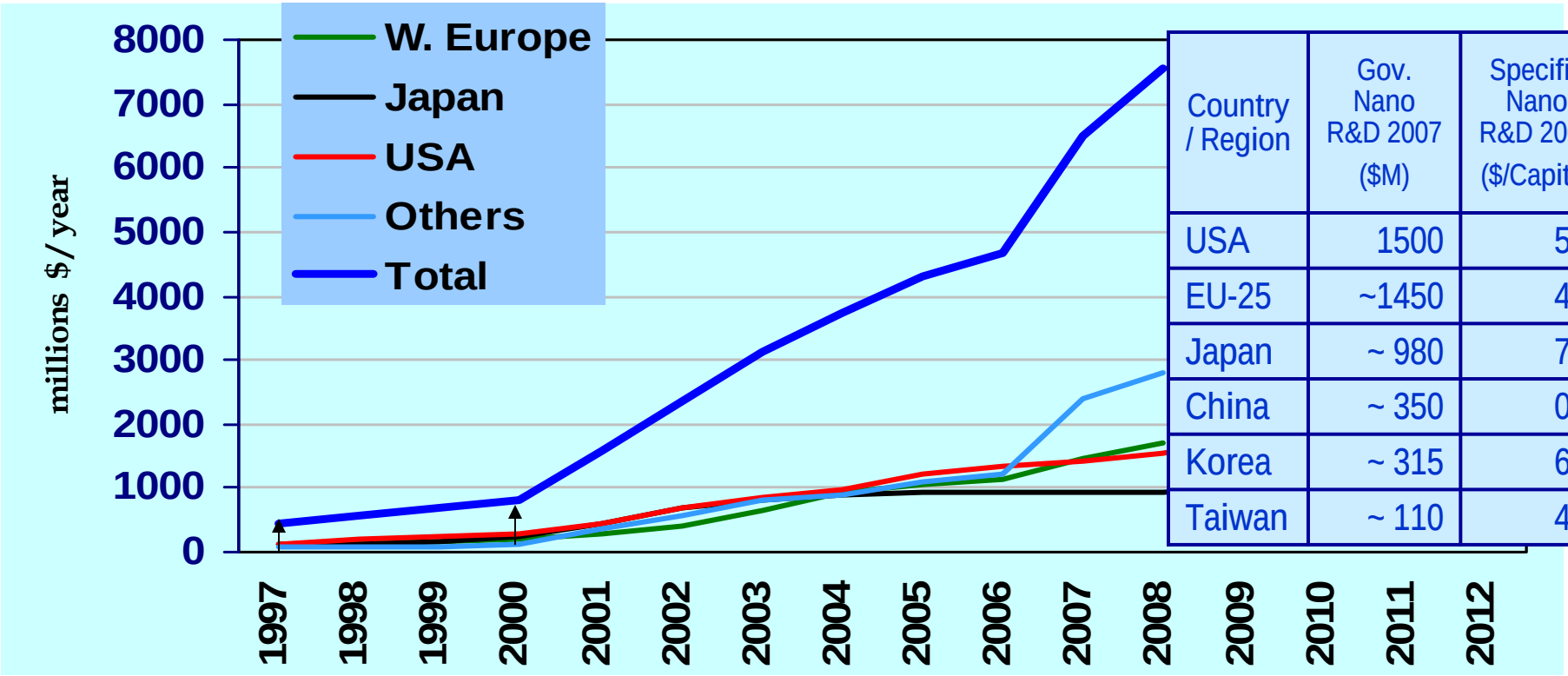
NSE patents at USPTO by country group

Assignee country group analysis by year, 1976-2008 ("title-claims" search)



MC Roco, Oct. 12 2009

2000-2009
Changing international context: government funding



Country / Region	Gov. Nano R&D 2007 ($M)	Specific Nano R&D 2007 ($/Capita)
USA	1500	5.0
EU-25	~1450	4.0
Japan	~ 980	7.5
China	~ 350	0.3
Korea	~ 315	6.0
Taiwan	~ 110	4.5

Seed funding (1991 -)

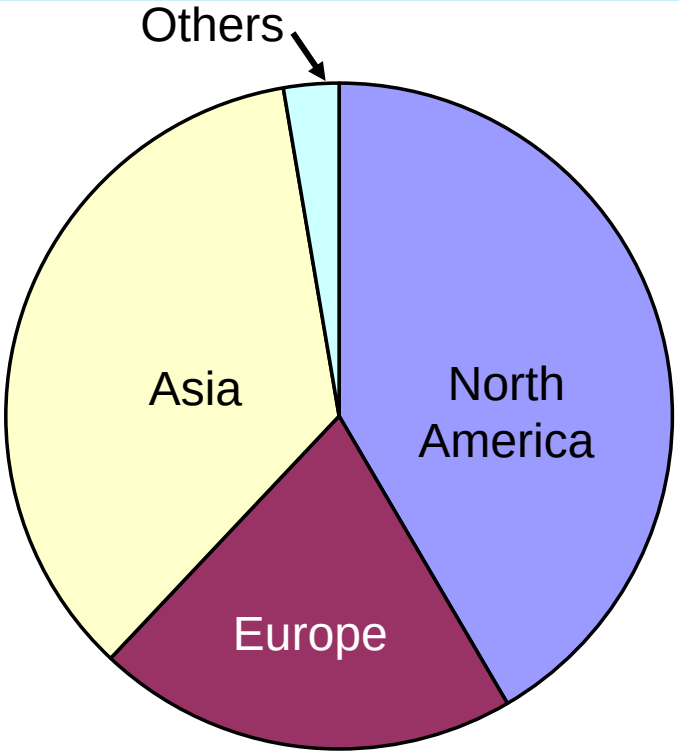
NNI Preparation (vision / benchmark)

1st Strategic Plan (passive nanostructures)

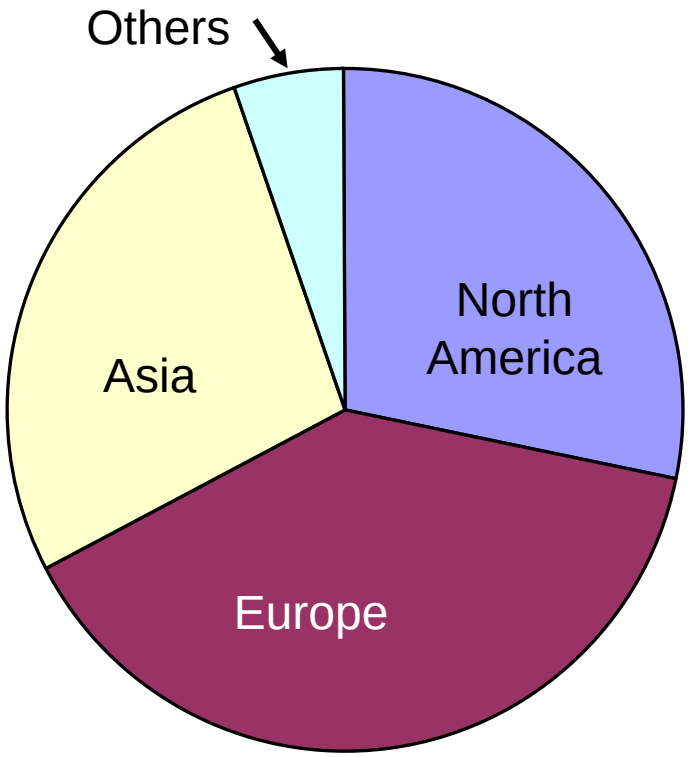
2nd Strategic Plan (active ns. & systems)

Industry R&D ($7.3B) has exceeded national government R&D ($6.5B) in 2007

Growing nanotechnology R&D investment - $13.8 billion in 2007



Private (Corp. + VC)
Total = $**7.3** billion



Public (National, regional, state)
Total = $**6.5** billion

National governments ~ $4.7 billion
Local governments and organizations ~ $1.8 billion

Source: Lux Research

Technological Comparison

Europe; Japan; U.S.

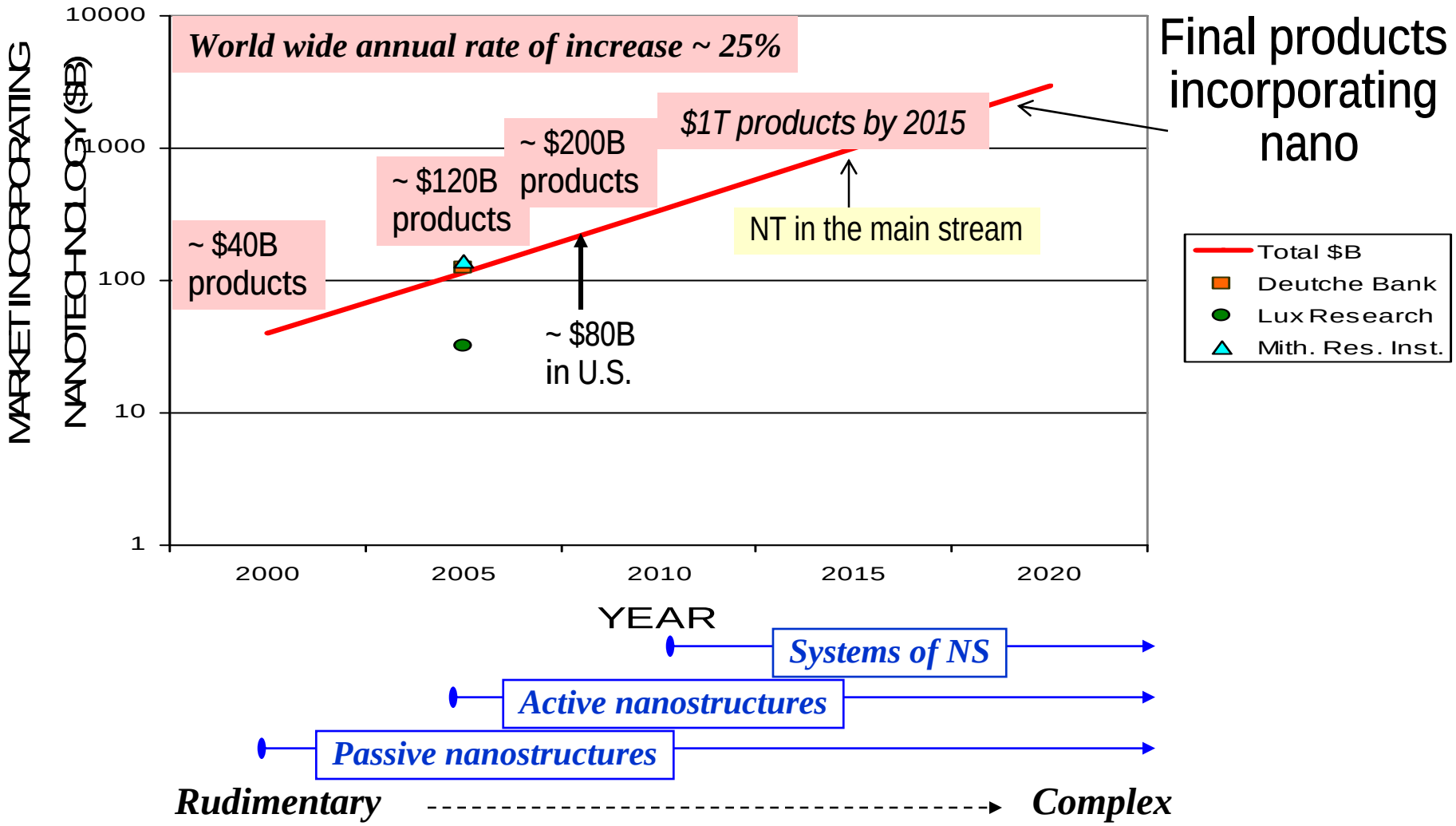
This is an extension in 2004 survey of the WTEC Nanotechnology Workshop's first evaluation in 1999

	Level 1	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		
	Highest			

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

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

(Estimation made in 2000 after international study in > 20 countries)



Reference: Roco and WS Bainbridge, Springer, 2001

National Nanotechnology Initiative
as a "bottom-up, science opportunity-born, general purpose technology" program

NNI has been established in FY 2001 that coordinates 25 Federal nanotechnology R&D, with an annual budget of about $1.6 billion.

R&D for a broad based technology (2000-2020),
similar to IT (1960-2000) and BIO (1980-2010).

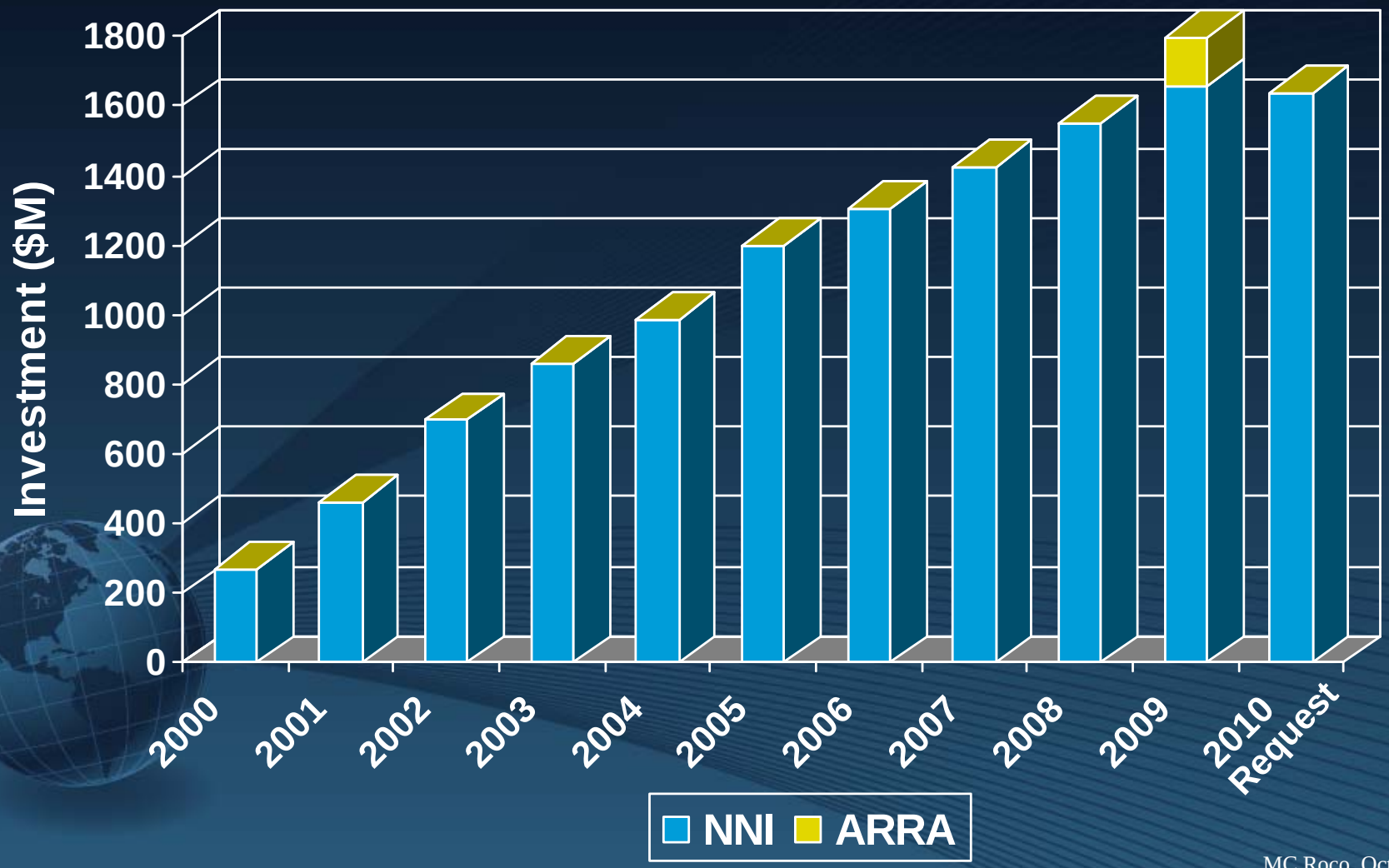
2009: Industry has exceeded government investment
States & local organizations contribute significantly
Over 60 countries have R&D programs on nano
(after U.S. – Japan, Korea; then China, EU, Australia….)

National Nanotechnology Initiative

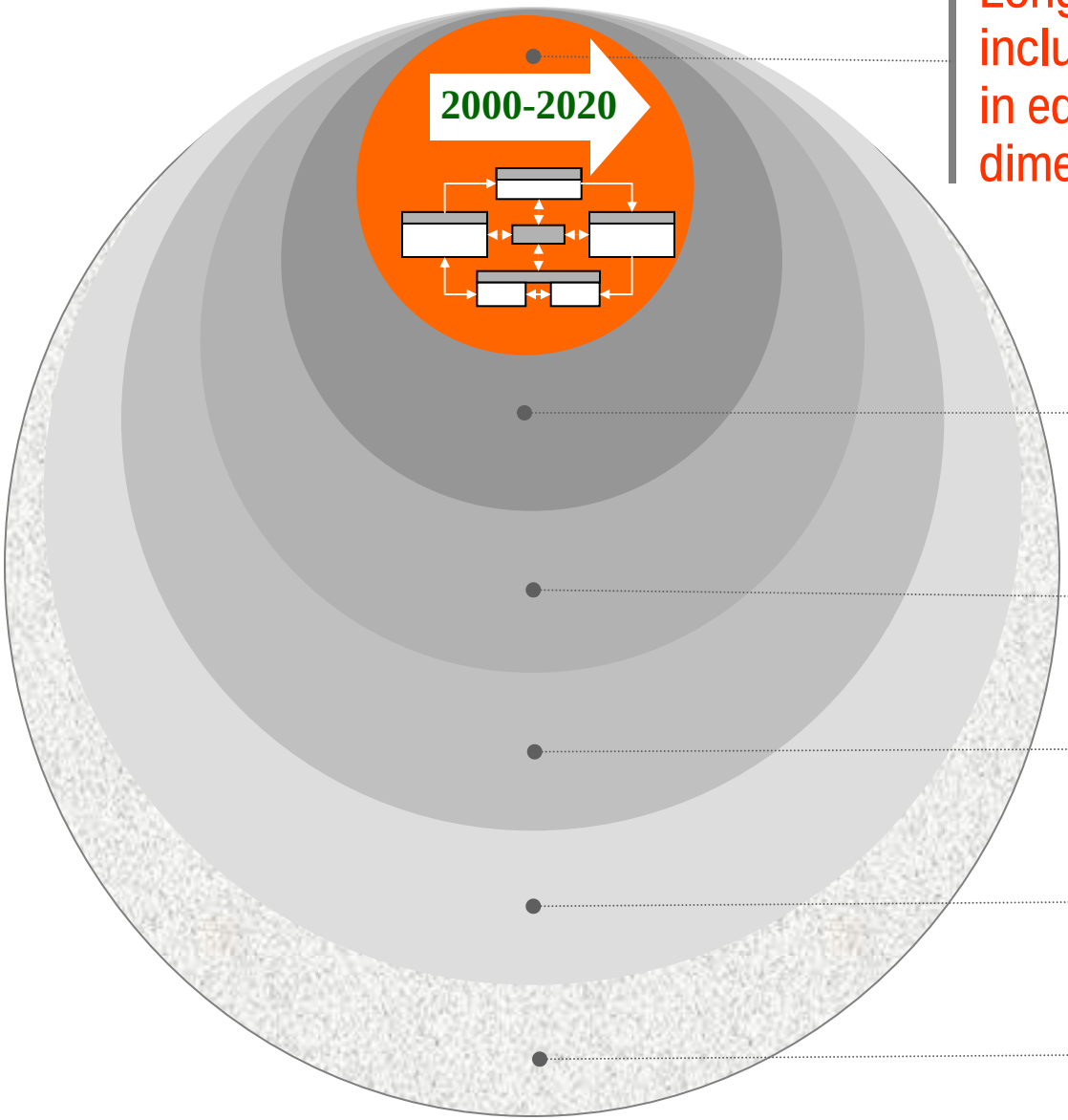
25 AGENCIES

NIH
OSTP
OMB
NSF
DOD
DOE
NIST
FDA
NASA
USDA
NIOSH
USDA FS
DOS
EPA
DOTr
NRC
DOT
USPTO
USGS
ITIC
DOL
DOJ
DOEd
DOC BIS
DHS
CPSC
ITC

National Nanotechnology Initiative
FY 2010 Budget Request: $1.636B



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

Governance of nanotechnology development: four main functions

- Transformative
  investment policy, S&T policy, support innovation & informatics, prepare pipeline in education, facilitate commercialization; use NBIC integration tools; management (build-up, solicitations)
- Responsible development
  EHS, ELSI+, methods for risk governance, effective oversight, communication & participation (incl. public), voluntary measures
- Inclusive, collaborative
  Building national capacity; multi-sector partnerships; international capacity, leveraging, and research strategy
- Visionary
  Long-term and global view in planning & investment, setting priorities, human development/progress

Possibilities for a Global Governance of Nanotechnology

Transformative function

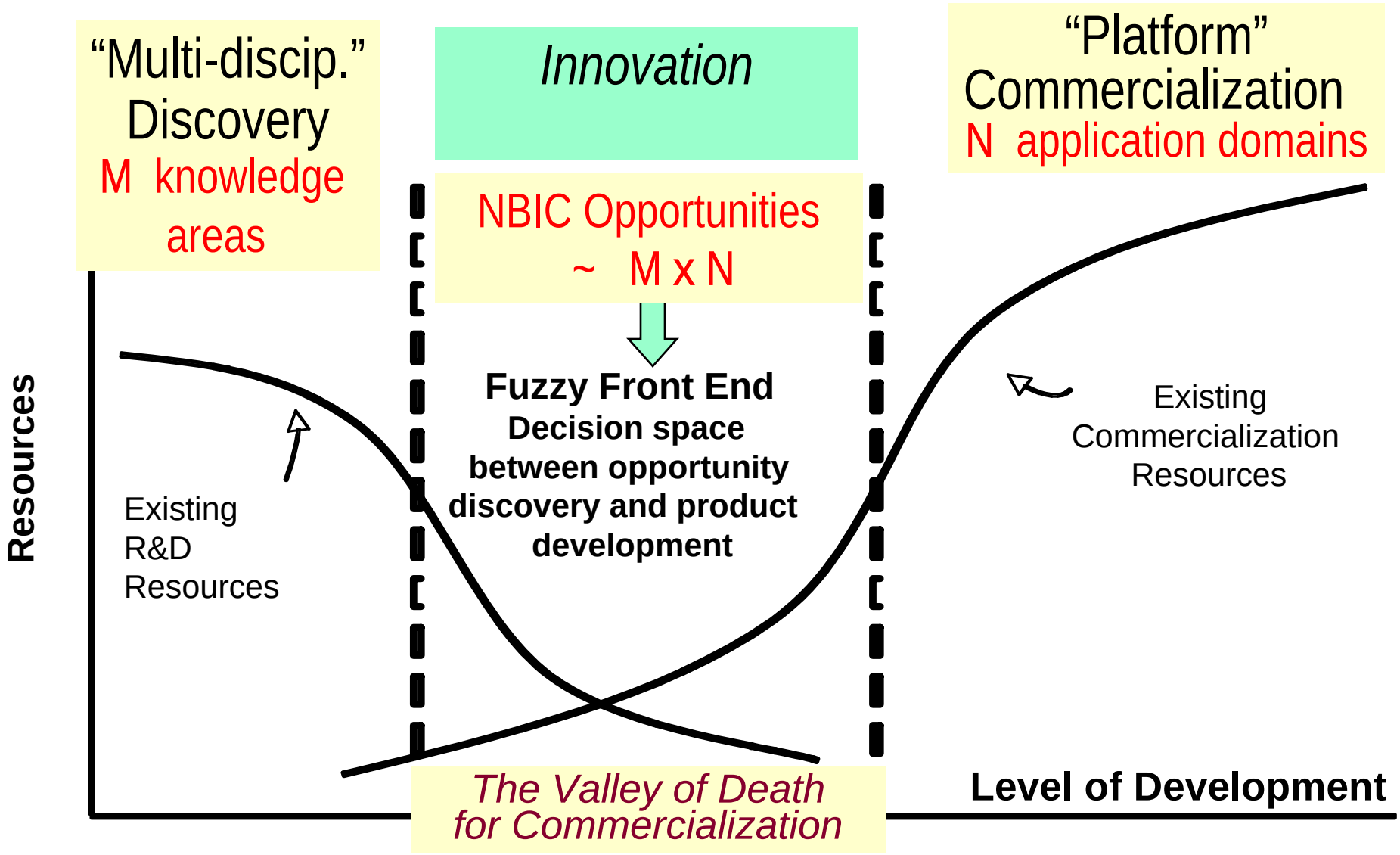
- Support tool development, knowledge creation, innovation, informatics, and commercialization for nanotechnology

- Creating better opportunities in developing countries

- Allocation of development funds for common topics: nomenclature, metrology, standards, patent evaluation, databases, and EHS methodologies

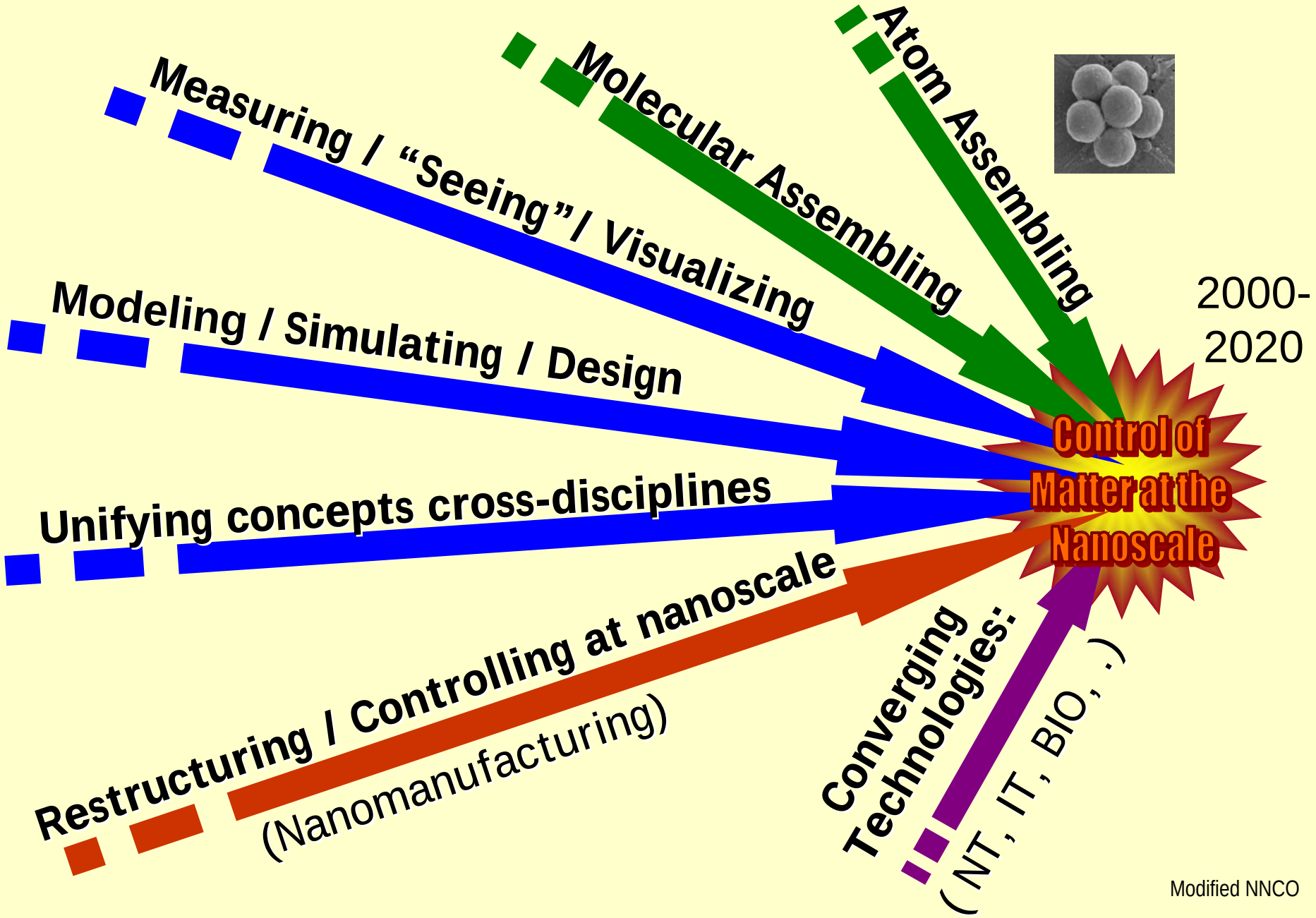
- Use “incentives” and “empowering stakeholders” in the open and global ecosystem

Nanotechnology for enhanced innovation



INNOVATION opportunities increase ~ M x N times

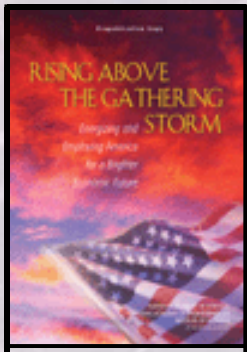
Nanotechnology innovation: *concurrence of capabilities*



The call for innovation: United States (2004 -)

- Three reports on innovation (2004-2005):
  - "Engineering Research and America's Future: Meeting the Challenges of a Global Economy" (National Academy of Engineering)
  - "Innovate American" (Council of Competitiveness)
  - "Rising Above the Gathering Storm" (National Research Council)
- Presidential Decree:
  "American Competitiveness Initiative" (2005)

  Congressional Act:
  "US National Competitiveness Act" (2006, 2007)



National Academies recommendations are realized in ACI.

The call for innovation in European Union (2006 -)

EU *Communication,* September 2006

- ***The aim: "a broad based innovation strategy for Europe that translates investments in knowledge into innovative products and services".***

- **Innovation strategy with ten priority actions**
  - Establish innovation-friendly education systems
  - Establish a "European Institute of Technology"
  - Work towards a, single and attractive labor market for researchers
  - Strengthen research-industry links
  - Foster regional innovation through the new cohesion policies
  - Reform R&D and innovation state aid rules for R&D tax incentives
  - Enhance intellectual property rights protection (IPR)
  - Digital products and services – initiative on copyright levies
  - Develop a strategy for innovation friendly "lead markets"
  - Stimulate innovation through procurement

The call for innovation in other regions (2006 -)

- ➔ Japan
- ➔ China
- ➔ Australia
- ➔ South Korea and other countries

Comments:

- Due to globalization and shifting research priorities - the relative technology/economical ranking of various countries changes
- Fast dissemination of similar policies, concepts and measures for stimulating innovation 2004-2006 (just in 2 years)
- A main difference between economies is in the implementation

200-2009
Changing NNI R&D infrastructure

Over 80 large centers, 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

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

2000 **NT Graduate education** (curriculum development)

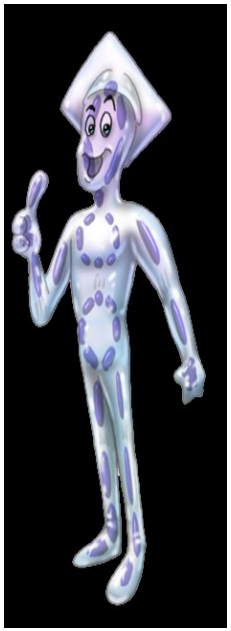
2002 **NT Undergraduate Education (NUE, others)**

2003 **NT High school education (NSEE, others)**

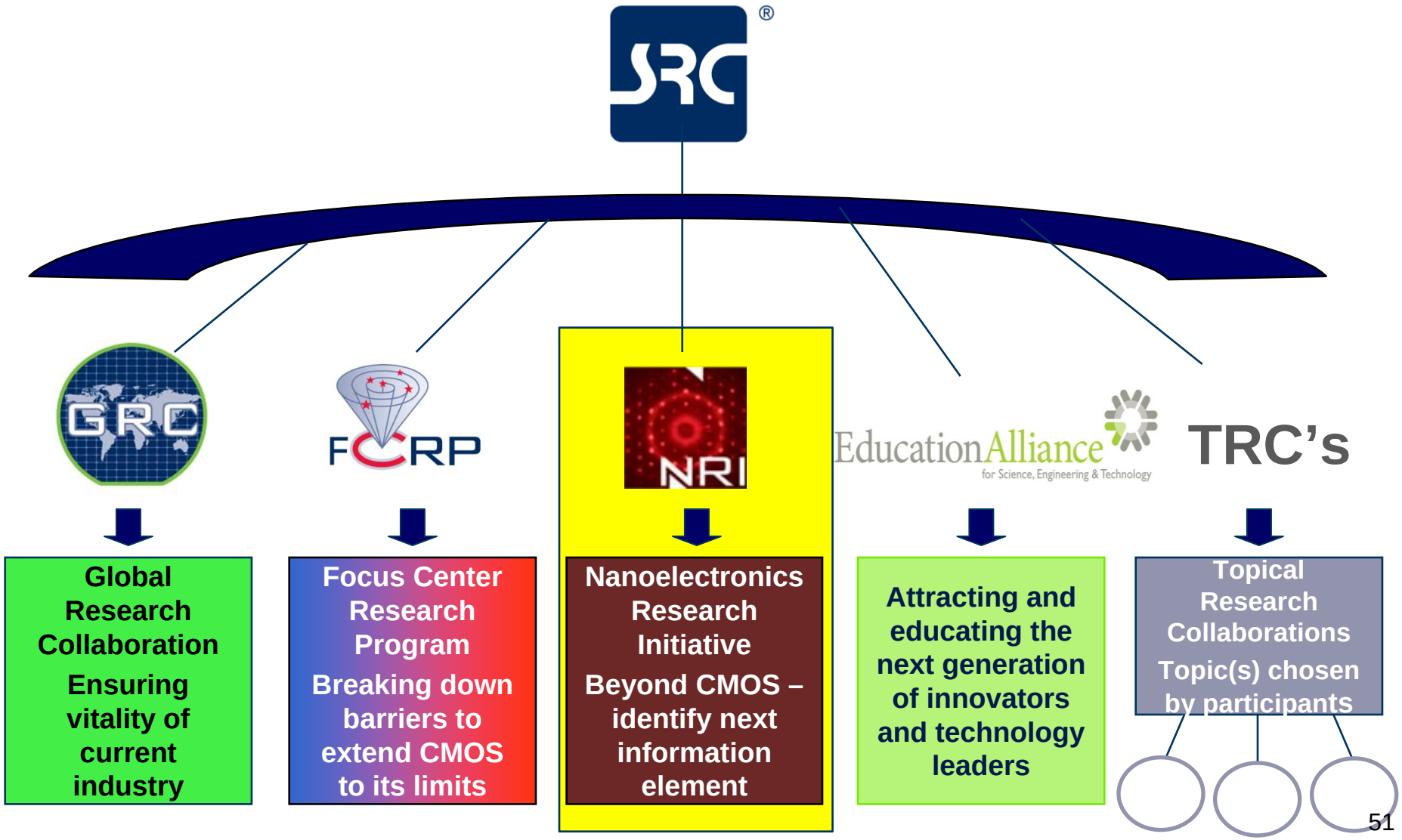
2004 / 2005 **K – 12 and Informal Science Education (NISE, others)**

2006 Technological Education Network (NACK, others)

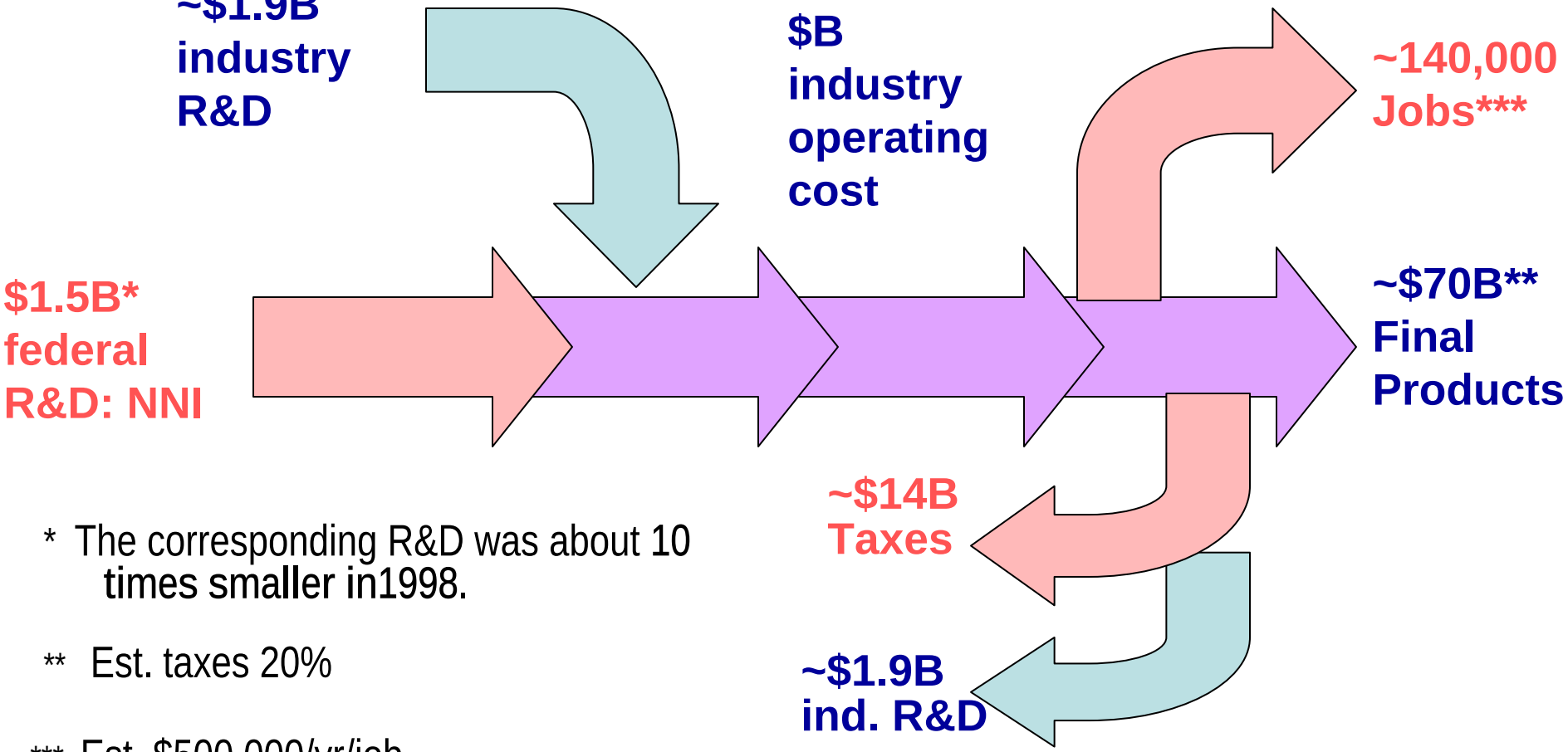
K – 16



Example of EM organization:
Semiconductor Research Corporation



Estimation of Annual Implications of Federal Investment in Nanotechnology R&D (2008)



* The corresponding R&D was about 10 times smaller in1998.

** Est. taxes 20%

*** Est. $500,000/yr/job

Possibilities for a Global Governance of Nanotechnology

Responsible development function

- Development with priority of general benefit applications such as increasing productivity and sustainable nanomanufacturing; Applying nanotechnology for improving availability of common Earth resources such as water, food, energy, and sustainable clean environment

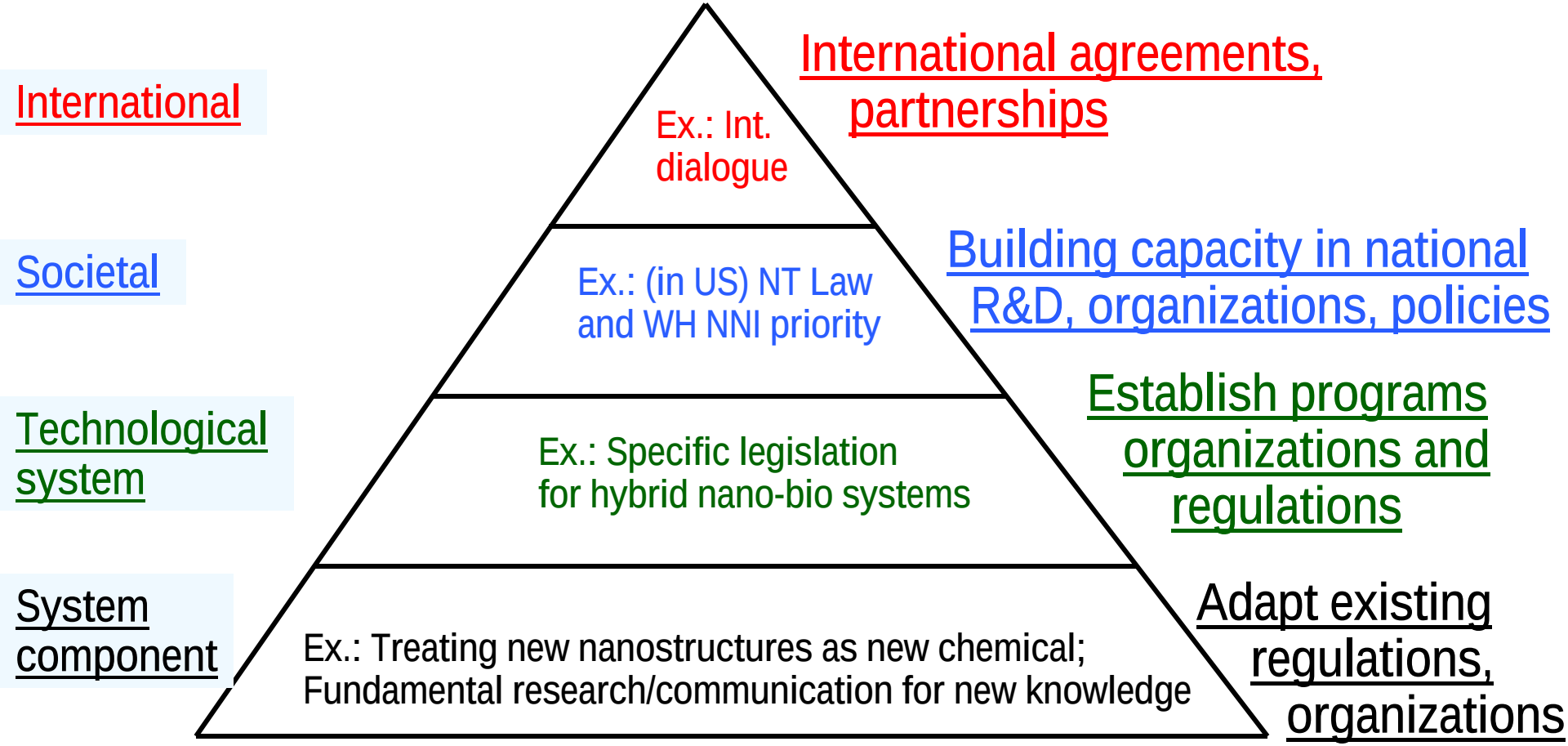
- Voluntary measures and science-based decision for risk management ; Predictive models for human- and eco-tox

- Public inclusion and participation globally

- Develop organizational capacity for effective oversight

Responsible development

Multi-level structure of risk governance



Examples from nanotechnology

The Risk Management Escalator and Stakeholder Involvement

(from Simple via Complex and Uncertain to Ambiguous Phenomena) with reference to nanotechnology

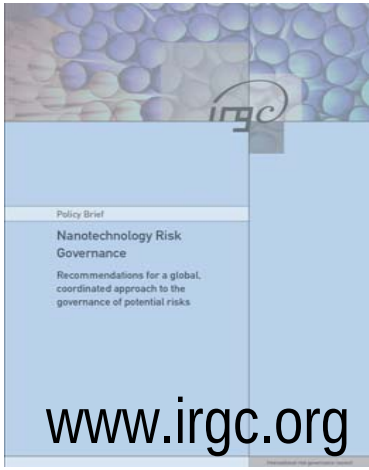
IRGC

Naturally nanostructured materials	Engineered nanostructured materials	Active nanostructures and systems	Large and molecular nanosystems
		Risk Balancing Necessary + Probabilistic Risk Modelling	Risk Trade -off Analysis & Deliberation necessary + Risk Balancing + Probabilistic Risk Modelling
		Remedy	**Remedy**
	Probabilistic Risk Modelling	• Cognitive • Evaluative	• Cognitive • Evaluative • Normative
	Remedy	**Type of Conflict**	**Type of Conflict**
Statistical Risk Analysis	Cognitive	• Agency Staff • External Experts • Stakeholders - Industry - Directly affected groups	• Agency Staff • External Experts • Stakeholders - Industry - Directly affected groups - General public
Remedy	**Type of Conflict**		
• Agency Staff • External Experts	• Agency Staff • External Experts • Stakeholders		
Actors	**Actors**	**Actors**	**Actors**
Instrumental	Epistemological	Reflective	Participative
Type of Discourse	**Type of Discourse**	**Type of Discourse**	**Type of Discourse**
Simple	Component Complexity induced	System uncertainty induced	Ambiguity induced
Risk Problem	**Risk Problem**	**Risk Problem**	**Risk Problem**
Frame 1		**Frame 2**	

Changing public perception since 2000

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

2000-2003: Are there self-duplicating nano-bots?
Could they create "grey-goo"?



> *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, ..)
Concerns on using nanotech in food, reaction to accidents, perception of transhumanism, buzz word

2008: ~ 30% know something; ~ 70% benefits > concerns

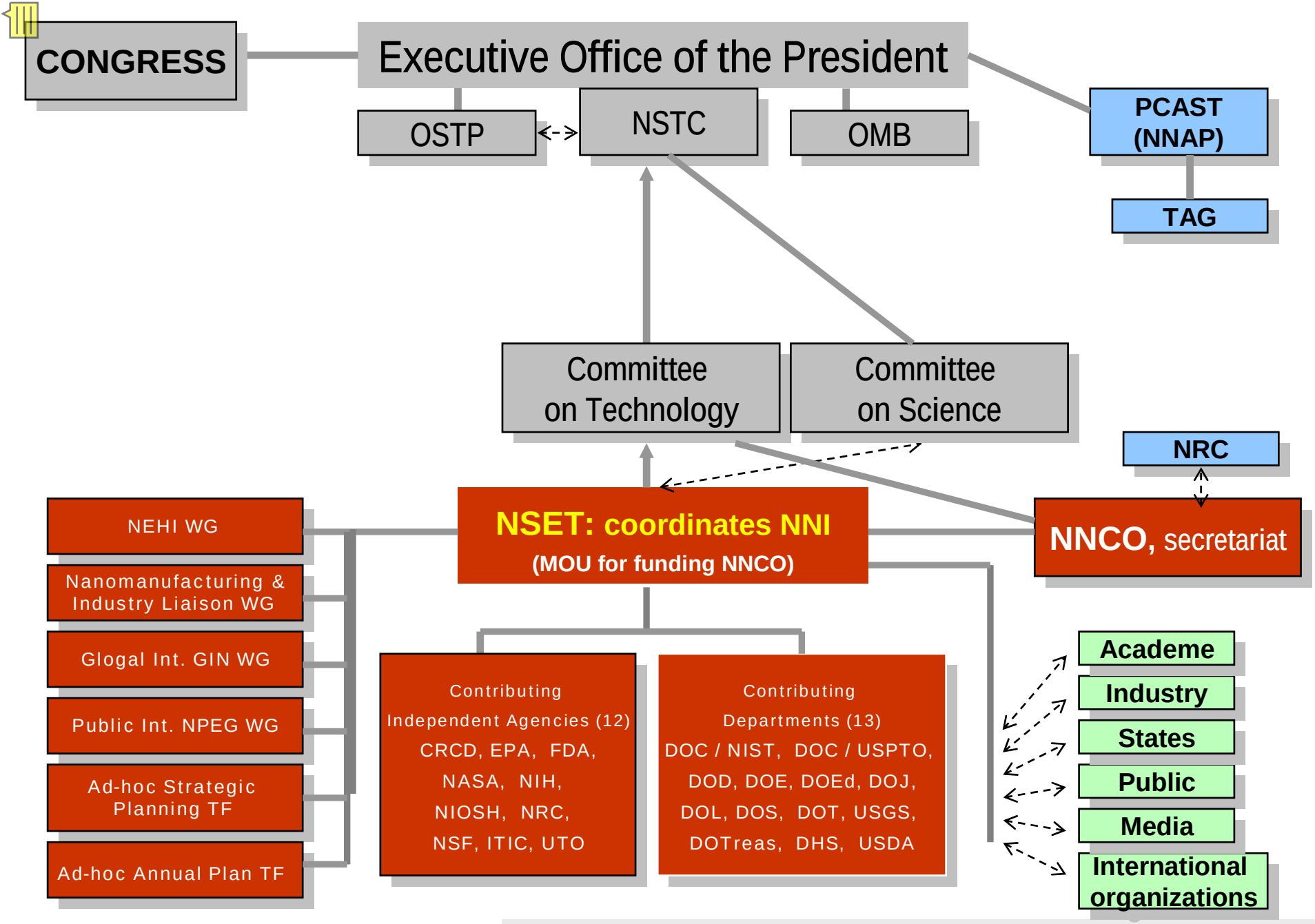
NNI Evaluations

- Agency evaluation process: GPRA, COV, PART, etc.
  each year since 2001
- Academies (NRC): 2002-03, 2006, 2009 (~ each 3 years)
- OMB, EOP White House, Congress:
  each year since 2001
- PCAST reports to the President and Congress:
  12/2000, 5/2005, 3/2008 (~ each 3 years)
- Many research, industry, non-governmental and
  international organizations (after 2003)

Possibilities for a Global Governance of Nanotechnology

Inclusiveness and partnership function

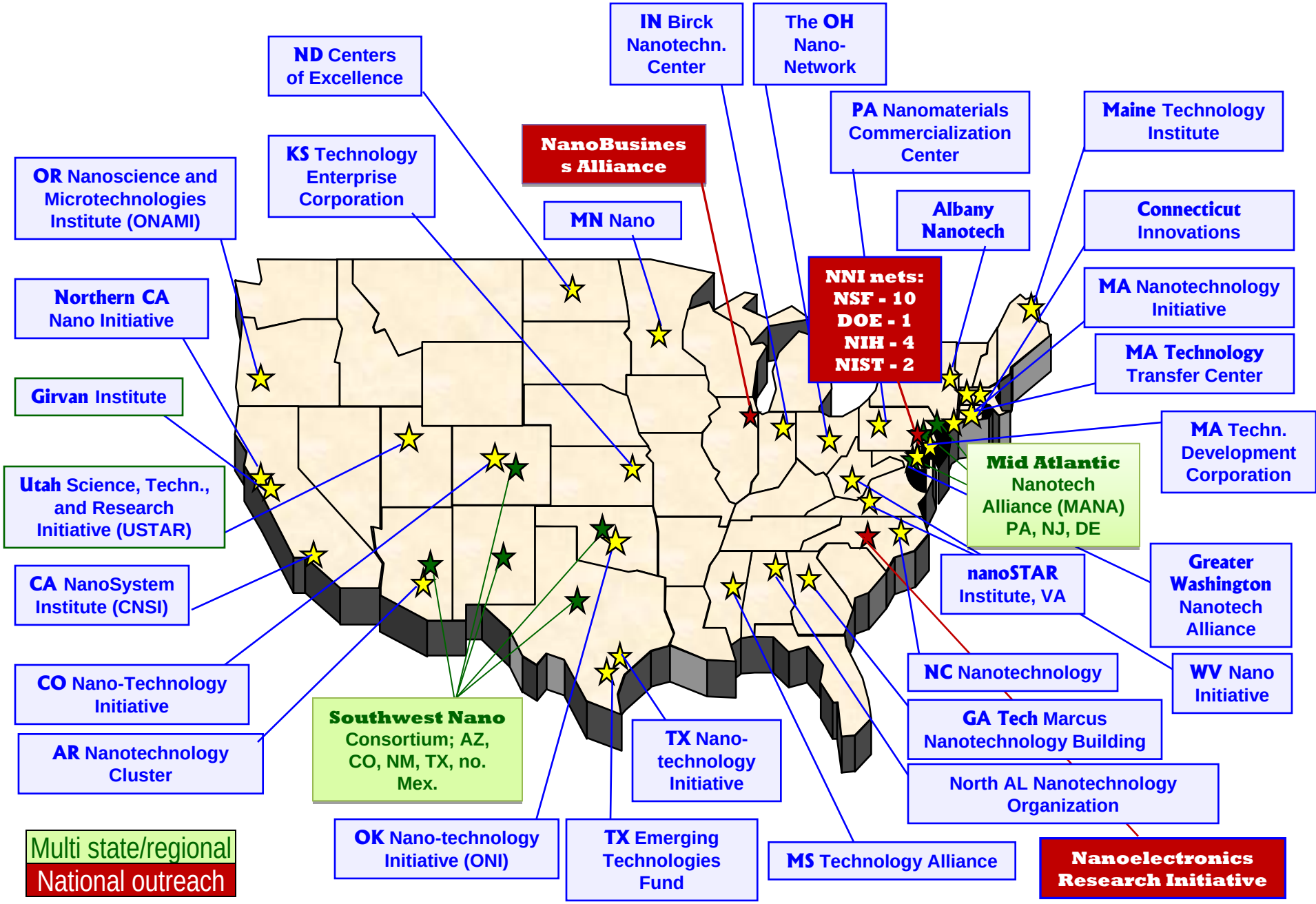
- Supporting partnerships between various stakeholders active in nanotechnology and related emerging technologies;
- Global communication and information
- Involving international organizations to advance multi stakeholder global challenges
- Encourage international and cross-sector interactions



Organization chart of the NNI

Grey: supervising organizations; Red: organizations implementing NNI; Blue: organizations evaluating NNI; Dash lines: infromational links

Nanotechnology Regional, State, and Local Initiatives (34)



International Dialogue on Responsible Nanotechnology R&D since 2004

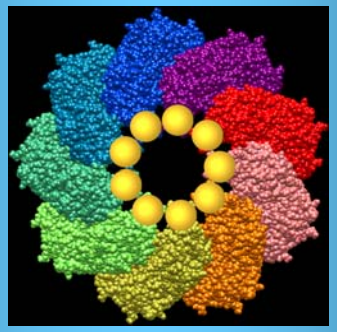
First: 2004, Virginia, USA
Second: 2006, Japan
Third: 2008 Brussels, EC

Survey Investments

Current Norms

Recommended measures

International Dialogue



26 countries

Joint Statement

Immediate Actions

June 2004, Virginia

http://www.nsf.gov/home/crssprgm/nano/dialog.htm

Foster suitable international organizations

Ex: International <u>standards</u> organizations working on nanotechnology

National Body International Standards Organizations

Treaty-Based International Standards Organizations

Standards Development Orgs. With Global Reach

ASME International

Foster suitable international organizations

Ex: OECD Working Party on Nanotechnology

Working Party on Nanotechnology held its first meeting in Leuven, Belgium, on 8-9 May 2007, and decided to establish steering groups for 6 potential projects, to implement in 2007 and 2008:

A. Statistics and Measurement
B. Impacts and Business Environment
C. International Research Collaboration
D. Outreach and public engagement
E. Dialogue on Policy Strategies
F. Contribution of Nanotech to Global Challenges

Possibilities for a Global Governance of Nanotechnology

Commitment to long-term view

- Detecting earlier signs of change using international expert groups; adopt real time technology assessment
- Commitment to long-term planning and priority setting using global scenarios, anticipatory measures and organizations for nanotechnology development
- Integrate nanotechnology development with other emerging and converging technologies; Conduct research specific for future generations of NT
- Evaluate the trends for exponential growth of nanoscale knowledge and technology capabilities

Time and impact scales of NNI

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")

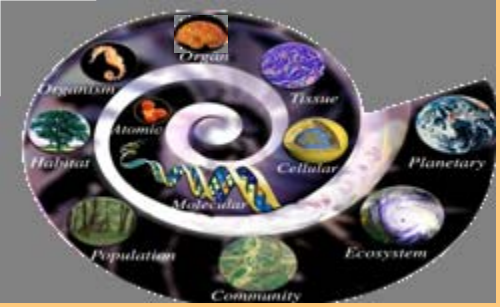
  Societal implications ("NSF Report", 2000)

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

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

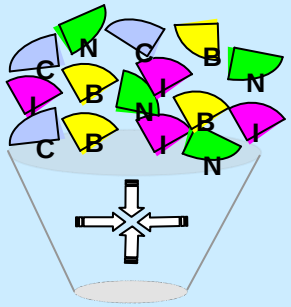
- Combine four time scales in planning (2001-2005):

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



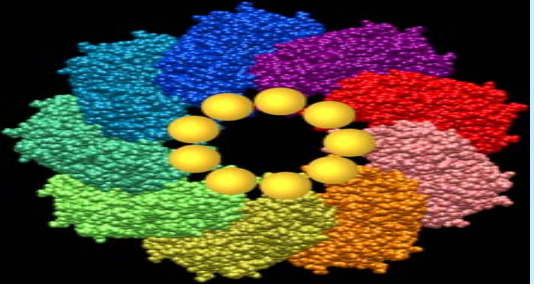
Nanotechnology in 2009 - identifying trends and opportunities

- Characterization & standards of nanomodules using internal structure
- Direct measurements and simulations of a domain of biological or engineering relevance with atomic precision and time resolution of chemical reactions; understand basic phenomena and collective effects
- New disciplines (nanophotonics, synthetic biology, etc.) and new industries (beyond CMOS, etc.) because new concepts and integration
- Manufacturing Processes – science-based design and processing
- Nanotechnology products – add nanosystems leading to revolutionary new products; mass use of nanotechnology in several industries, medical fields and sustainability
- New innovation ecology – high added value, automation, NBIC (in OECD)
- Knowledge for risk governance – anticipatory and adaptive organizations, risk management, and oversight; predictive models for toxicity



Lessons learned from NNI

- A well defined concept and time scale are needed
  vs. a domain of science / application
- Clearly communicate the balance of benefits
  vs. risks of new science and technology
- Participation of many stakeholders is essential
  vs. top-down decision
- Small group for exploratory planning
  vs. large groups
- Adaptive management based on incentives, competition
  vs. authoritarian approach



Possibilities for improving nanotechnology governance

Using **open-source and incentive-based** mechanisms in the global self - regulating ecosystem

Establishing corresponding science and engineering **platforms** with multiple nanotechnology applications

Developing **institutional capacity** to address uncertainty and unexpected consequences of nanotechnology

Institute **voluntary and science-based measures** for risk management before anticipatory, adaptive **regulations**

Implementing **long-term planning**

Several Background References

- "Societal Implications of Nanoscience and Nanotechnology", Springer (Roco and Bainbridge, 2001)
- "Coherence and Divergence of Megatrends in S&E" , Proc. Swiss Academies, 2000; and J. Nanoparticle Research, Vol. 4 (Roco, 2002)
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- "Nanotechnology: Societal Implications - Maximizing Benefits for Humanity", 2 vols., Springer (Roco and Bainbridge, 2005)
- "The NNI: Past, Present and Future", in Handbook on Nanoscience, Engineering and Technology, CRC, Taylor and Francis, (Roco, 2007)
- "Nanotechnology Risk Governance" (Roco and Renn, 2007), in book Global Risk Governance: Applying and Testing the IRGC Framework, Renn and Walker (eds.), Springer
- "Possibilities for Global Governance of Converging Technologies", J. Nanoparticle Res. (Roco, 2007)