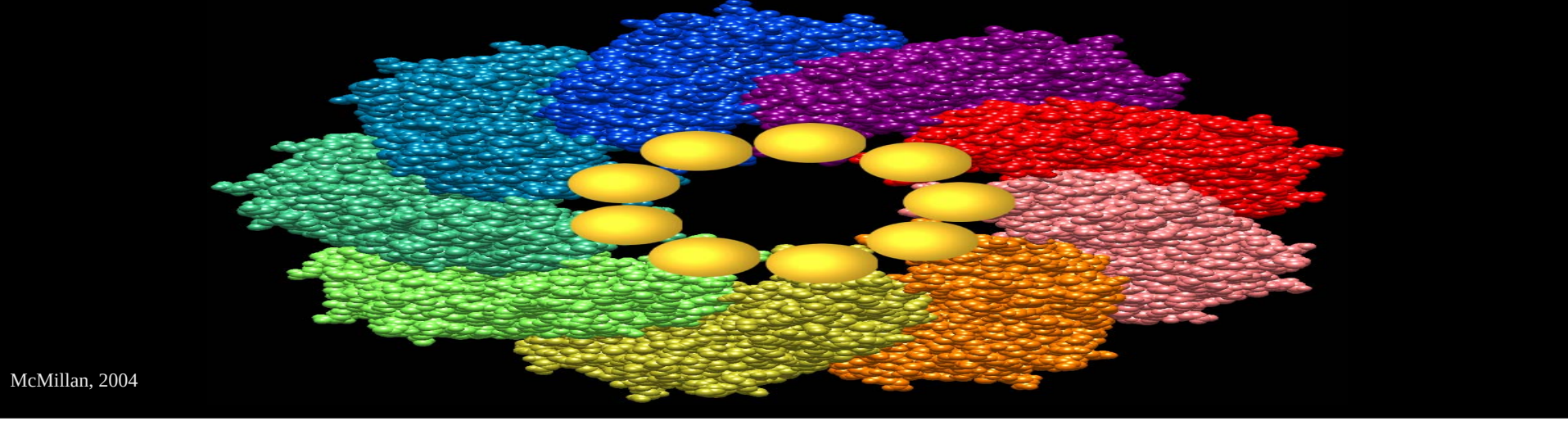
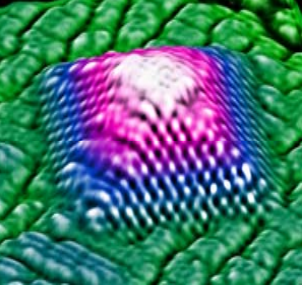


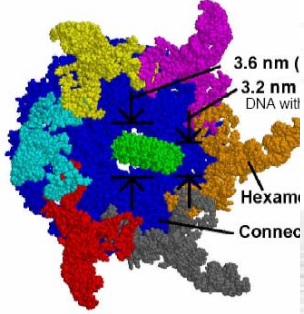
The Changing Face of Nanotechnology in a Global Context

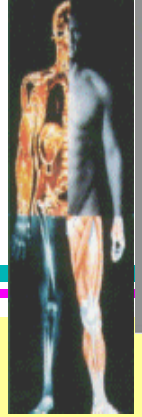
M.C. Roco

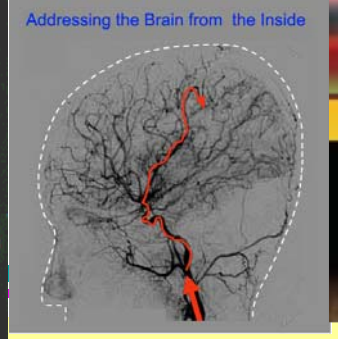
National Science Foundation and
National Nanotechnology Initiative

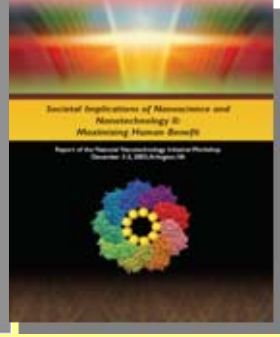
University of Maryland, November 1, 2007











TOPICS

Defining nanotechnology and its R&D targets

Governance of nanotechnology development

4 + 1 generations of nanotechnology products

NNI in the international context

Benchmark with experts in over 20 countries

"Nanostructure Science and Technology"

Book Springer, 1999

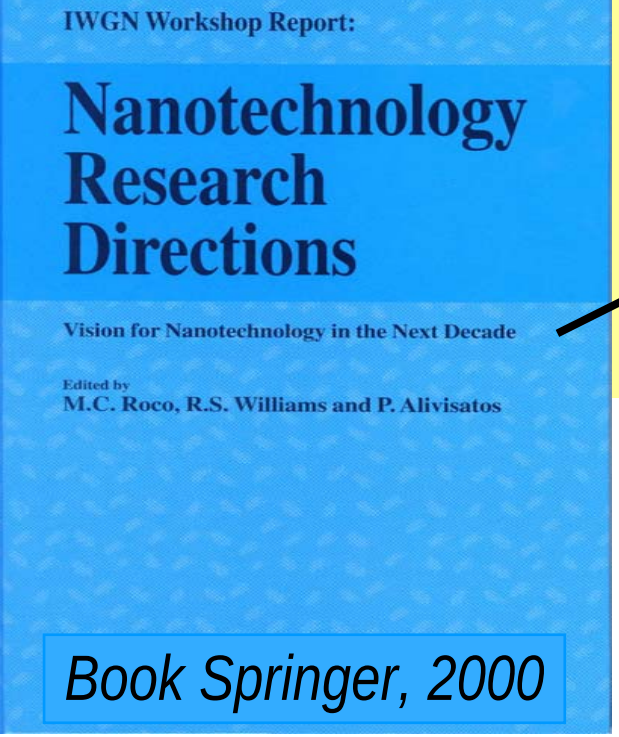
Nanotechnology

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

where new phenomena

enable new applications.

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



Book Springer, 2000

Nanotechnology discovery

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

While miniaturization is of interest

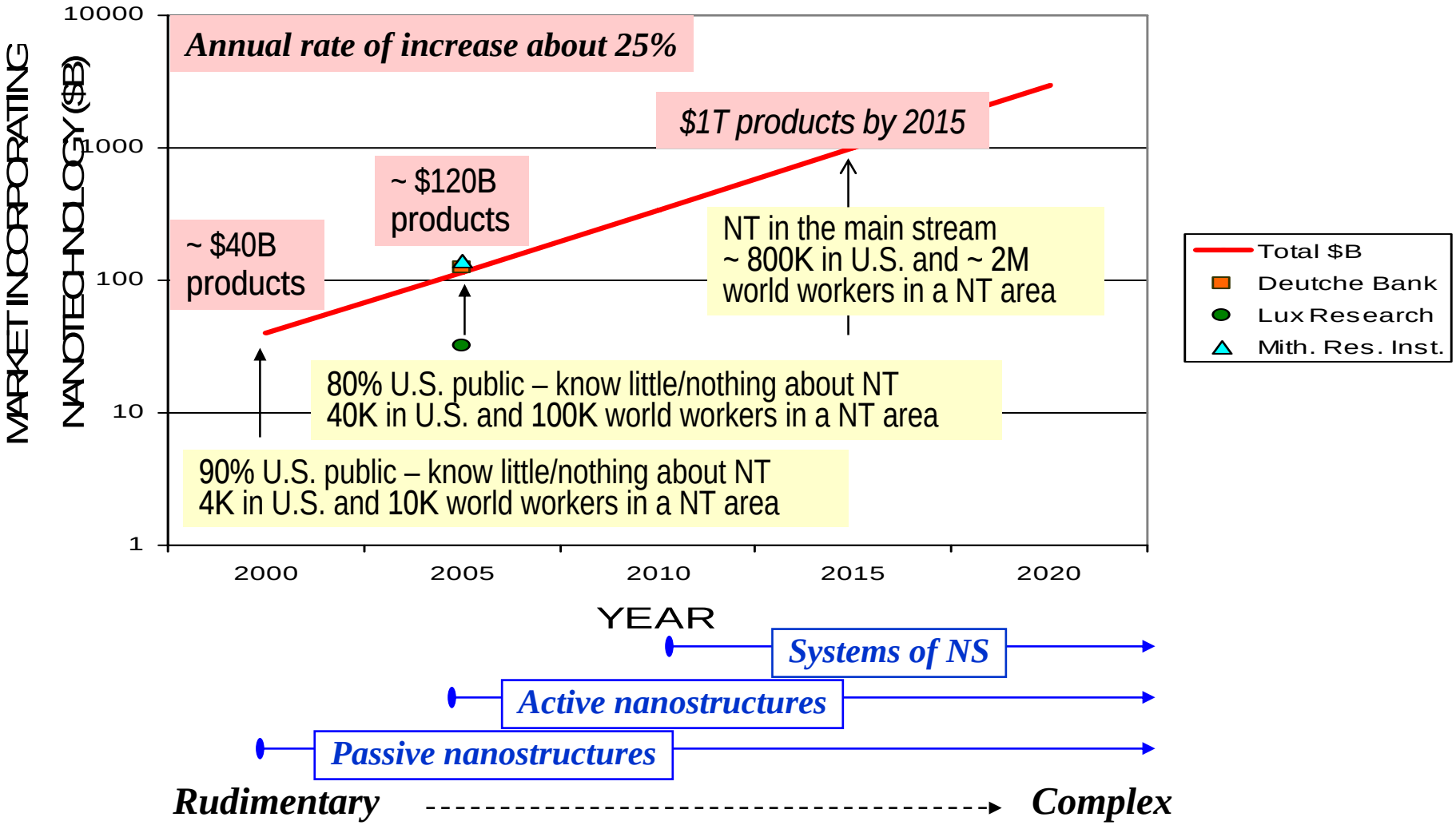
Less space, faster, less material, less energy

More important:

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

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY (2000-2015)

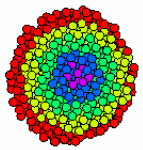
(Estimation made in 2000 after international study in > 20 countries)



Reference: Roco and Bainbridge, 2001

M.C. Roco, 11/01/2007

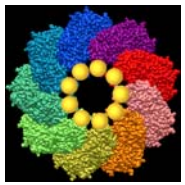
Four Generations of Products (200-2020): Timeline for beginning of industrial prototyping and nanotechnology commercialization



1st: Passive nanostructures (1st generation products)

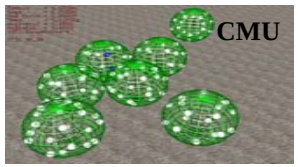
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2000



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

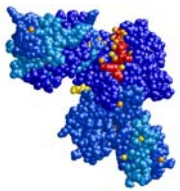
~ 2005



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

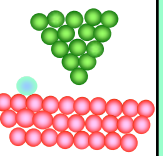
~ 2015-2020

New R&D challenges

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

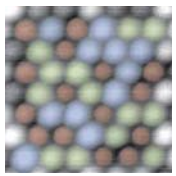
AIChE Journal, 2004, Vol. 50 (5), M. Roco

Four stages for nanoscale investigative methods
(experiments, theory, design/synthesis of nanostructures)



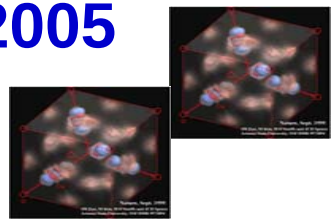
1st: Passive nanostructures
Mainly empirical, external to nanoscale modules, in isolation

~ 2000



2nd: Active nanostructures
Transition to science-based creation of nanomodules

~ 2005



3rd: Systems of nanosystems
Transition to science-based creation of complex nanosystems

~ 2010

?

4th: Molecular nanosystems
Direct experiments/simulations of nanosystems

~ 2015-2020

More science - based

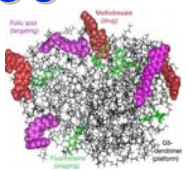
M.C. Roco, 11/01/2007

Perceived Higher Risks Areas

changing with the four generation of products

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

~ 2000



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

~ 2005

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

~ 2010

?

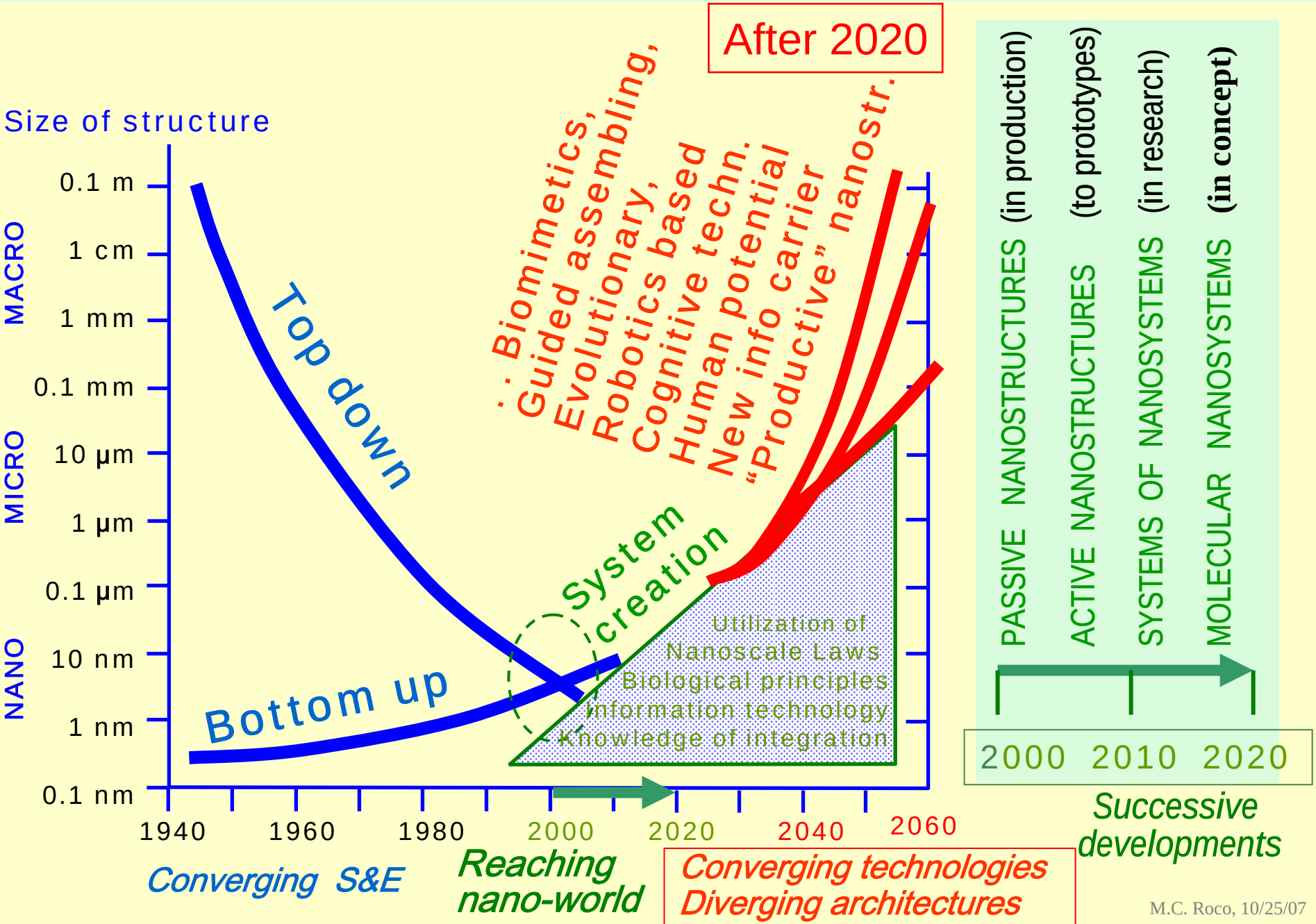
4th: Molecular nanosystems *Ex: Neuromorphic eng., Complex systems, Human-machine interface*

~ 2015-2020

Higher risk

M.C. Roco, 11/01/2007

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



M.C. Roco, 10/25/07

NNI Vision (2000 -):
Systematic control matter on the nanoscale will lead to a revolution in technology and industry

Two concepts:

- Changing the foundation of understanding, control, manufacturing and medicine from the macro and micro domains to the nanoscale, where all fundamental material structures, properties and functions can be efficiently established and changed

- Create general purpose technology that will affect almost all sectors of the society. It will disrupt – produce structural changes - markets, industrial organizations and business models (ex: 50% of new products in advanced industrial areas will use NS&E by 2015)

R&D towards the Next Industrial Revolution

Develop metrics - 2000,
Check the progress - 2005,
To satisfy first criteria – 2015

Five basic "Metrics" (in NNI proposal and NT Research Directions - 1999)

1. Systematic control of matter at the nanoscale

   "The progress is on target" → evaluations by COV / NSF(2004)
   NRC Studies on NNI (2002, 2006); PCAST report (2005);
   Contributions by various industry sectors (2003-)

2. New products and processes that were not possible before because of technical or economical barriers

   Commercialize novel materials (see Lux Research after 2003, WWCS, worldwide studies); Ten outcomes → on target

R&D towards the Next Industrial Revolution

3. Half of the *newly designed* products in advanced industrial area (materials, electronics, pharmaceutics, chemicals, aeronautics, devices for molecular medicine) will use nanoscale S&E

   Surveys industry, Soc. Impl. Report (2004) → At least half (2015)

4. $1 trillion world market of final products with key component based on nanotechnology, 2 million jobs worldwide

   Increasingly supported by studies → On of before 2015

5. Establish an interdisciplinary community (called "grand coalition" in Research Directions 1) and suitable workforce

   COV / NSF evaluation (2004) → "a big achievement"

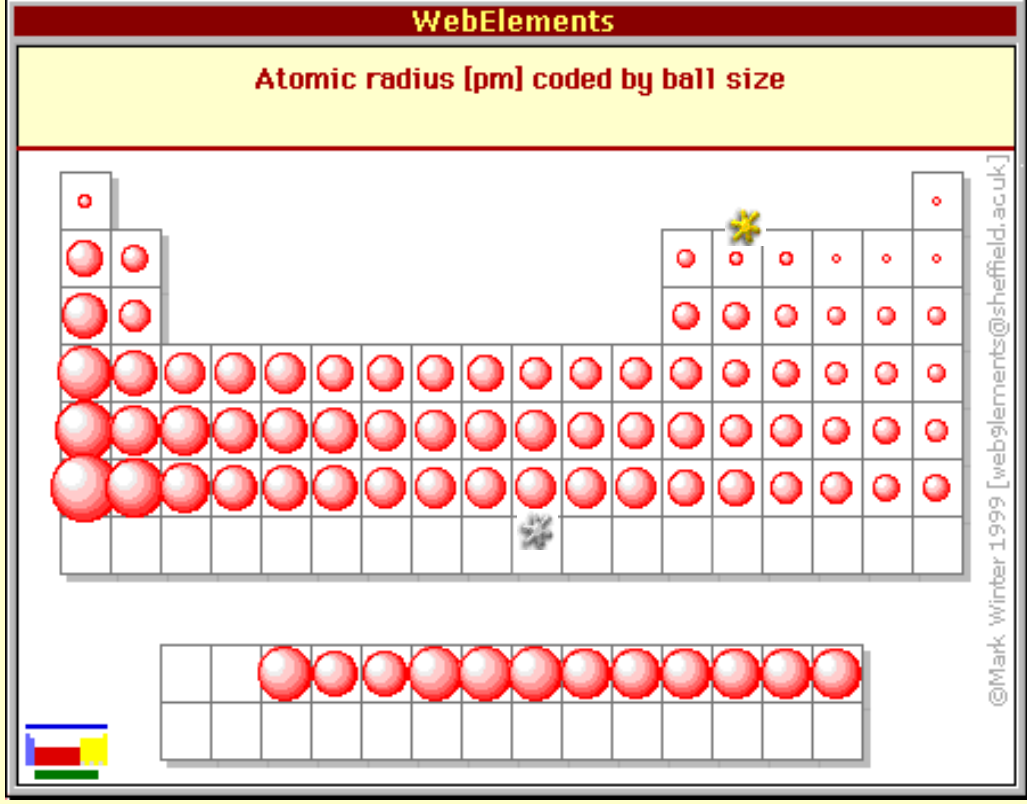
   NRC evaluation in 2002 - good strategic view

   Industry / academia / Federal government / state partnerships

   Systemic changes and earlier NT education, workforce

Basics

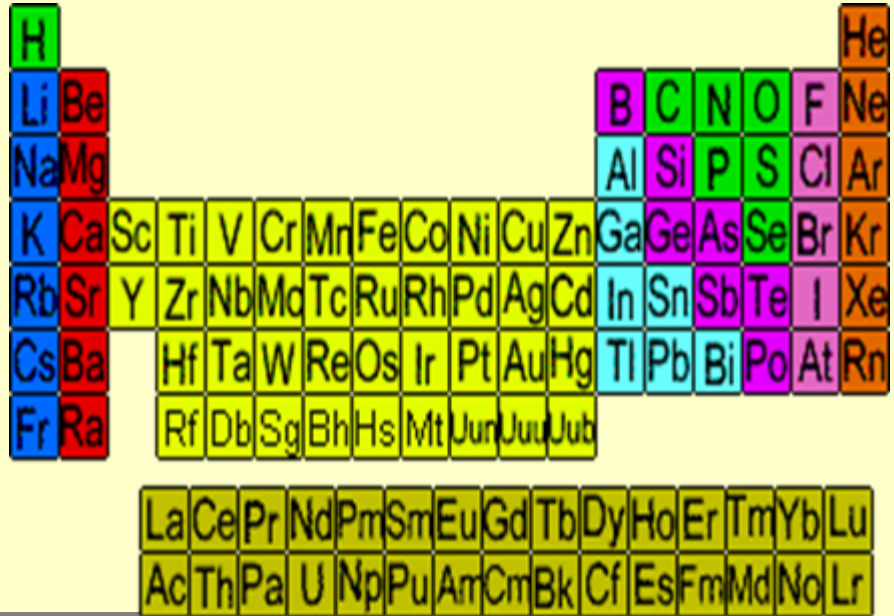
Nanotechnology works with atoms, molecules and supramolecules



Atom diameters vary in size
~0.1 nm Hydrogen, Carbon
~0.5 nm Gold, Platinum

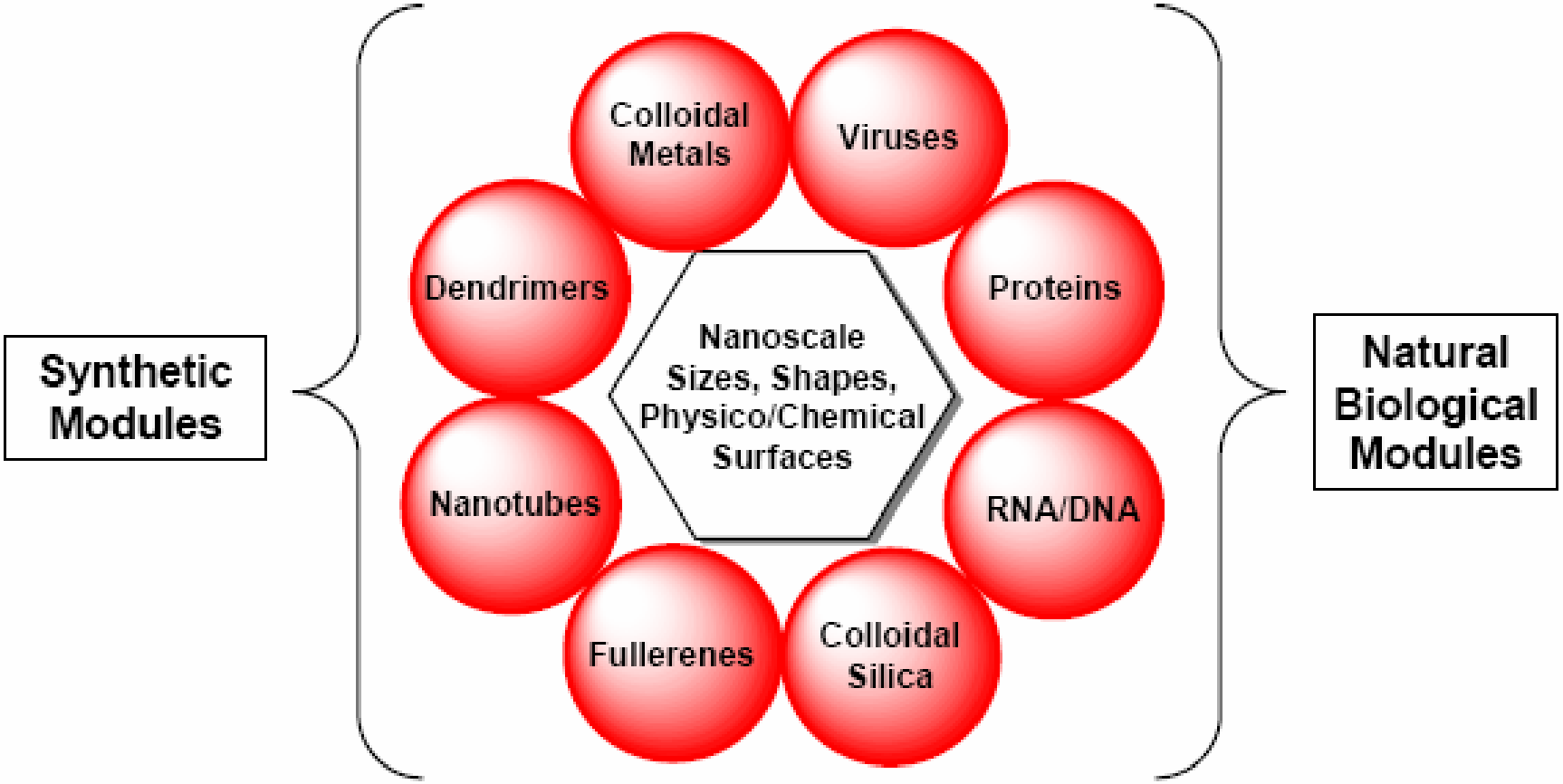
Only about 20 -25 atoms are frequently used in applications

A molecule may be from about 1nm to tens of nm



Natural and synthetic nanoscale modules / building bocks

(typical examples for first level of organization of atoms and molecules)



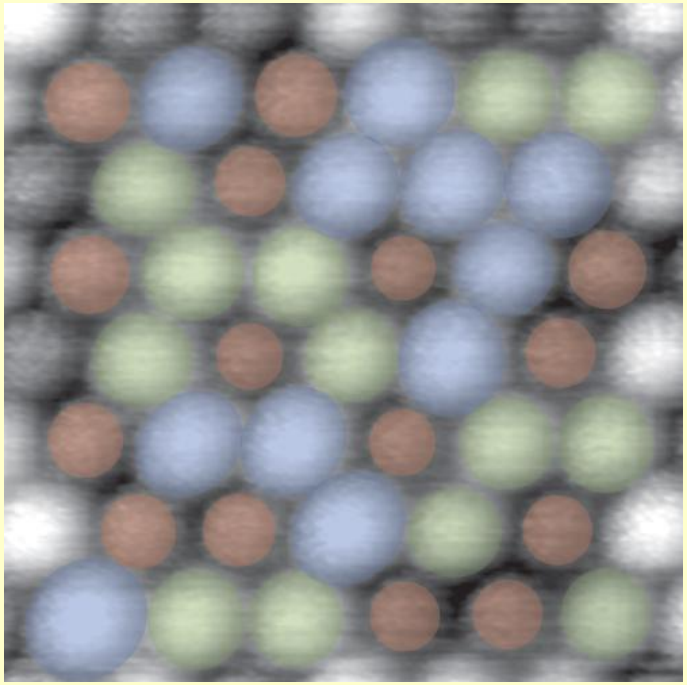
Basic challenges: tools, creating nanoscale modules, exploit new behavior

Nanotools – key challenge for advancing NT

Example:

Microscope discerns atoms of different elements

- AFM with chemical fingerprint at room temperature
- Useful for designing devices at the molecular level



Yoshiaki Sugimoto at Osaka University in Japan, New Scientist, Feb. 2007

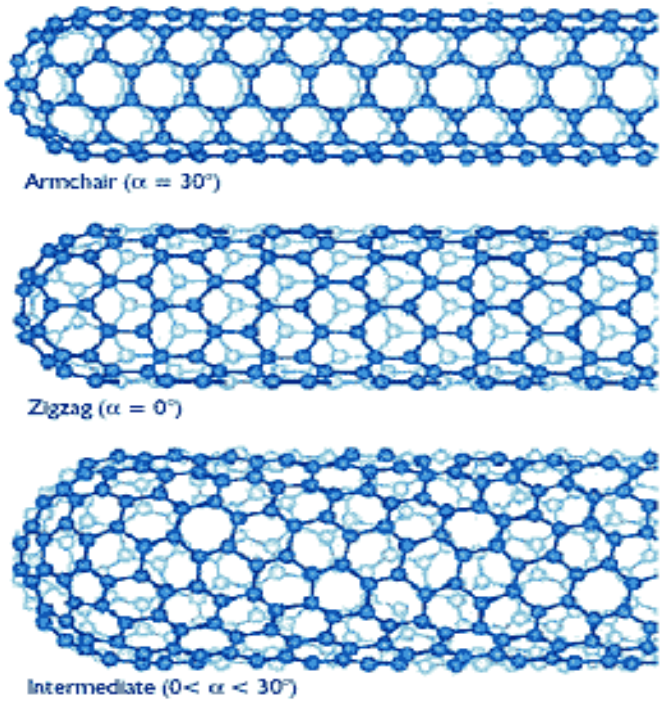
Creating nanostructures – key challenge for advancing NT

Example (single chemical composition)

Carbon nanotubes (Iijima, 1991)

1-3 nanometer in diameter

Metallic or semiconducting nanotubes



Other nanostructures with carbon:

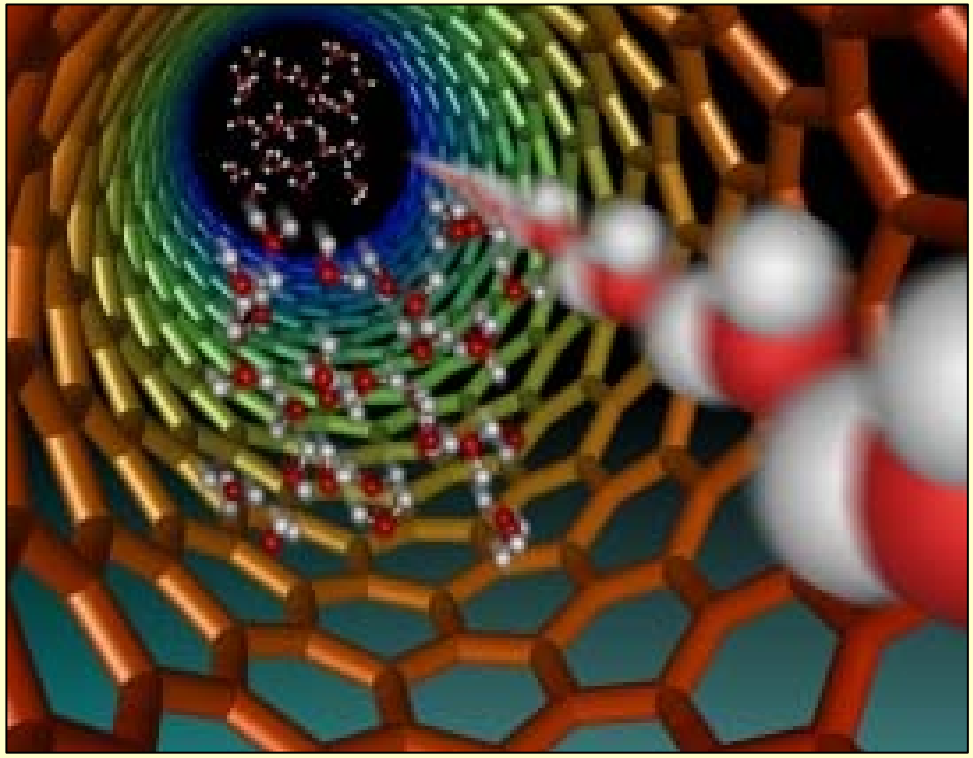
plane – **graphite**; hexagonal – **diamond**; conic – **batteries**; diverse – **bio**; ….

Understanding new behavior at nanoscale - quantum effects, large surface area, confinment, larger reactivity, many others

Example:

Significant Reduction of fluid friction in CNT

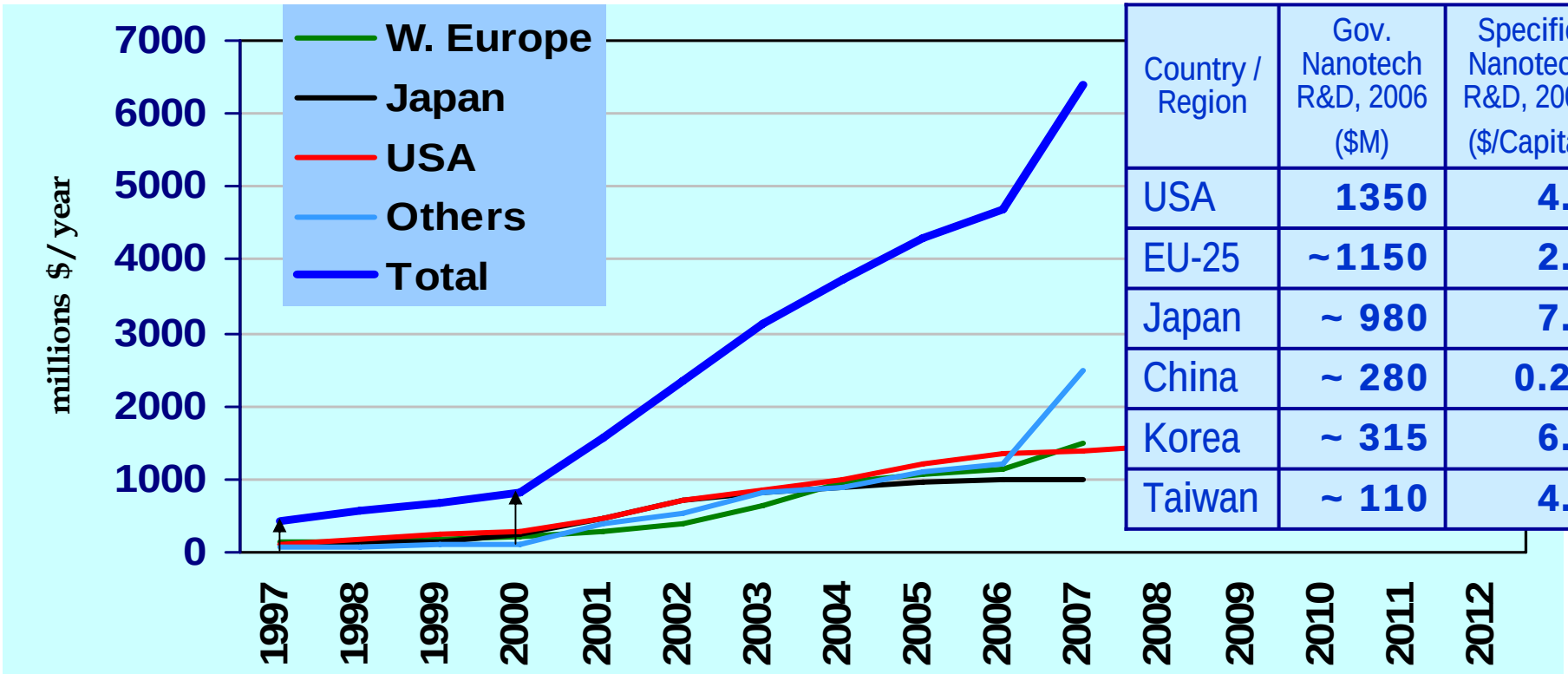
Theory University of Kentucky, 2006; after few months experimentally verified at the Sandia National Laboratory



Water is shown flowing through carbon nanotube membranes at a rate up to 100,000 times faster than micro scale models predict.

Context – Nanotechnology in the World

National government investments 1997-2006 (est. NSF)



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

Seed funding (1991 -)

NNI Preparation (vision / benchmark)

1st Strategic Plan (passive nanostructures)

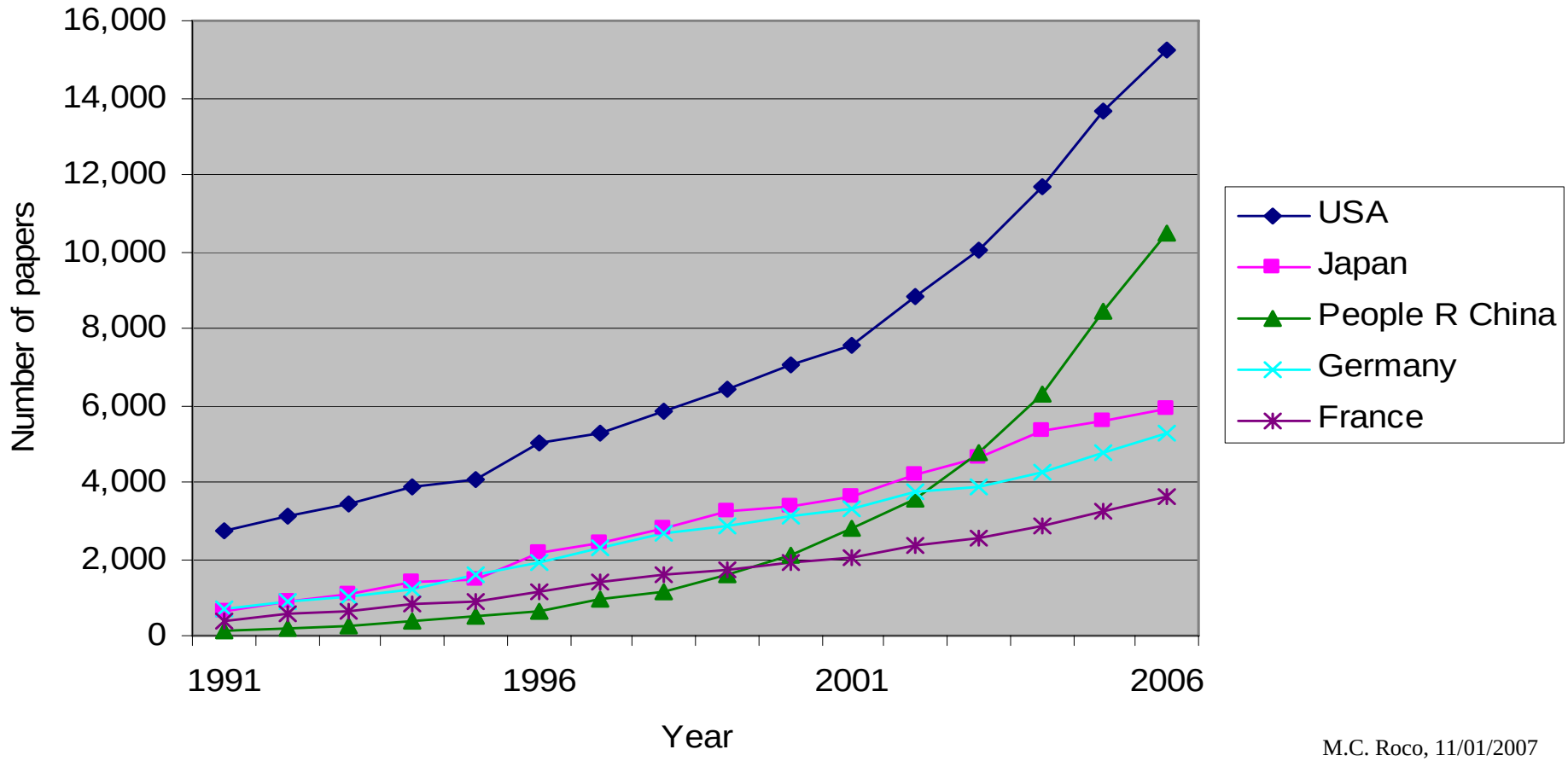
2nd Strategic Plan (active ns. & systems)

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

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

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

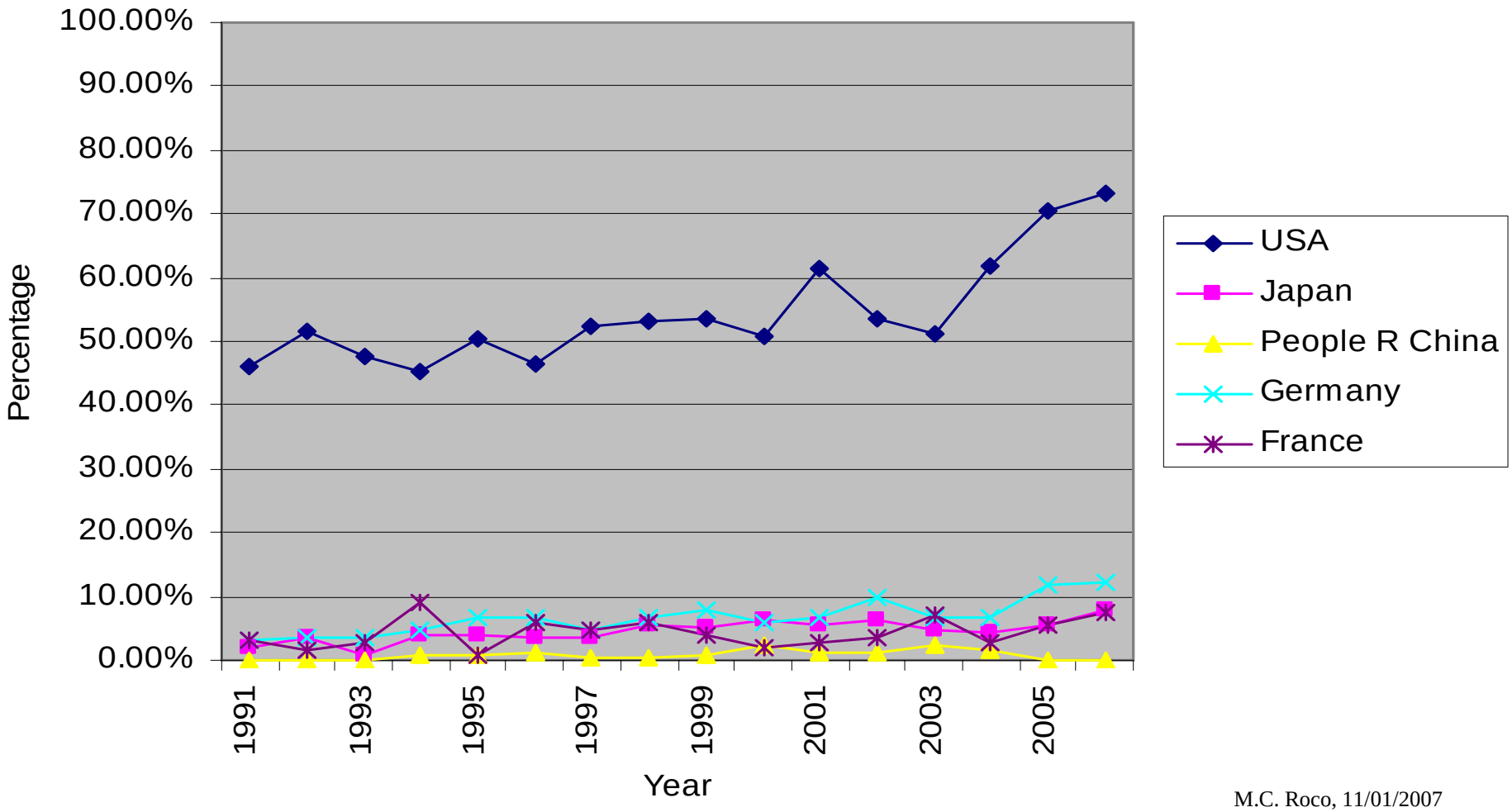
using “Title-claims” search in SCI database for nanotechnology by keywords
(using intelligent search engine, update J. Nanoparticle Research, 2004, 6 (4))



M.C. Roco, 11/01/2007

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

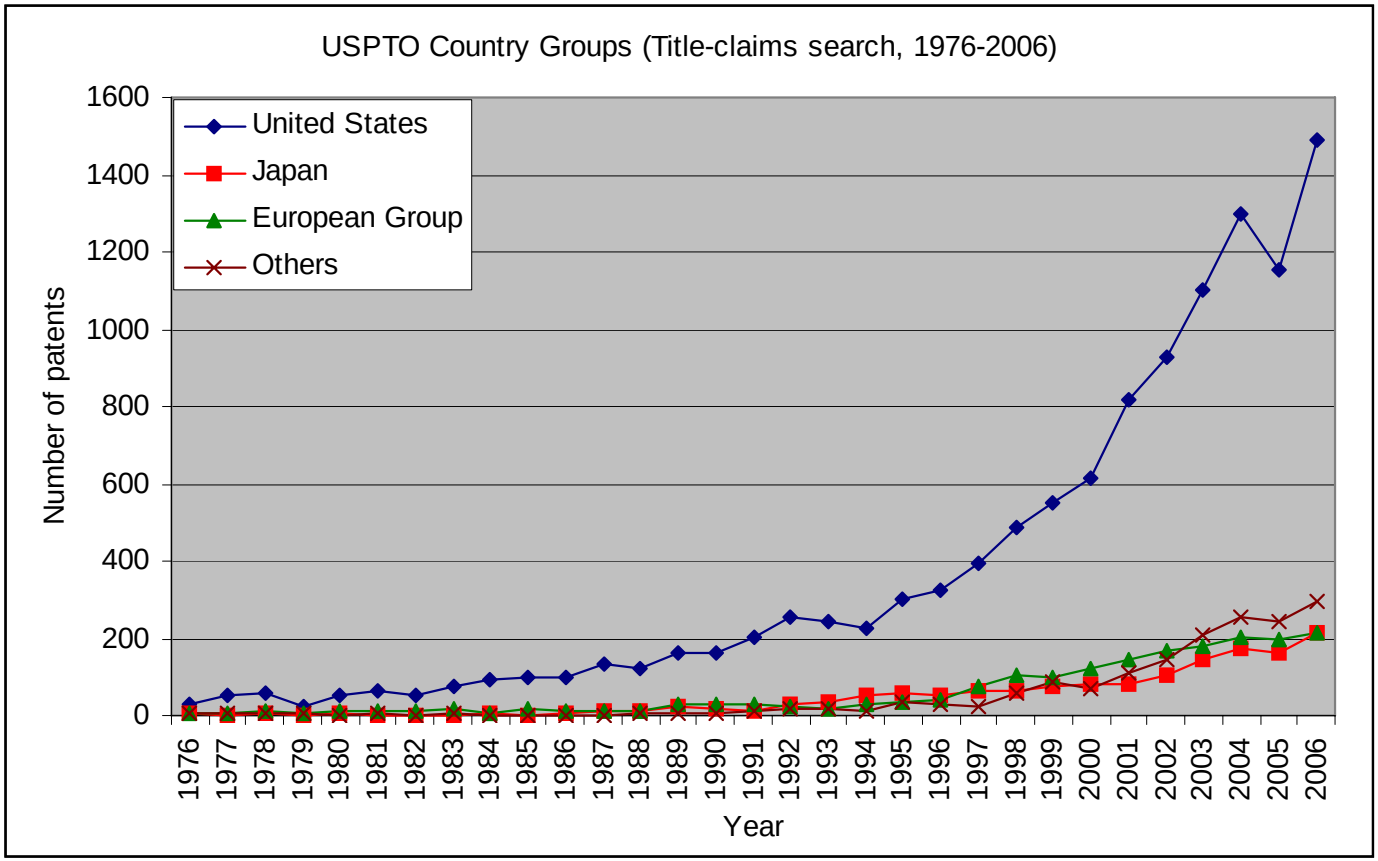
using "Title-abstract" search in SCI database for nanotechnology by keywords (using intelligent search engine, update J. Nanoparticle Research, 2004, 6(4))



M.C. Roco, 11/01/2007

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

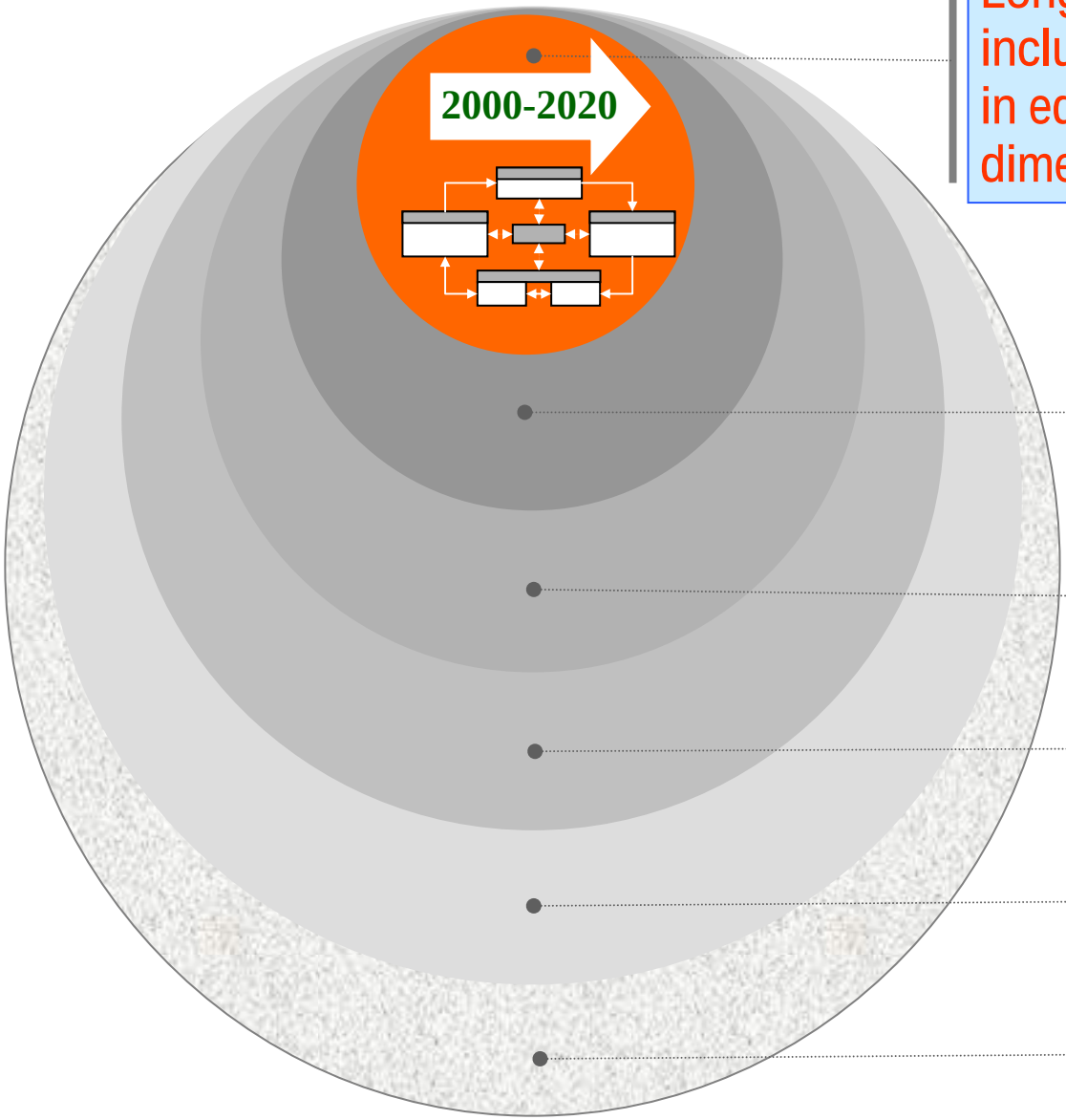
	1	2	3	
Synthesis & Assembly	U.S.	Europe	Japan	BASIC APPROACHES
Biological Approaches & Applications	U.S.	Europe	Japan	
Dispersions and Coatings	U.S./Eur	Japan		R&D for PRODUCTS 1st Generation
High Surface Area Materials	U.S.	Europe	Japan	
Consolidated Materials	Japan	U.S./Eur		
Nanodevices	Japan	U.S./Eur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

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

What is Governance?
(International Risk Governance Council, IRGC)

- "Governance" – a versalite term of widespread use
- Definition: Governance refers to processes, conventions and institutions that determine:
  - How power is exercised in the view of managing resources and interests;
  - How important decisions are made and conflicts resolved; and
  - How various stakeholders are accorded participation.
- Principles of "good governance" include e.g.:
  - Transparency
  - Responsibility
  - Accountability, and
  - Participation.
- Core substance and principles to be applied to nanotechnology

Nanotechnology GOVERNANCE OVERVIEW



Core Governance Process:

Long-term view, transforming, inclusive, horizontal/vertical, priority in education, addressing societal dimensions, 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

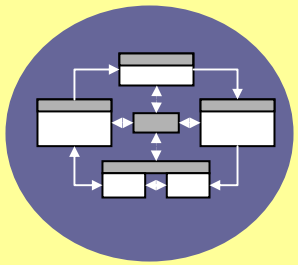
International Interactions

NT Governance and Risk Governance

NT
GOVERNANCE

- Investment policy
- Science policy
- Risk governance
- Others

Four key functions



NANOTECHNOLOGY
RISK
GOVERNANCE (IRGC)

WHAT IS DIFFERENT

- Fundamental changes:
  4+1 generations; 2 frames
- Closer to social context in
  assessment (ELSI +)
- Governance approach:
  corrective and adaptive
- Global, many stakeholders

Possibilities for a Global Governance of Nanotechnology

General approach

- Facilitate and provide reference models to the global self - regulating ecosystem (too complex for top-down):
  - open source models of NT development and its institutions, discovery, innovation, education, human resource, informatics
  - emerging and converging technology infrastructure;
  - use economical incentives for accelerating NT production;
  - foster suitable international organizations and agreements
- Focus on bottom-up and lateral interactions and less on top - down measures
  - using political leadership and democratic principles,
  - social consensus in knowledge based societies
- System of global communication and participation in all phases of governance, facilitated by international organizations

Reference: "Global Governance of Converging Technologies", MC Roco, J. Nanoparticle Research, On-line Springer (2007)

Foster suitable international organizations

Ex: OECD Working Party on Nanotechnology

Working Party on Nanotechnology, established in May 2007, with steering groups for 6 projects for 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

Governance of nanotechnology development: four roles

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

Possibilities for a Global Governance of Nanotechnology

Transformative function

- Support tool development, knowledge creation, innovation and informatics, and commercialization for nanotechnology, in the international context;

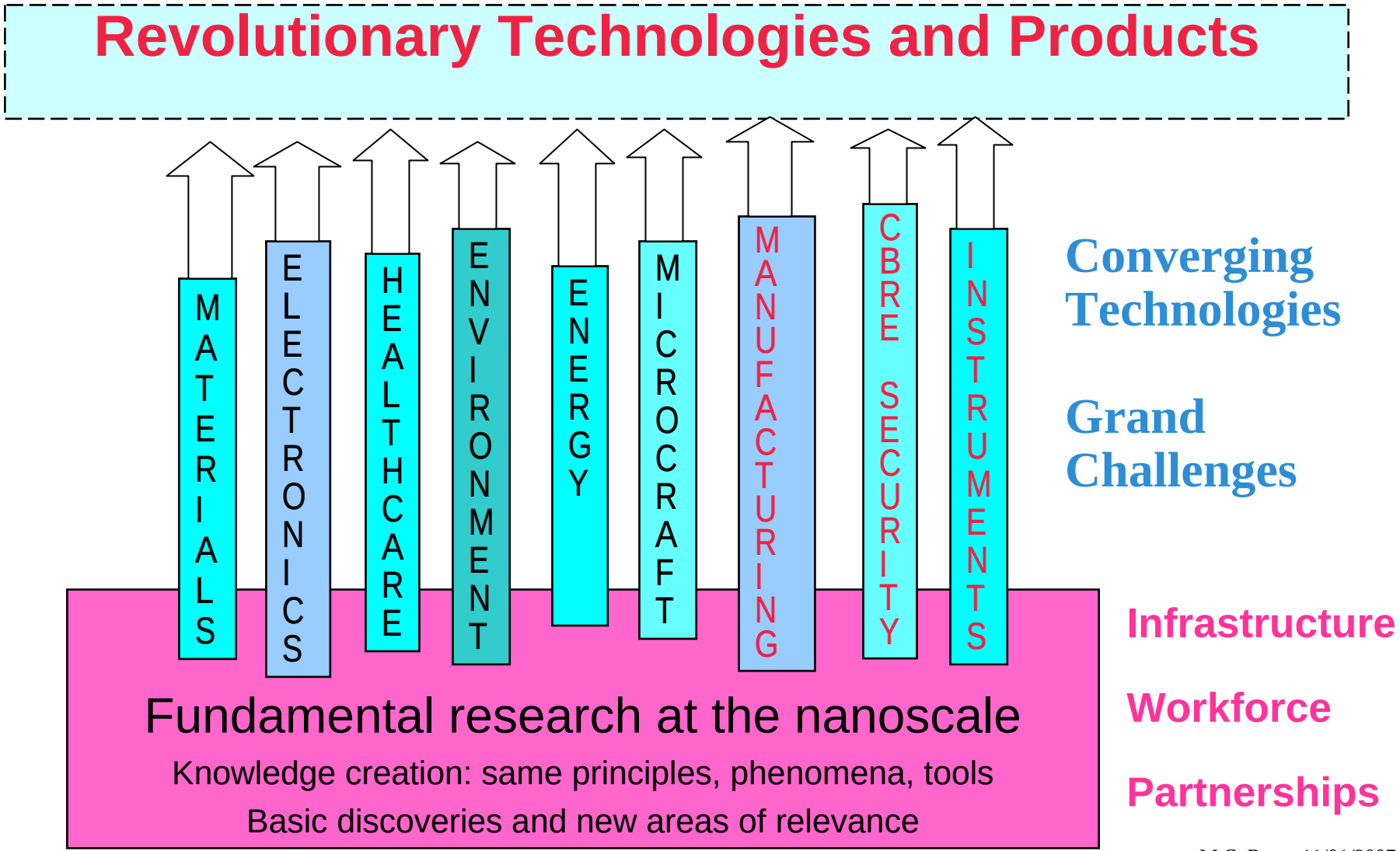
- Creating better opportunities for development of nanotechnology in developing countries;

- Allocation of development funds for common topics: nomenclature, metrology, standards, patent evaluation, databases, and EHS methodologies including for a predictive toxicology approach for nanomaterials;

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

Transformative: Stimulate innovation

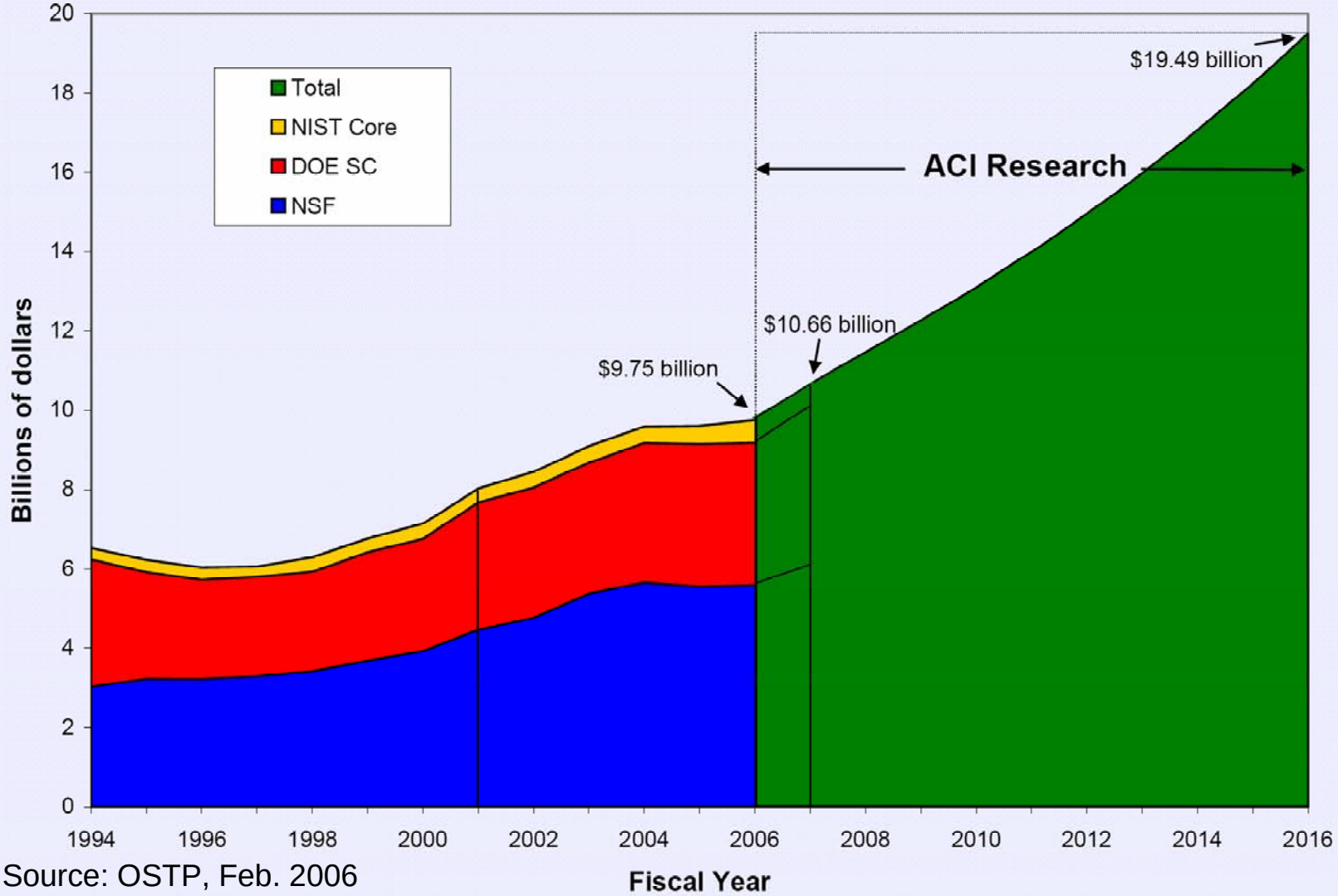
Interdisciplinary "horizontal" knowledge creation vs. "vertical" transition from basic concepts to Grand Challenges



M.C. Roco, 11/01/2007

Investment plan: American Competitiveness Initiative

For fiscal years 2007 – FY 2016; Nanotechnology a key component



Source: OSTP, Feb. 2006

Foster suitable international organizations

Ex: International standards organizations working on nanotechnology

National Body International Standards Organizations

Treaty-Based International Standards Organizations

Standards Development Orgs. With Global Reach

ASME International

Possibilities for a Global Governance of Nanotechnology

Responsible development function

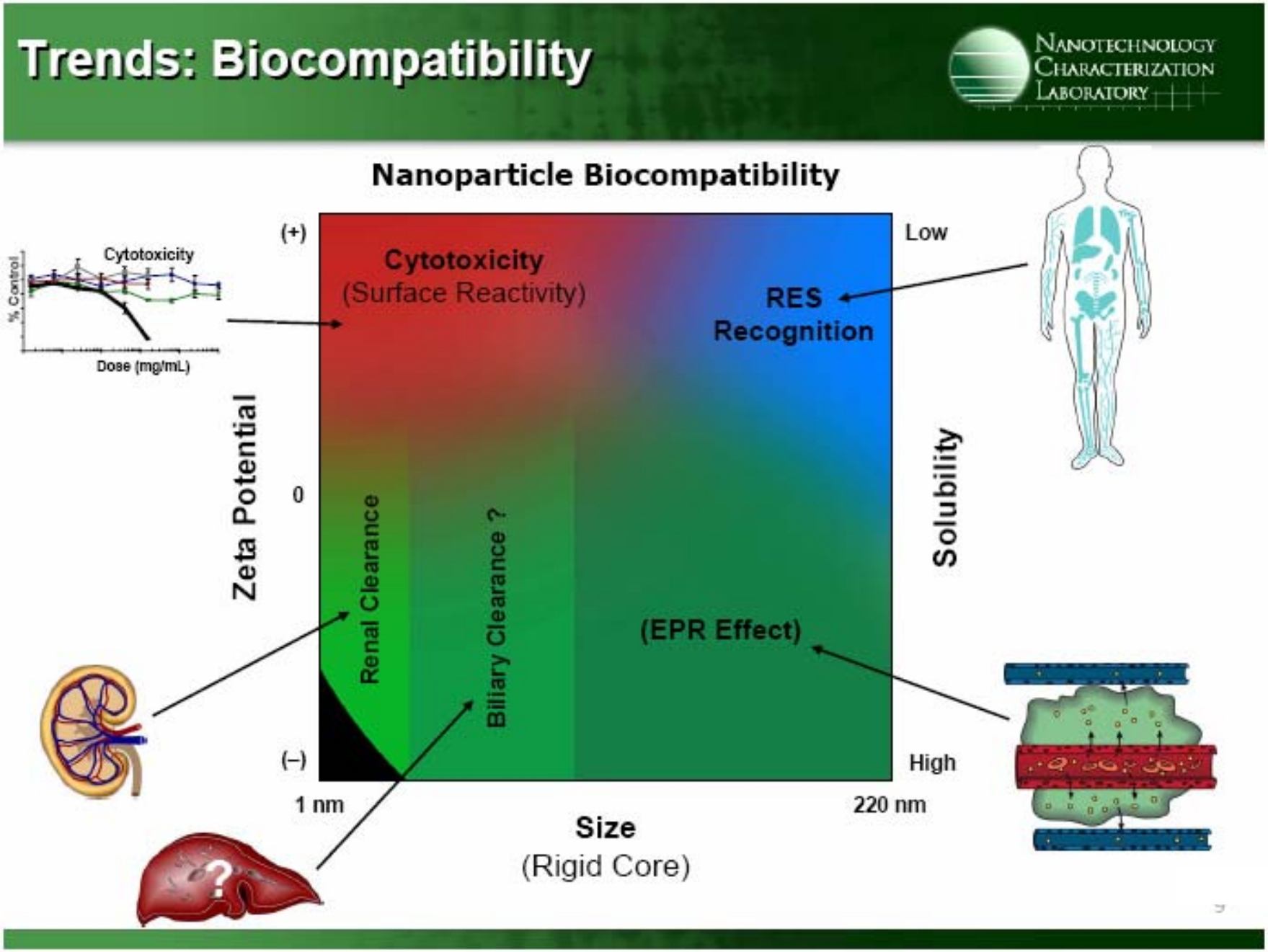
- Development with priority of general benefit applications such as: increasing productivity; sustainable, resource-efficient nanomanufacturing; improving availability of common Earth resources such as water, food, energy, and sustainable clean environment
- Voluntary measures and science-based decision for risk management by industry
- Public inclusion and participation in national and international activities
- Develop organizational capacity for effective oversight

Nanotechnology risk governance issues

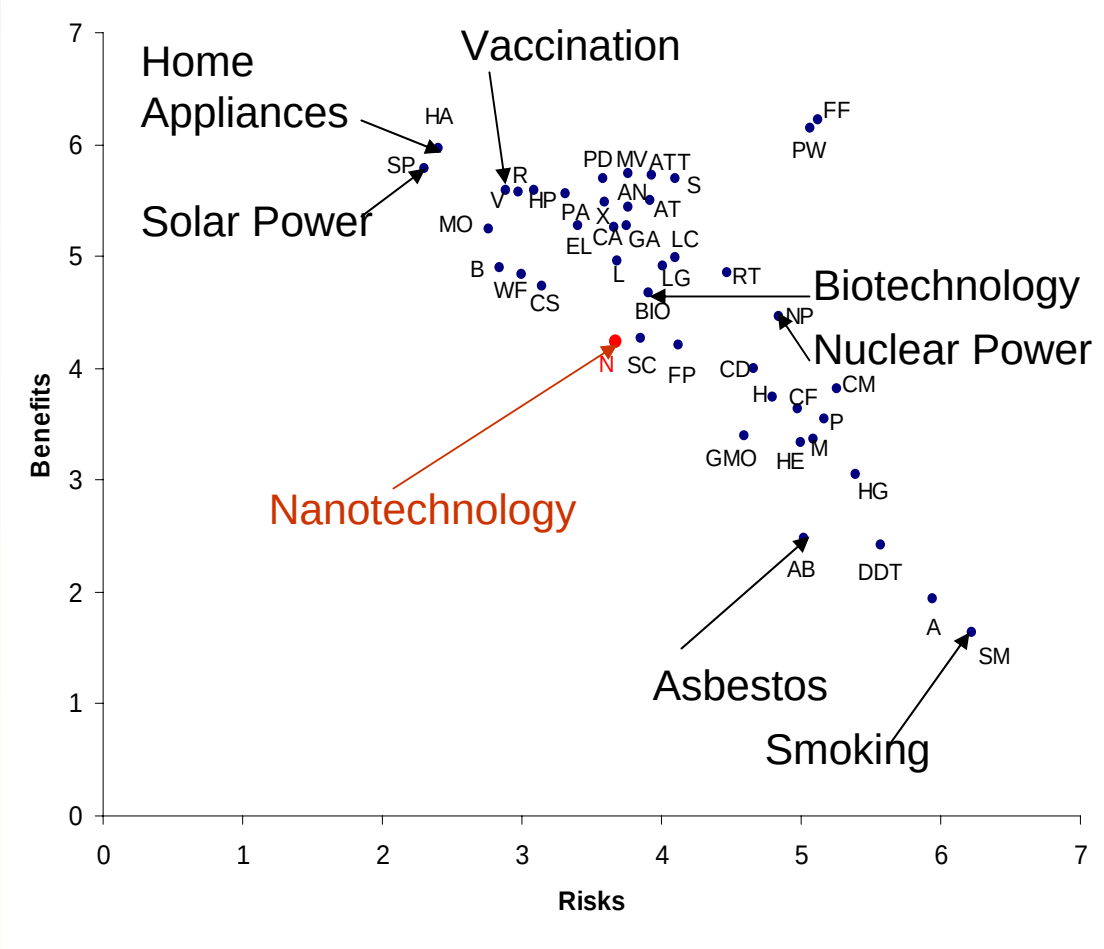
EHS, ELSI, Education Gap, Human Development, Political and Security

- Investment policies (R&D, infrastructure) for best and equitable outcomes in society
- Occupational safety
- Consumer safety
- Environmental safety
- Legal framework (science testimony, new cases; at national and international levels) and its impact on international trade
- Individual rights to education and knowledge
- Social implications: human integrity and dignity; new opportunities and losses; societal structure; etc.)
- International relationships: IP, North-South divide, equity between haves and have-nots
- Long-term human development – need for anticipatory measures
- Need for principles to be converted to defined and planned actions

First, the scientific foundation. For illustration:



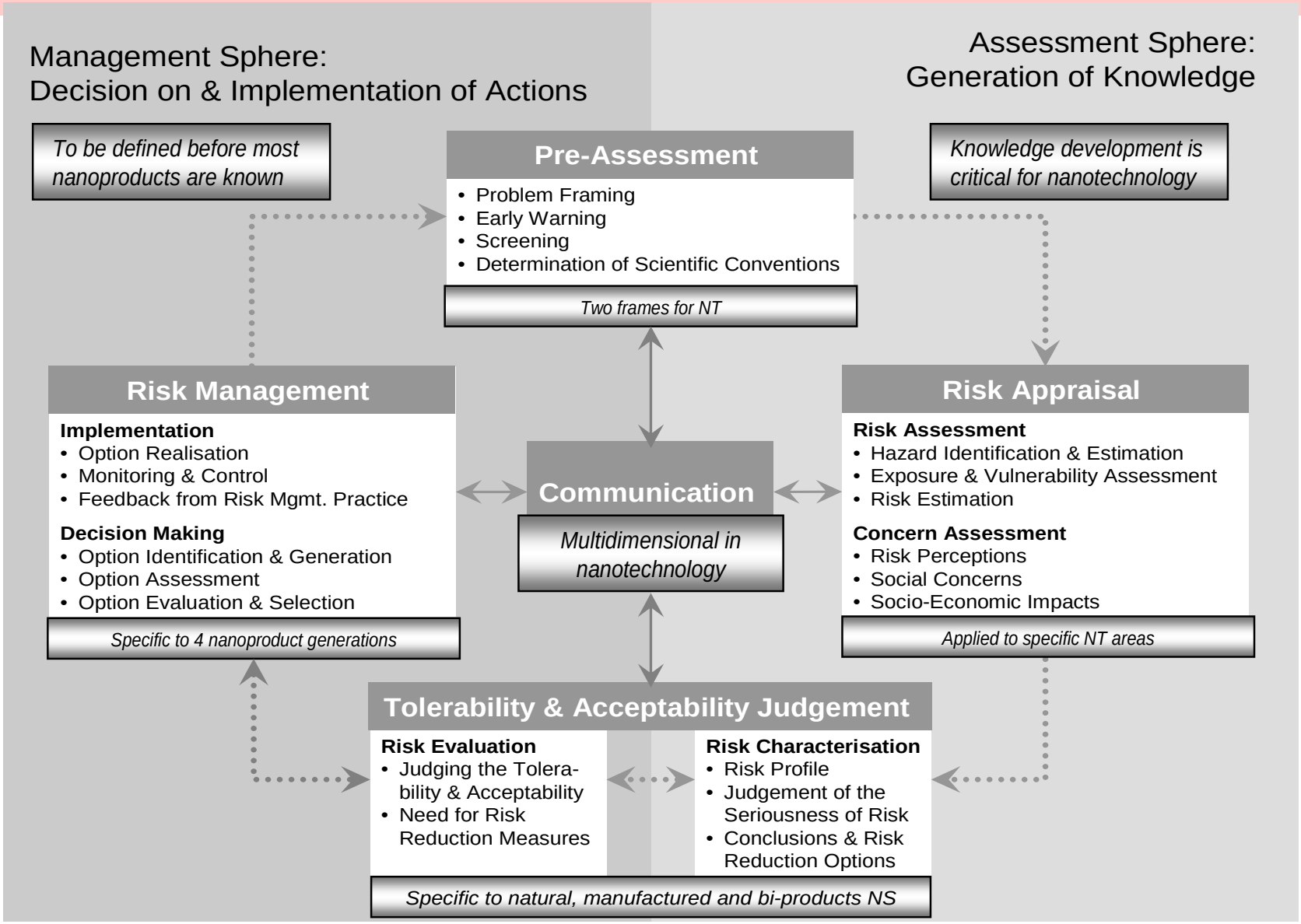
Steven Currall et al. Survey on Public's Risk-Benefit Perceptions



Air travel	AT
Alcoholic beverages	AB
Anesthetics	AN
Asbestos	A
Automobile travel	ATT
Bicycles	B
Biotechnology	BIO
Chemical disinfectants	CD
Chemical fertilizers	CF
Chemical manufacturing plants	CM
Commercial aviation	CA
Computer display screens	CS
DDT	DDT
Electric power	EL
Fire fighting	FF
Food preservatives	FP
General aviation	GA
Genetically modified organisms	GMO
Handguns	HG
Herbicides	H
Home appliances	HA
Human genetic engineering	HE
Hydroelectric power	HP
Large construction	LC
Lasers	L
Liquid natural gas	LG
Microwave ovens	MO
Motor vehicles	MV
Motorcycles	M
Nanotechnology	N
Nuclear power	NP
Pesticides	P
Police work	PW
Prescription antibiotics	PA
Prescription drugs	PD
Radiation therapy	RT
Railroad	R
Smoking	SM
Solar power	SP
Stem-cell research	SC
Surgery	S
Vaccinations	V
Water fluoridation	WF
X-rays	X

Source: *Nature Nanotechnology*, Dec. 2006, 1:153-155.

IRGC RISK GOVERNANCE FRAMEWORK FOR NANOTECHNOLOGY



Strategies as a function of the generation of nanotechnology: Application to Frame 1 and Frame 2 (pre-assessment)

Increased
- *Complexity,*
- *Knowledge needs*
- *Implications*

Strategy escalator

Nanosystems

Active nanostructures

Passive nanostructures

Frame 2 longer term
Unknown
(Higher ambiguity in society)

Frame 2 shorter term
Technological System Uncertainty

Frame 1
Component Complexity
R&D underway
Regulatory measures considered

Future work on social and global dimensions (focus on ELSI +)

Broader "strategy", design and recommendations are needed (focus on EHS, ELSI)

Some specific problems, with a focus on regulators (focus on EHS)

NT application areas

J. Nanoparticle Research, 2006, Vol. 8(2)

M.C. Roco, 11/01/2007

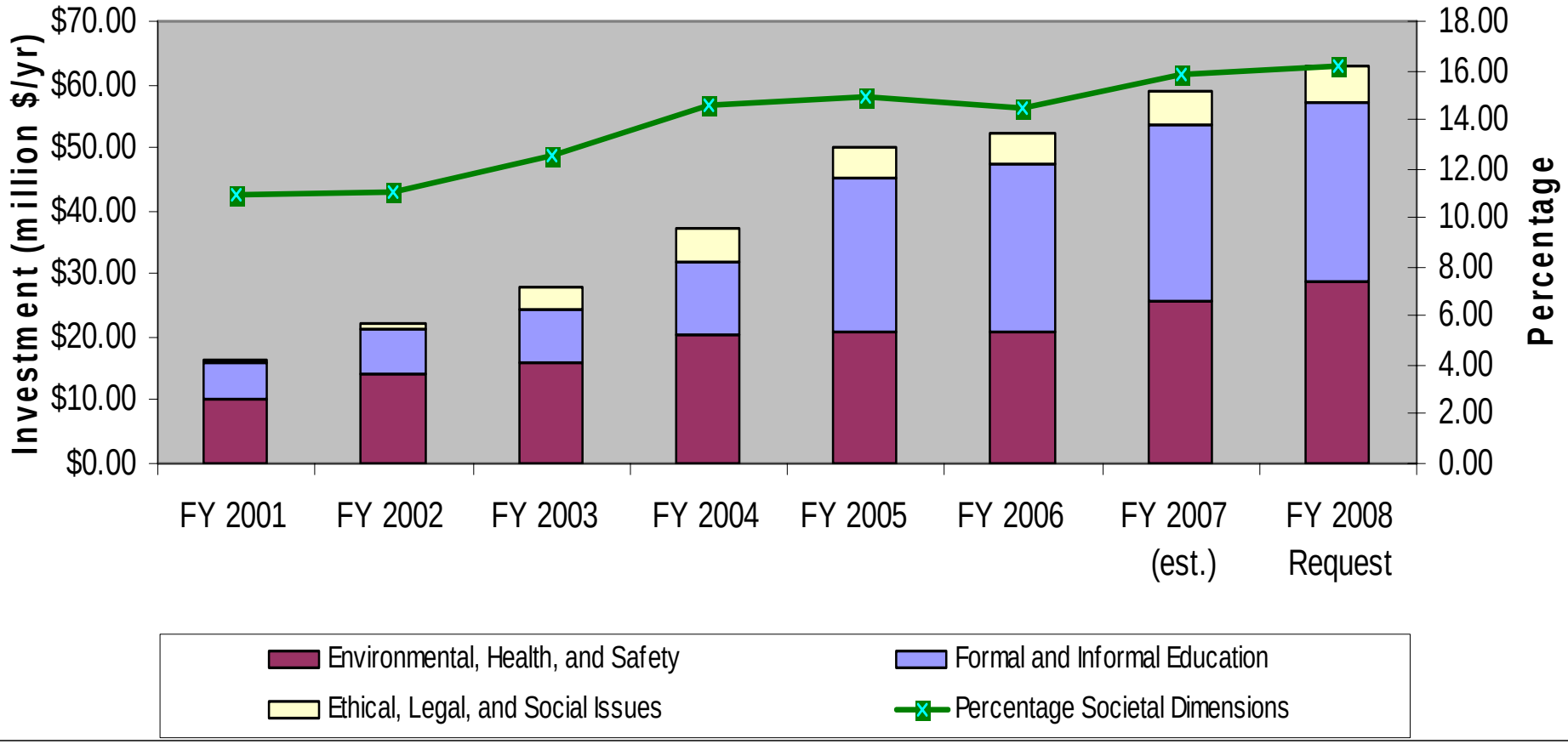
The Risk Management Escalator and Stakeholder Involvement

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

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**	

NSF Investment in Societal Dimensions of NT

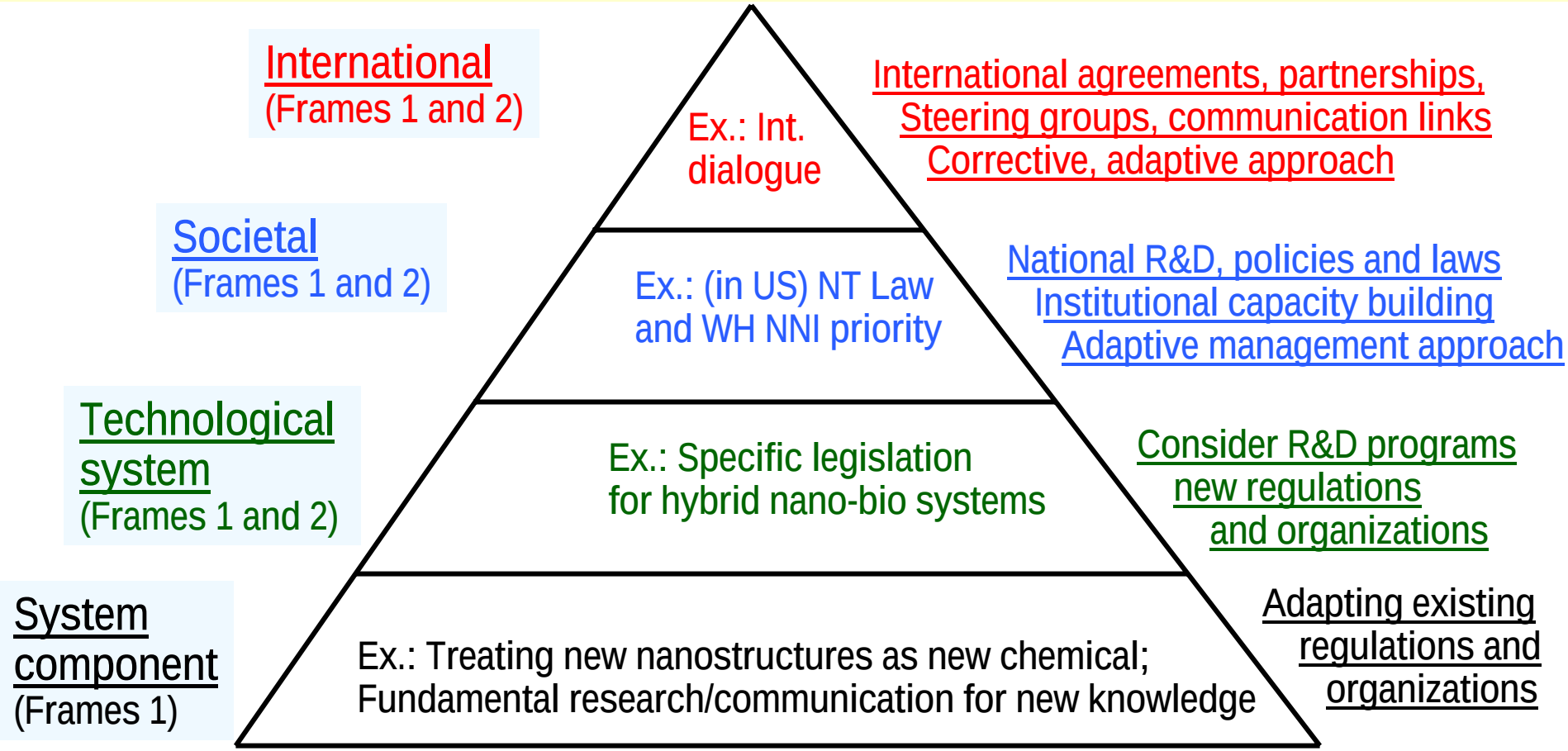
Of FY 2008 NNI/NSF request of $390 M, $63 M or 16.1% is for SI, and $28.8 M (7.4%) for nano EHS



Building capacity for responsible development

Multi-level structure of risk governance

Implication Domain / Examples of RG activities / Implementation approach



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

Possibilities for a Global Governance of Nanotechnology

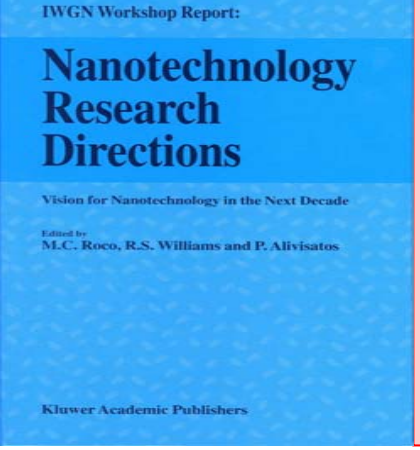
Inclusiveness and partnership function

- Supporting partnerships between various stakeholders active in nanotechnology applications and related emerging technologies

- Global communication and information, cross-sector, including for coordinated risk research strategies

- Involving international organizations to advance multi stakeholder global challenges

- Encourage international and cross-sector interactions



Inclusive: industry, academe, government, non-government and international organizations, communication institutions, public at large.

EX: S&T agencies 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

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**

Ex.: International Dialogue on Responsible Nanotechnology R&D

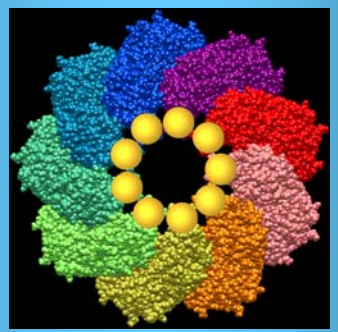
First: June 2004, Virginia, USA
Second: June 2006, Japan
Third: March 2008, Brussels, EC

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

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 and anticipatory measures on nanotechnology development
- Integrate nanotechnology development with other emerging and converging technologies; Conduct research specific for future generations of nanotechnology products (Frame 2, IRGC)
- Evaluate the trends for exponential growth of nanoscale knowledge and technology capabilities

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

The communication gap between emerging CT development and governance decisions

The Valley of Death
For Governance

EMERGING CT

RESEARCH
Creation of new information

COLLECT
VALIDATE
PRESENT
CRITIQUE

INFORM

FILTER
ORGANIZE
EXPLAIN
SUMMARIZE

EDUCATE

SYNTHESIZE
DEBATE
COMPARE

FRAME

GOVERNANCE

DECIDE
Recommend Actions

Modified M. Roco, ICON

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*

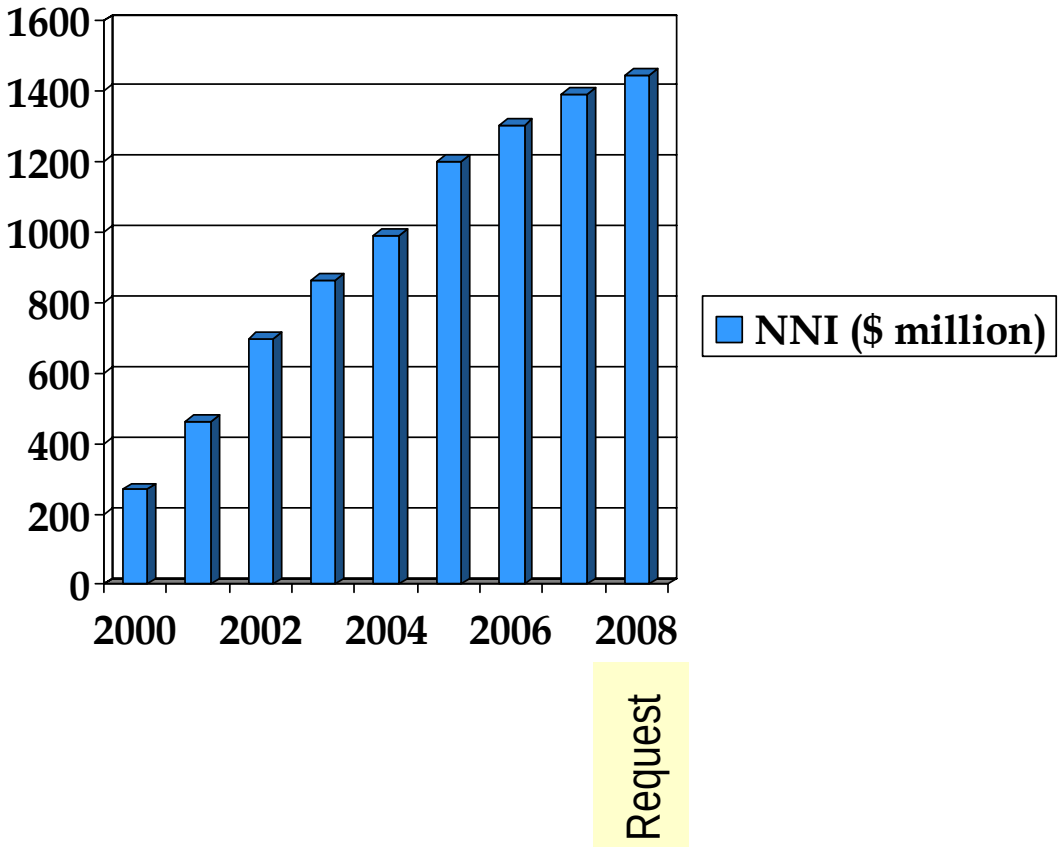
4. Support *global communication and international partnerships*

5. Commitment to *long-term, priority driven, global view* using scenarios and anticipatory measures

FY 2008 NNI Budget Request $1,445 million

Average rate of increase since 2000: <u>over 30% per year</u> 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

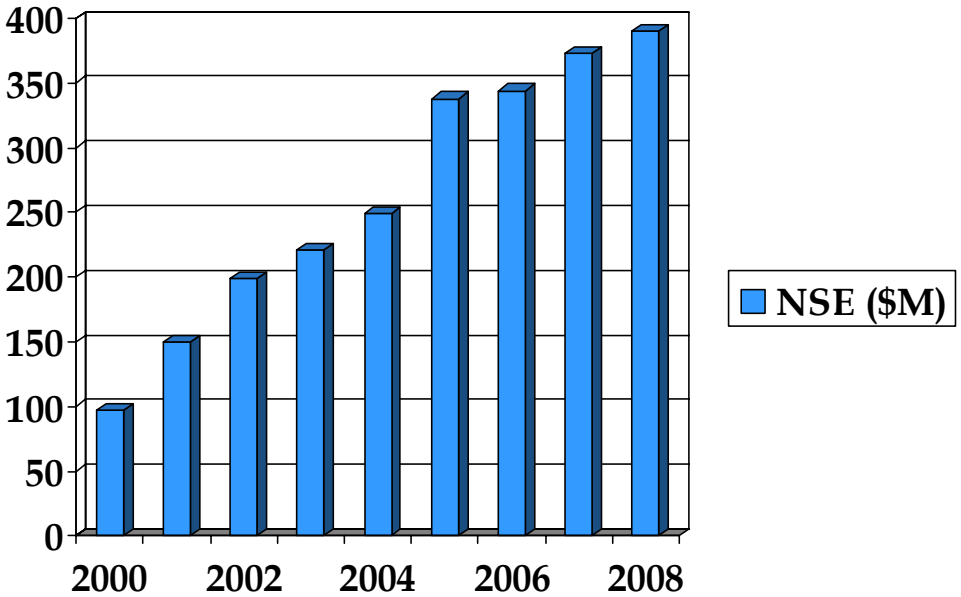
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

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 3,500 active projects; 24 large centers, 2 user facilities (NNIN, NCN), multidisciplinary teams
- Training and education – over 10,000 students and teachers/yr

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



M.C. Roco, 11/01/2007

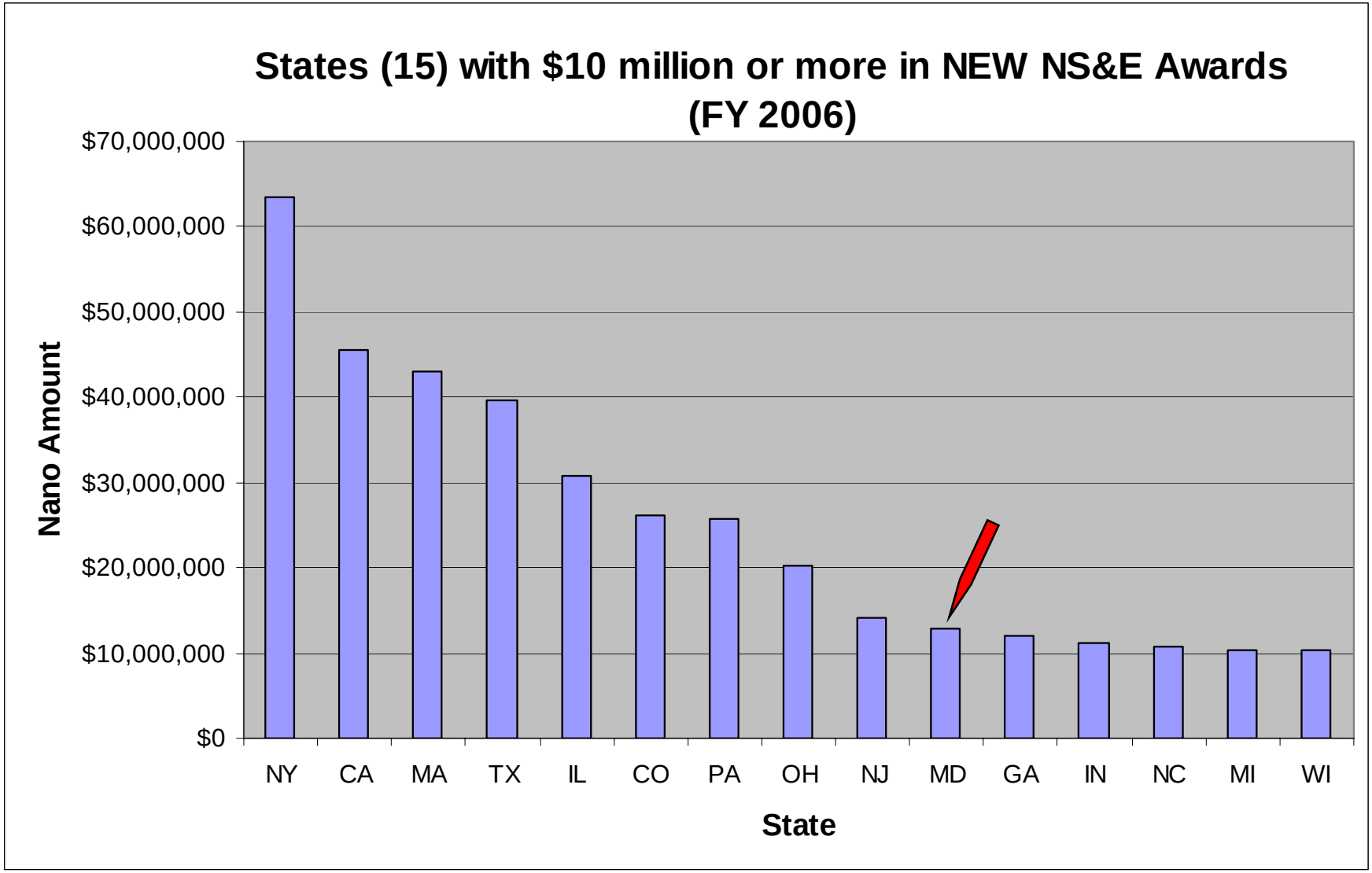
NNI Accomplishments (1)

- Developed foundational knowledge for control of matter at the nanoscale:
  about 5000 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

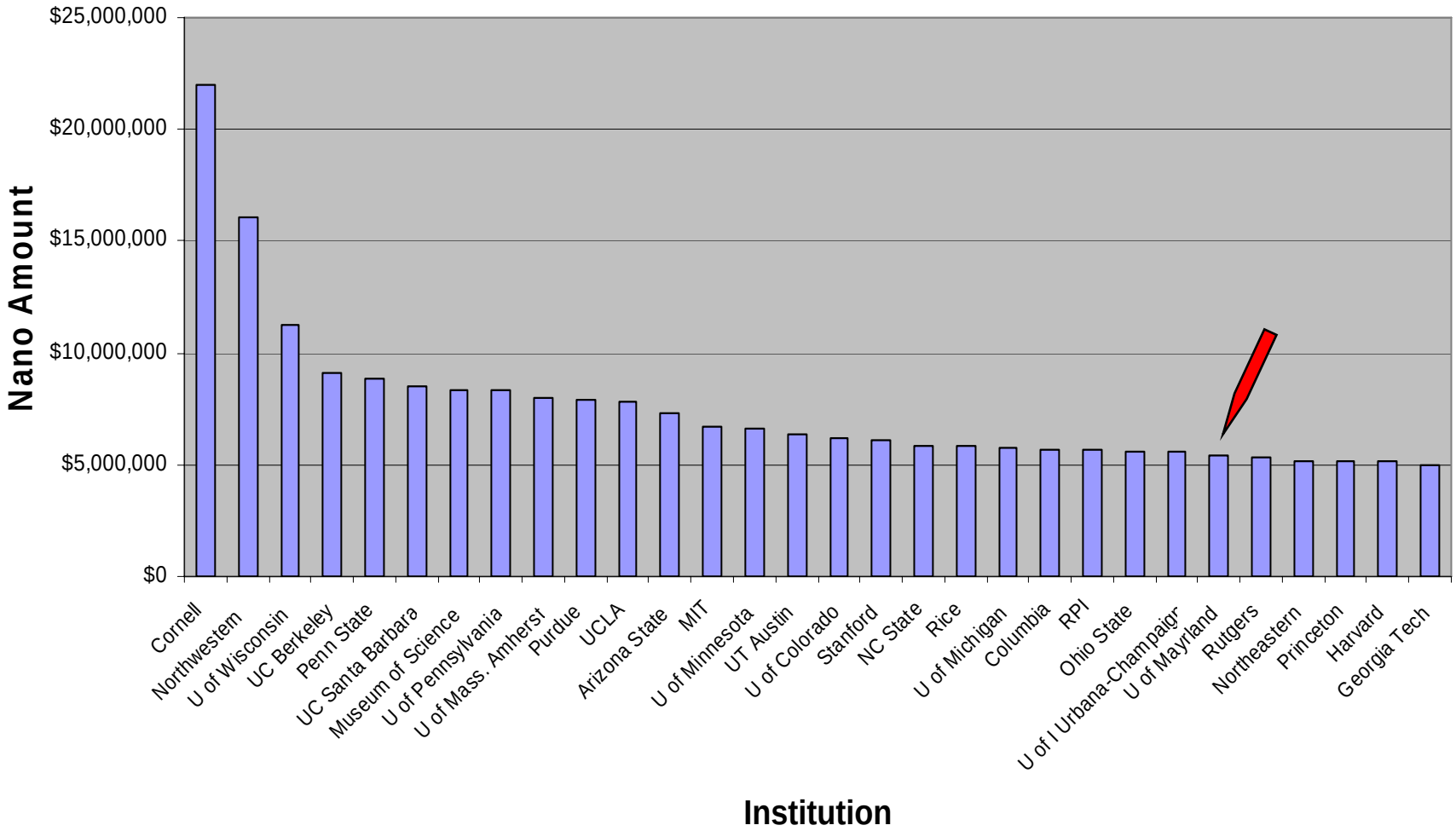
([1]) NSF Committee of Visitors, 2004; ([2]) Journal of Nanoparticle Research, 2004; ([3]) NanoBusiness Alliance, 2004

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 l education
- Global outreach: The U.S. NNI has catalyzed global activities in nanotechnology and served as a stimulus for other programs.


States (15) with $10 million or more in NEW NS&E Awards (FY 2006)
$70,000,000
$60,000,000
$50,000,000
$40,000,000
$30,000,000
$20,000,000
$10,000,000
$0
Nano Amount
NY
CA
MA
TX
IL
CO
PA
OH
NJ
MD
GA
IN
NC
MI
WI
State

Institutions with $5,000,000 or More in ACTIVE FY 2006 Awards Allocated to NS&E



Ex.: NNI Networks and User Facilities

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

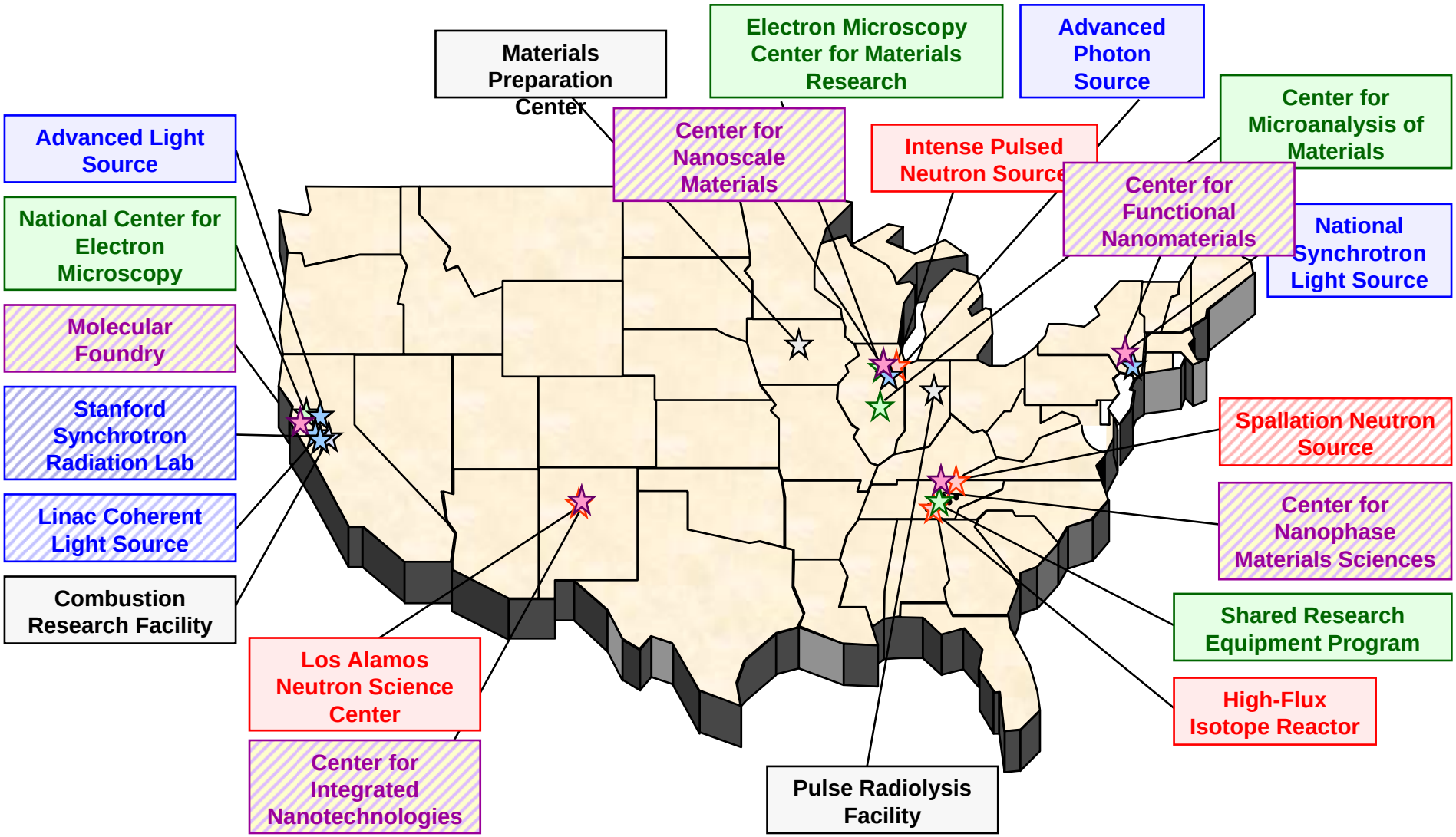
Eight Nanoscale Science and Engineering networks with national outreach

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

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

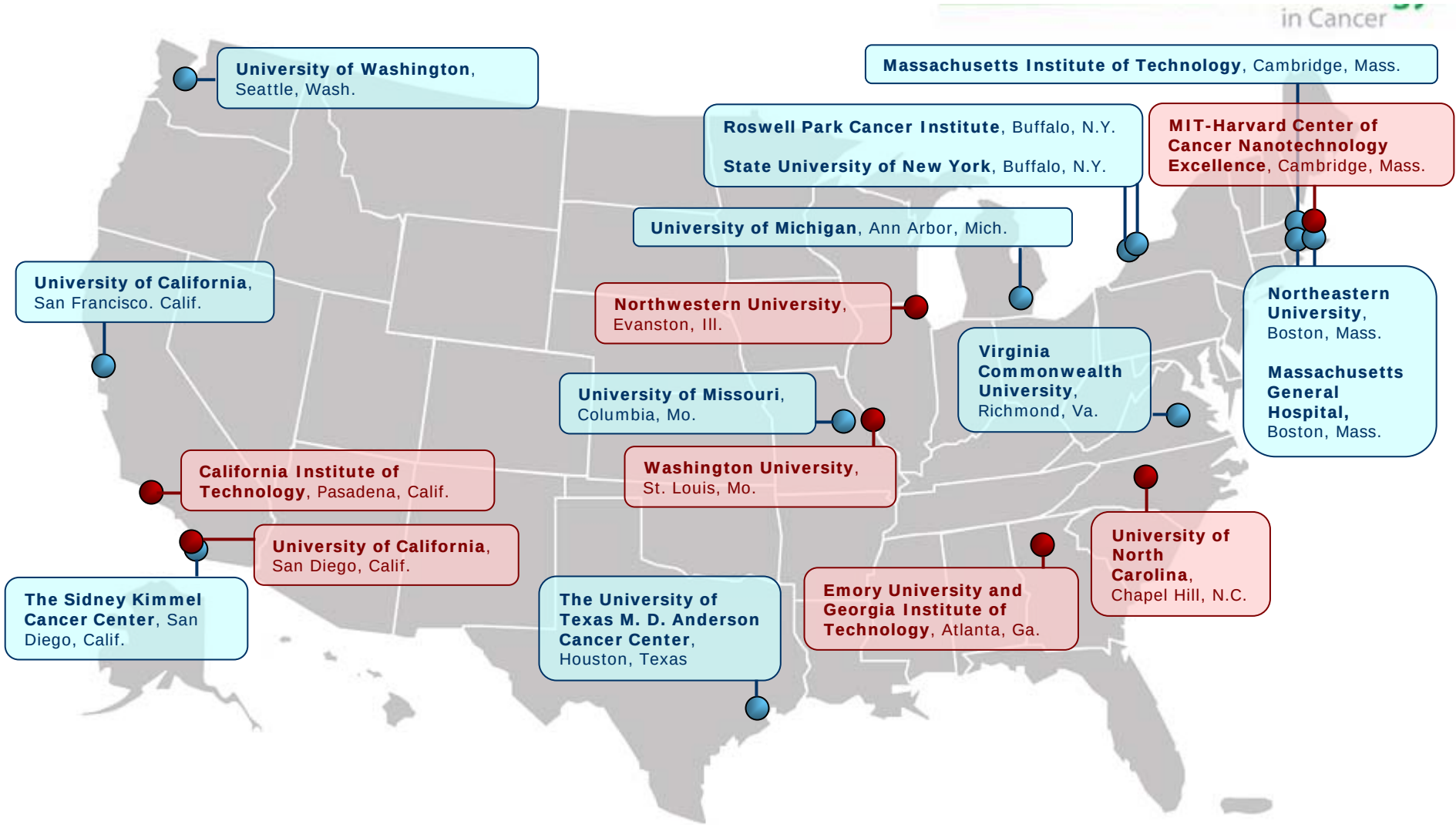
NSEC Network (2001-) *17 research & education centers*
MRSEC Network (2001-) *6 new research & education centers since 2000*

Department of Energy Scientific User Facilities



M.C. Roco, 11/01/2007

National Cancer Institute (NIH) Alliance Program Awards



Centers of Cancer Nanotechnology Excellence (8)

Cancer Nanotechnology Platform Partnerships (12)

M.C. Roco, 11/01/2007

Notes on nanotechnology governance

Investments

- Government R&D investment increase > 30% per year (2000-2008)
- U.S. industry R&D investment (1.7 billion/year in 2007) > government R&D
- Increase > 25% per year new products incorporating nanotech since 2000

Significant developments in U.S. agencies since 2005

- NIH, USDA - biosystems, biomedical
- NIST – expanded role in nano metrology, standards, manufacturing
- Increased role for partnerships with industry sectors, CBAN (NRI, others)
- NSF role in fundamental research – moving to complex nanosystems

Evolving role of government (governance)

Instead of top-down control: facilitate new investments, innovation, informatics, etc.; Increased role of science policy and global view

4 + 1 generations of nanotechnology products (2000-2020; after 2020)

NT in 2007, 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
- 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

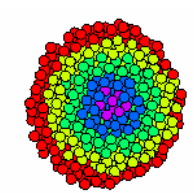
Defining Nanomanufacturing

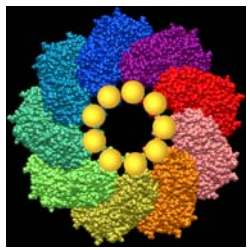
- Fragmentation
- Patterning
- Bulk restructuring
- Lithography, ..

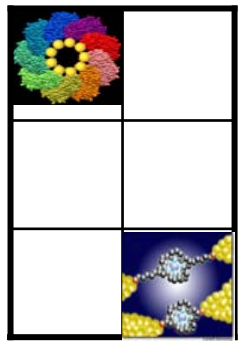
- Interfaces, field & boundary control
- Positioning parts
- Integration, ..

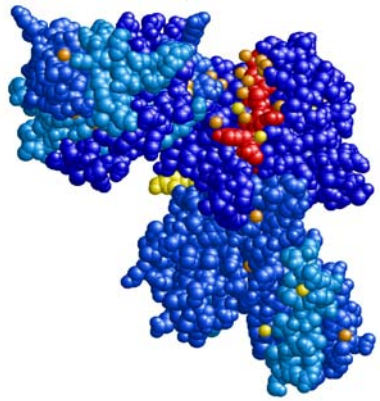
- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration..









Assembling

- Directed selfassembling
- Templating
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

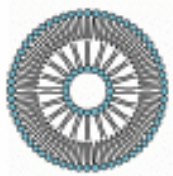
- Eng. molecules as devices,
- Quantum control,
- Synthetic biology..

PASSIVE NANOSTRUCTURES - ACTIVE NANOSTR. - SYSTEMS OF NANOSYSTEMS - MOLECULAR NANOSYSTEMS

NANOPRODUCTS

Portfolio of Nanoparticles (2007)

NANOTECHNOLOGY CHARACTERIZATION LABORATORY



Liposome

- M. Kester (Penn State)
- Ester Chang (Georgetown)
- R. Blumenthal (NCI)
- J. Nagy (Nanomed)
- J. Connor (Penn State)

Gold nanoshell

- NanoSpectra (Rice)

Colloidal gold

- CytImmune Sciences
- TedPella Inc.
- A. Wei (Purdue)
- K. Katti (U. Missouri)
- J. Barchi (NCI)

Fullerene

- Arrowhead Research / Tego Bioscience

Dendrimer

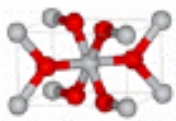
- Dendritic Nanotechnologies (DNT)
- Avidimer Therapeutics
- M. Brechbiel (NCI)
- E. Simanek (Texas A&M)

Quantum Dot

- S. Weiss (UCLA)
- Evident Technologies
- J. Barchi (NCI)

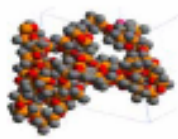
Nanoemulsion

- M. Amiji (Northeastern)
- Nanoscan



TiO_2

- US FDA



Polymers

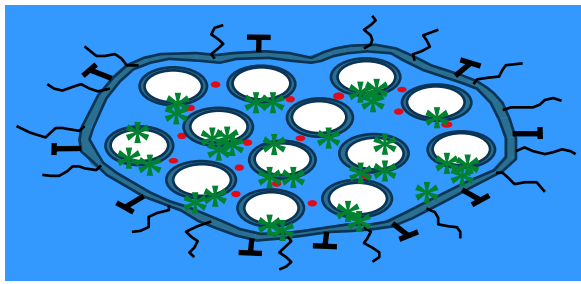
- J. Ljubimova (Mt. Sinai)
- Alnis
- M. Amiji (Northeastern)
- N. Tarasova (NCI)

Example new topics after 2005:

Synthesis and control of nanomachines

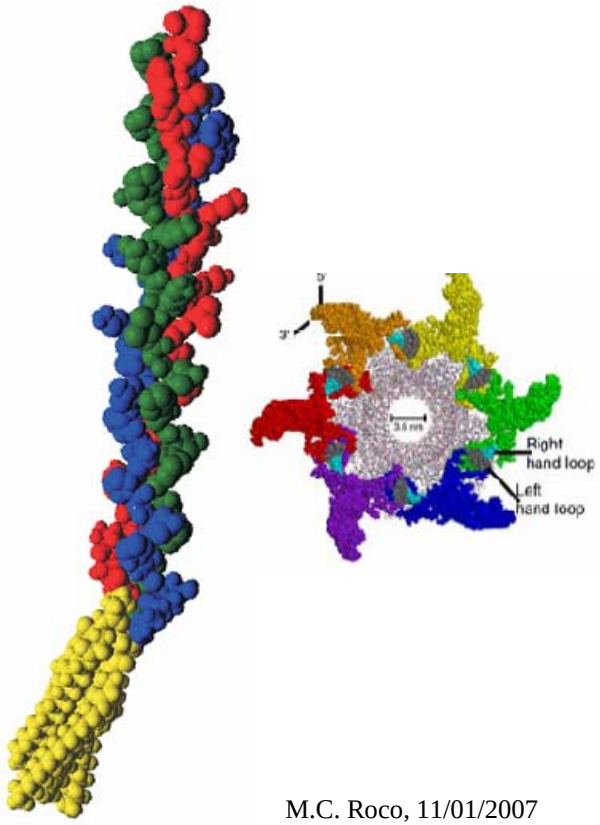
(www.nseresearch.org - 400 NSF projects)

- **Self-assembly processing** of nanoscale bio-materials and devices for micromachines components (UCSB)



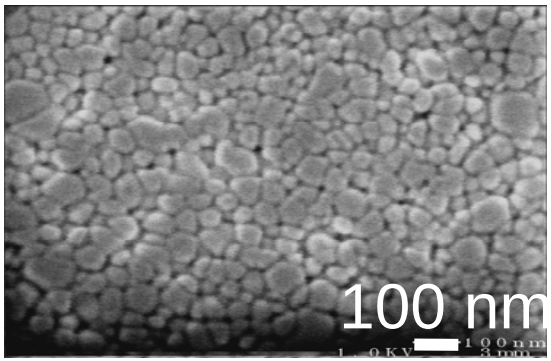
- Chemistry to synthesize components of **nano machines to work on surfaces** and b activated by external electromagnetic fields (UCB)

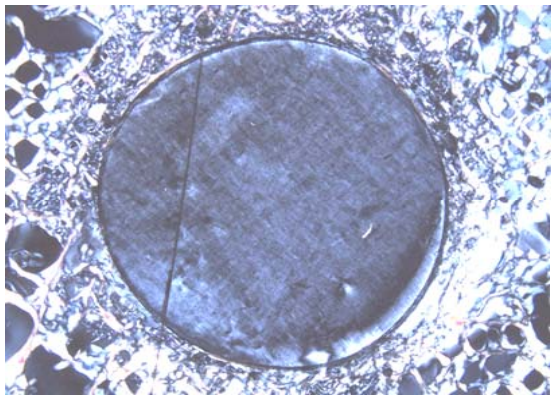
- **Light driven molecular motors** (U. Nevada)



Example 1st generation

Angstrom Medica's nanostructured calcium phosphate technology for bone-based orthopedic implants





NanOss™ Calcium Phosphate Nanocrystals

$Ca_{10}(PO_4)_6(OH)_2$ and $Ca_3(PO_4)_2$

Composition and morphology of bone
Enhanced bioactivity and strength

Bone bonding in 2 weeks and osteointegration in 4 weeks because the nanostructure closely match that found in human bone

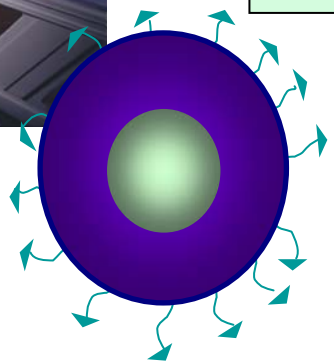
Angstrom Medica received SBIR in 2003 (NSF-0232733) and 2004 (NSF-0349884)

The product received "marketing clearance" from FDA in 2005

Example 1st generation – platform for passive nanostructures

Aircraft Engines

Healthcare



Nanotechnology Platform

NanoTubes and NanoRods

NanoParticles

NanoCeramics

NanoStructured Metal Systems

Hybrid Materials

Water

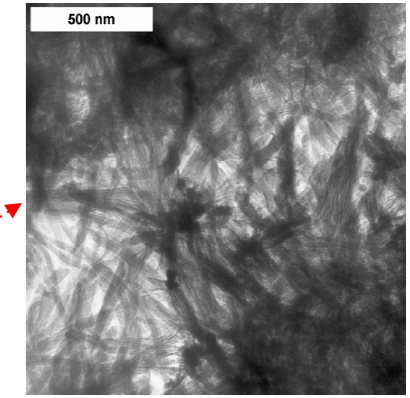
Energy

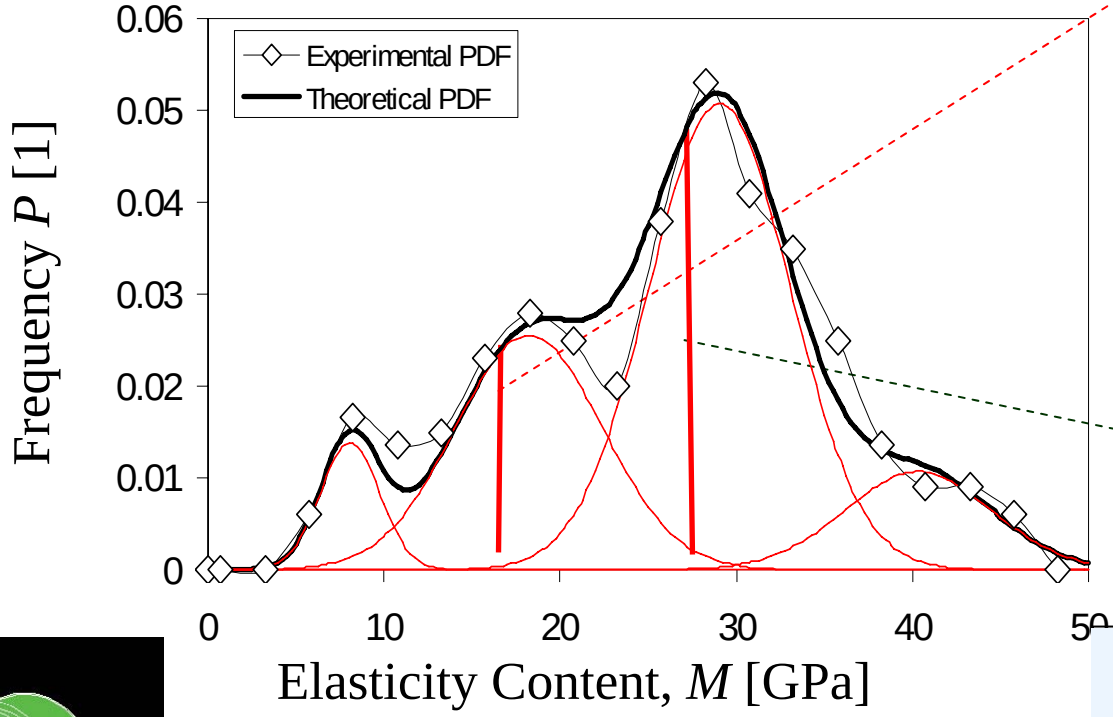
Nanotechnology at General Electric

Example 1st generation

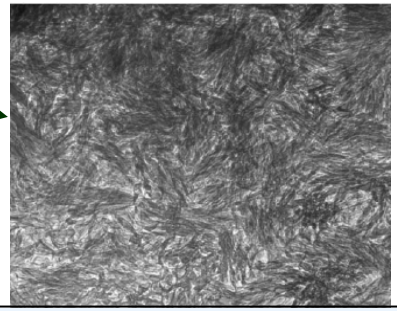
Nanostructured High Performance Concrete

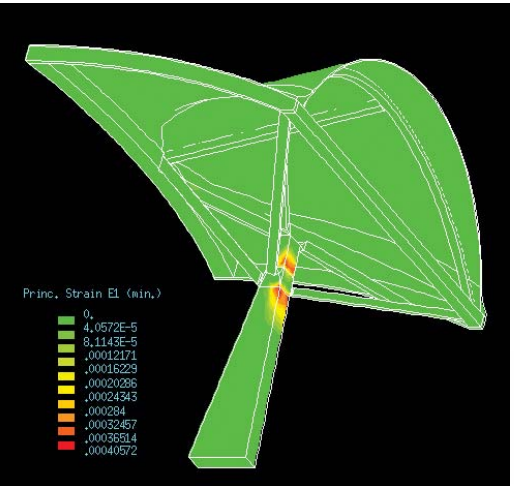
Low Density ~30%



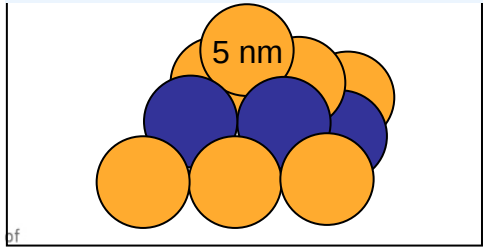


High Density ~70%





Spherical Limit Packing
Density = 0.74
No. of contact = 12/ sphere



Constantinides and Ulm, 2004

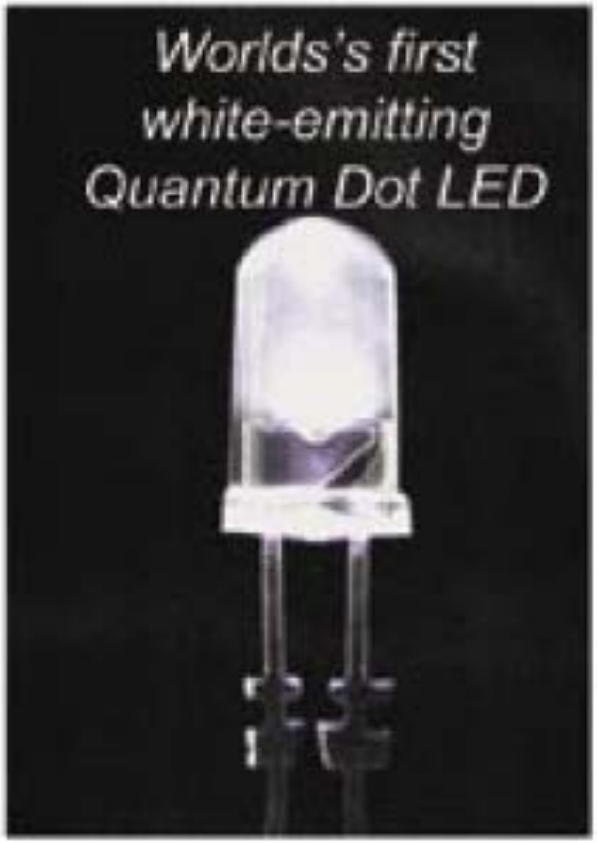
LAFARGE

MIT

Department of
Civil & Environmental Engineering
Massachusetts Institute of Technology

Example 1st generation

Laser Emitting Diodes Lighting



World's first white emitting LED using only QDs as phosphors. The LED chip is a 410 nm InGaN-based chip from Cree Research. [J. Simmons, Sandia National Laboratories]

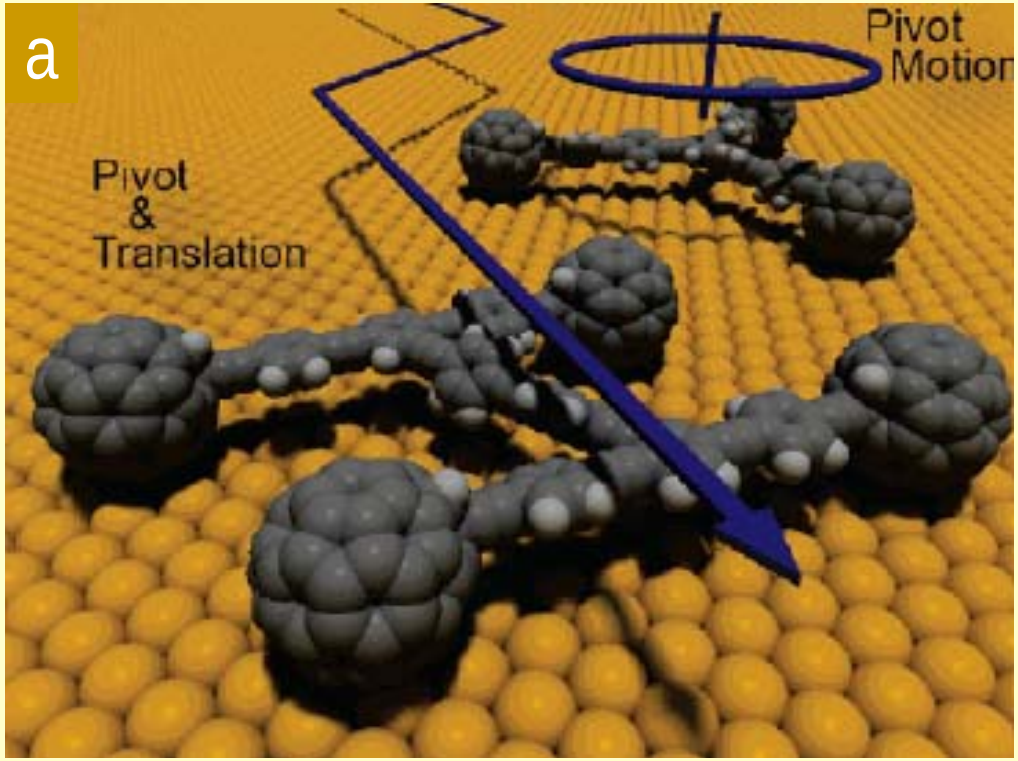
Quantum Dots Nanoparticles (Sandia National Lab) to replace layered LED. Basis for Next Generation Lighting Source Solid State Semiconductor Replacing Light Bulb

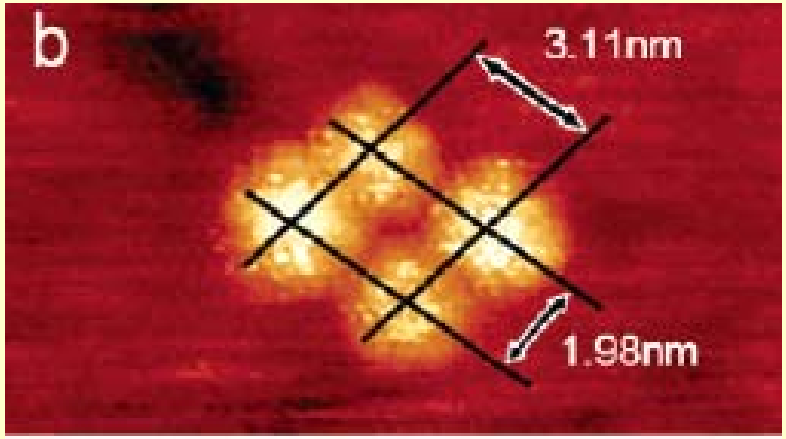
Ability to emit light representing the entire rainbow of colors from the same elemental material based solely on the size of the particles of that material being excited.

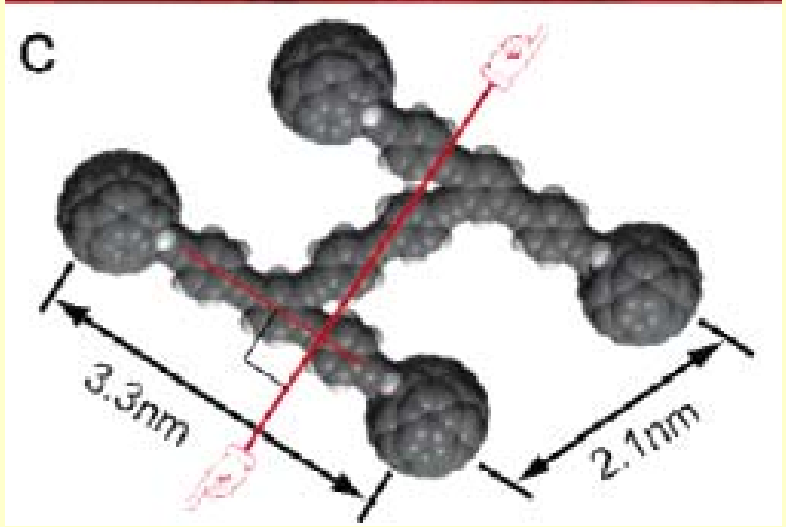
American Elements

Example 2nd generation - active nanostructure:

Nano-cars driven by light-activated or thermally driven nanomotors (rolling molecules). J. Tour group, Rice University, 2005-2006.



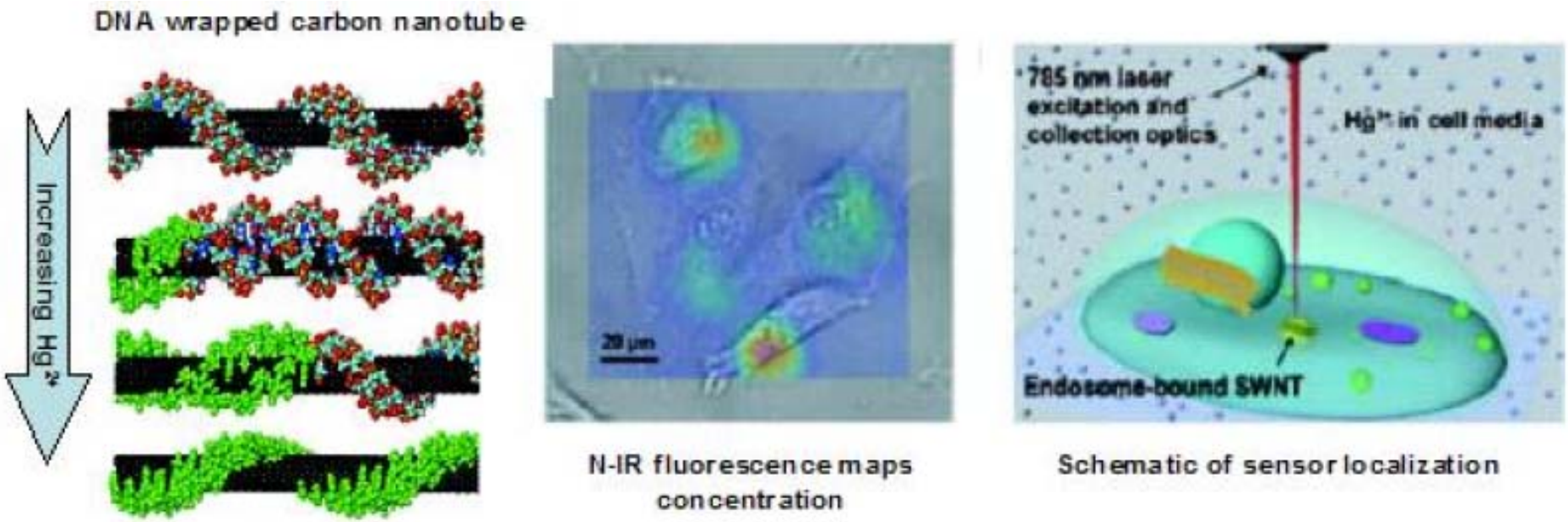




Nano Letters, Vol. 5, 2005; JACS, Vol. 128, 2006

Ex: Second generation of nanoproducts

Fluorexcent Nanotube Sensors for Measuring Toxic Chemicals Inside of Living Cells



N-IR fluorescence maps concentration

Schematic of sensor localization

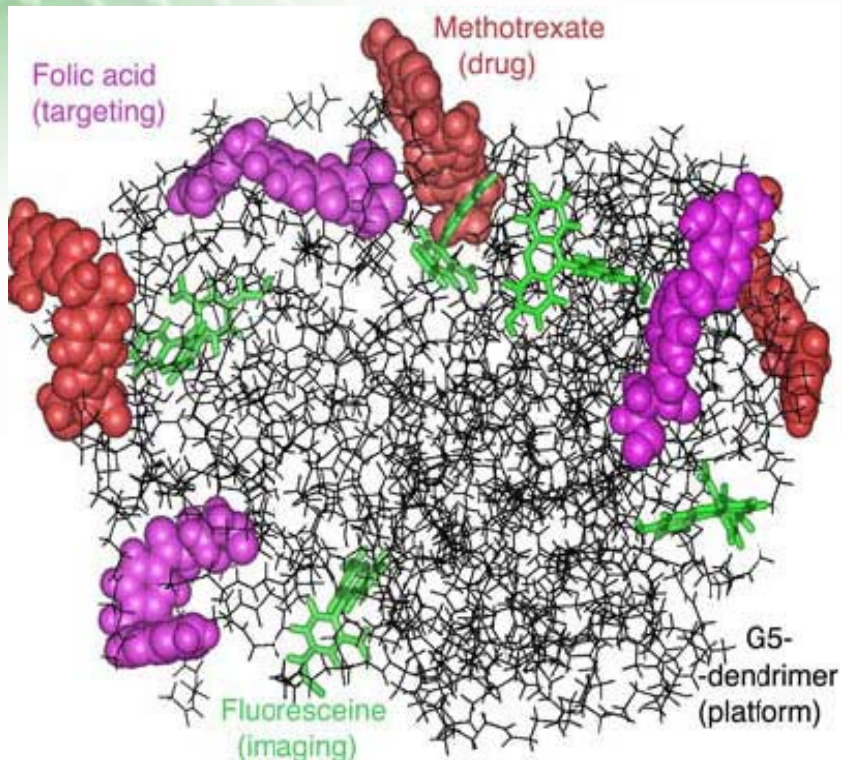
A biomolecular transformation of DNA on a carbon nanotube detects toxic mercury via infrared fluorescence from inside of living mammalian cells

M. Strano, UIUC

Example 2nd generation - active nanostructure

Multi-functional Nano-platforms: 'Find – Detect – Treat'

NCI Alliance for Nanotechnology in Cancer

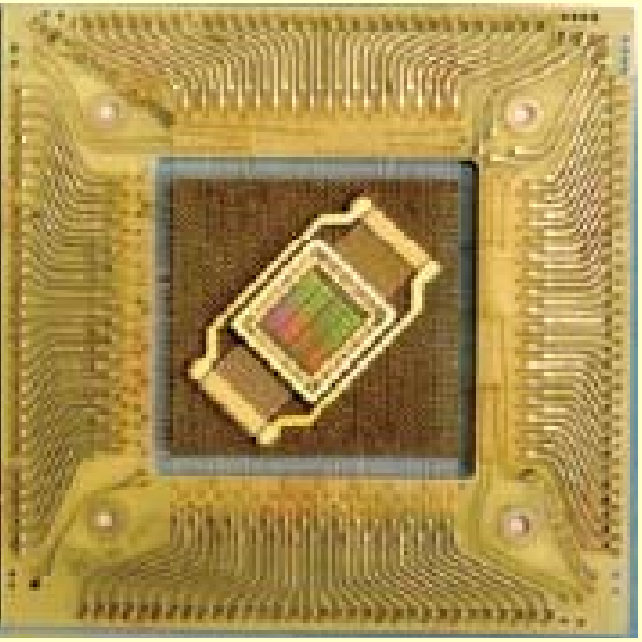


Kukowska-Latallo, Baker et al., *Cancer Research*, 65, 5317, 2005

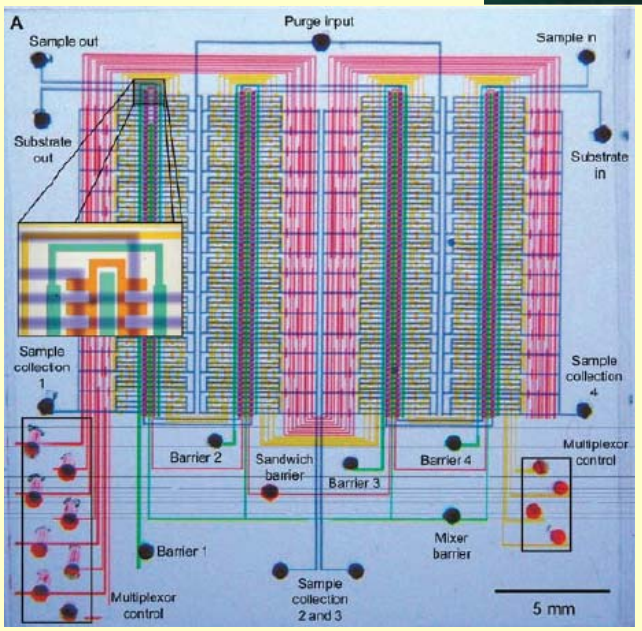
Systems Nanotechnology

- Create controllable systems built from nanoscale components. Addresses unifying principles that enable modeling, prediction, and control of emergent behavior in complex nanosystems
- Wide application: new materials, petascale computing, organ regeneration, biological sensors for health monitoring, high-specificity sensors
- Enable other goals for: nanomanufacturing, as well as for developing high-end computing capability; overcoming technological barriers to efficient and economic use of energy; and improvement of sensor detection capabilities

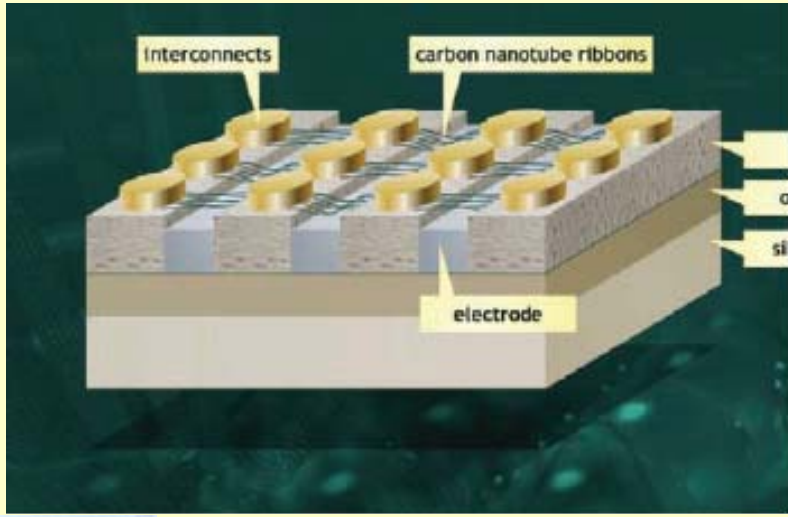
Other examples combining 2nd and 3rd generations



GMR/MRAM memory - 4 Mbits with 10 ns access time (courtesy of Motorola)



Microfluidics systems with nanocomponents (courtesy Thorsen et al.)



Platform for nanoelectronics using carbon nanotubes (schematic of the NRAM design)

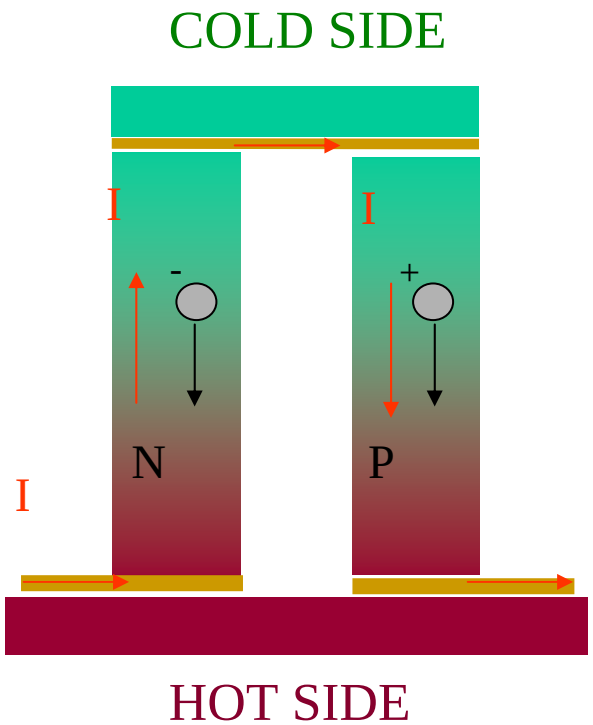
(courtesy of Nantero)

Solar Energy Cells: 42.8% efficiency

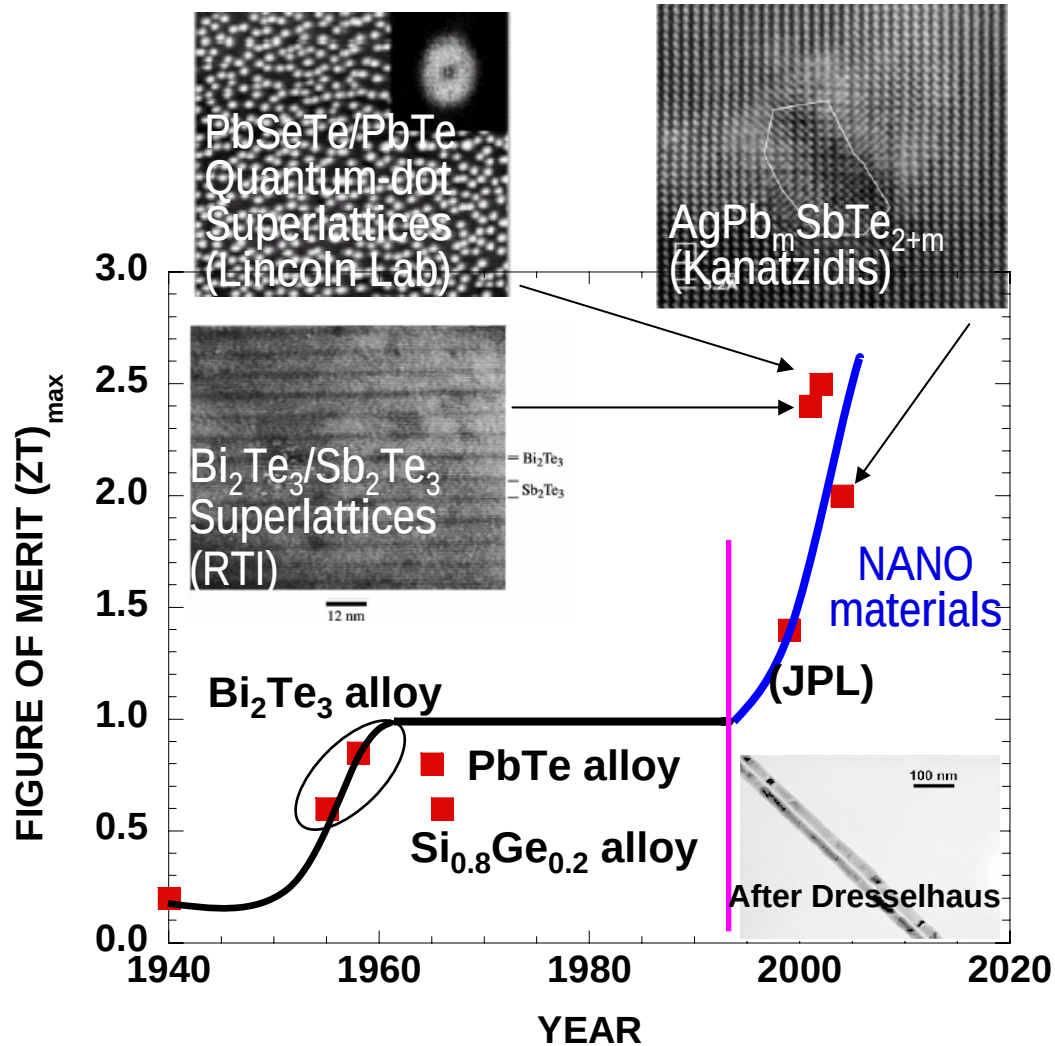
A consortium of researchers led by the University of Delaware has developed a high-performance crystalline silicon solar cell platform that has achieved a record 42.8 percent solar efficiency at standard terrestrial conditions.

The researchers are now working to achieve 50 percent efficiency (in production by 2010). "The low profile and lack of moving parts translates into portability, which means these devices easily could go on a laptop computer" http://www.azonano.com/news.asp?newsID=4546

Direct Thermo-electric Energy Conversion



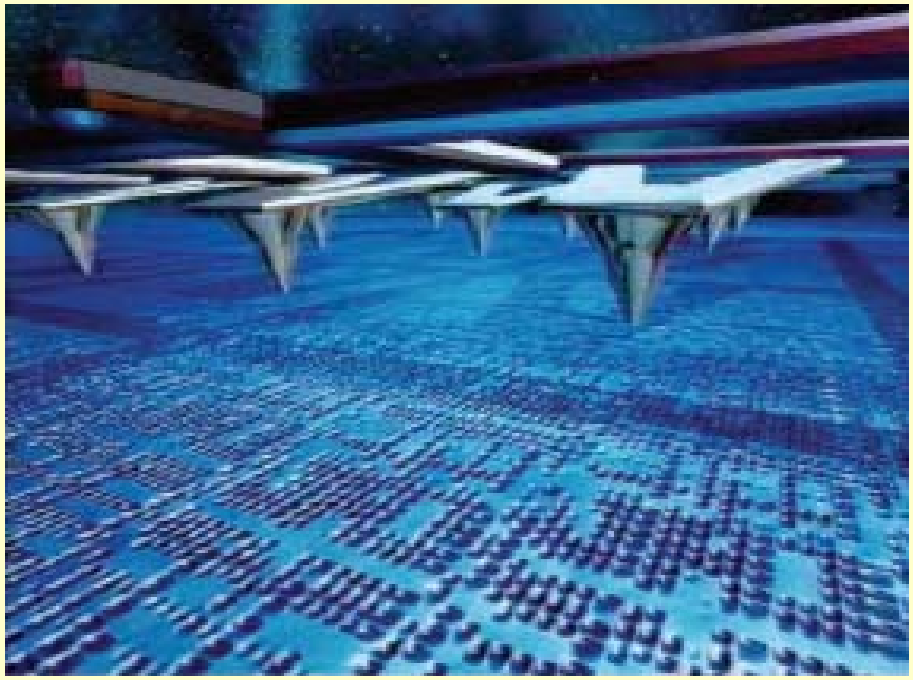
Electron flux vs. phonon flux



Using nanostructures promises figures of merit up to ZT =10 (MIT)

Example 3rd generation - nanosystems

Probe Array Nanofabrication (IBM / Millipede)



Millipede nanopatterning (courtesy of IBM Zurich Research Laboratory)

- Large arrays of cantilever probes, thermomechanically inducing quantum dot indentations in thin polymer films have been developed and used for ultrahigh density data storage (1 trillion bits per square inch in pilot testing, equivalent to 25 DVDs on a postage stamp area, and 20 times higher than magnetic storage)
- Each tip produces indentations 10 nm in diameter
- For storage and niche applications

Portable virtual reality using nanosystems for work, research and learning

- Learning tool
- Working environment
- Virtual laboratory experiments
- Observational Social and Economic Science
- Computer and information tool
- Advances in cognitive sciences and philosophy

Expected after 2010

M.C. Roco and W.S. Bainbridge, Converging technologies for improving human performance, Springer, 203; W.S. Bainbridge, Science 27 July 2007: vol. 317. no. 5837, pp. 472 – 476

Example 3rd & 4th generation – nanosystems and converging technologies

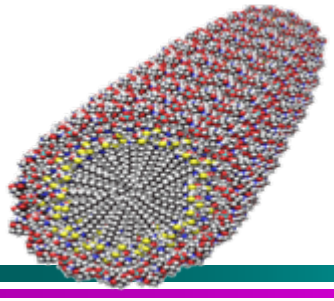
The core of Nanomedicine Initiative at NIH

The overarching goal is to create the conceptual and literal interface between biology and medical devices at the scale of biomolecular processes.

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" macromolecules, molecular complexes, organelles, cells, and tissues; and
- Use this knowledge of properties and design principles to develop new technologies, nanoengineered 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

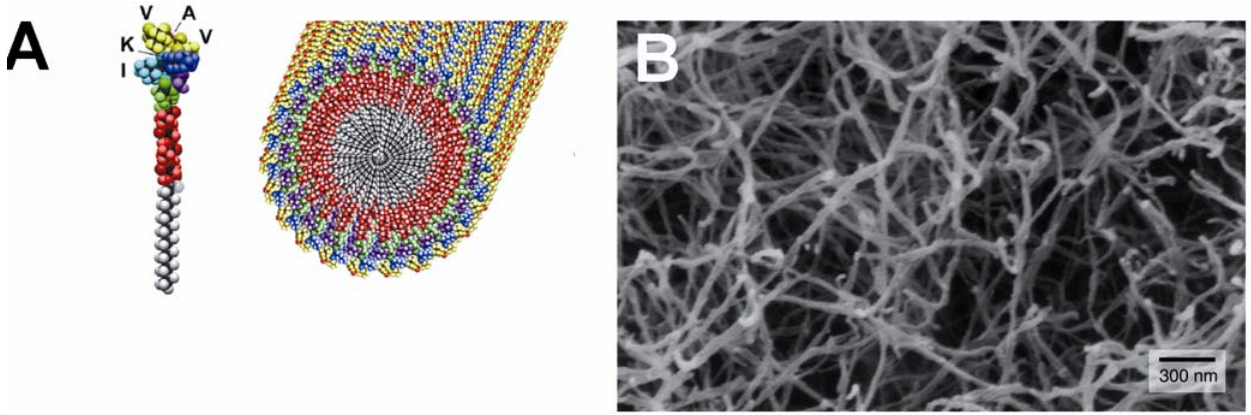


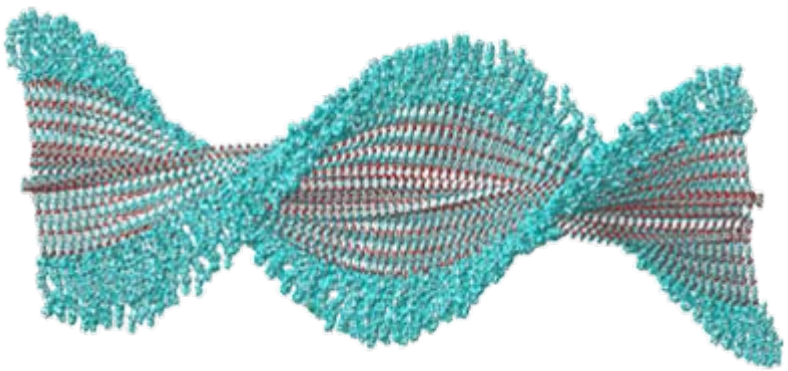
Example 4th generation

Designing molecules for hierarchical selfassembling

EX: SAMUEL I. STUPP, *Northwestern University*

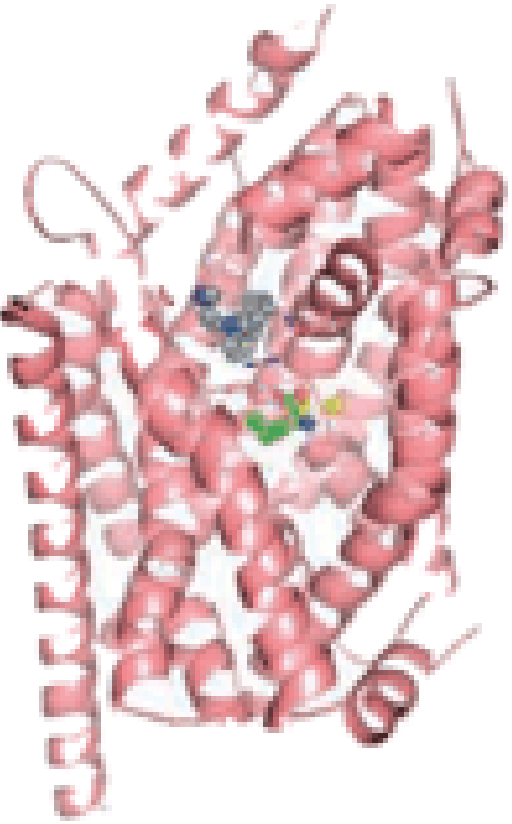
Application: biomaterials for human repair (nerves, tissues, wounds), reactive filters, others





Example 4th generation

The Molecular Machinery of Mood Swings



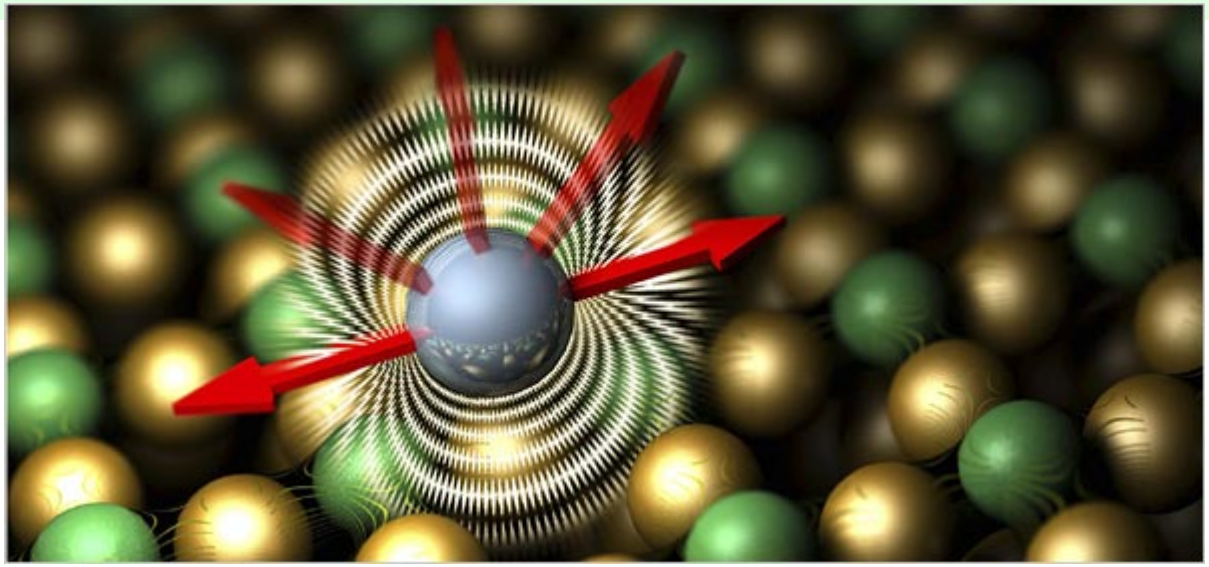
Monoamine neurotransmitters serve as signaling molecules in mood and motivation: they are released from the presynaptic nerve terminal and arrive into the cytoplasm via dedicated sodium-dependent plasma membrane transporters.

The crystal structure of a bacterial homolog (LeuT) of the mammalian monoamine transporters can be used as an equivalent antidepressant. <u>On the basis of homology modeling of the human transporters, one can obtain artificial replacements for mood change</u>.

Science 7 September 2007: vol. 317. no. 5843, pp. 1390 – 1393
Zhou et al., New York University School of Medicine

Example 4th generation

Individual atom information storage



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

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

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

Examples of other 3rd and 4th generation

- Nanoscale robotics on surfaces and 3-D domains
- Artificial organs using nanoscale control of growth
- Subcellullar intervention for treatment of cancer
- Bioassembly (ex. use of viruses, A. Belcher) of engineered nanomaterials and systems
- Evolutionary systems for biochemical processing
- Direct heat and solar energy conversion to electric energy
- Sensor systems with reactive mechanisms
- Simulation based experiments and design of engineered nanosystems from basic principles
- New molecules designed as devices or for assembling
- Hierarchical selfassembling for a micro or macro products
- Genetic modification controlled at the nanoscale

After 5 years of NNI:
New R&D potential targets for 2015 (ex., 1)

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

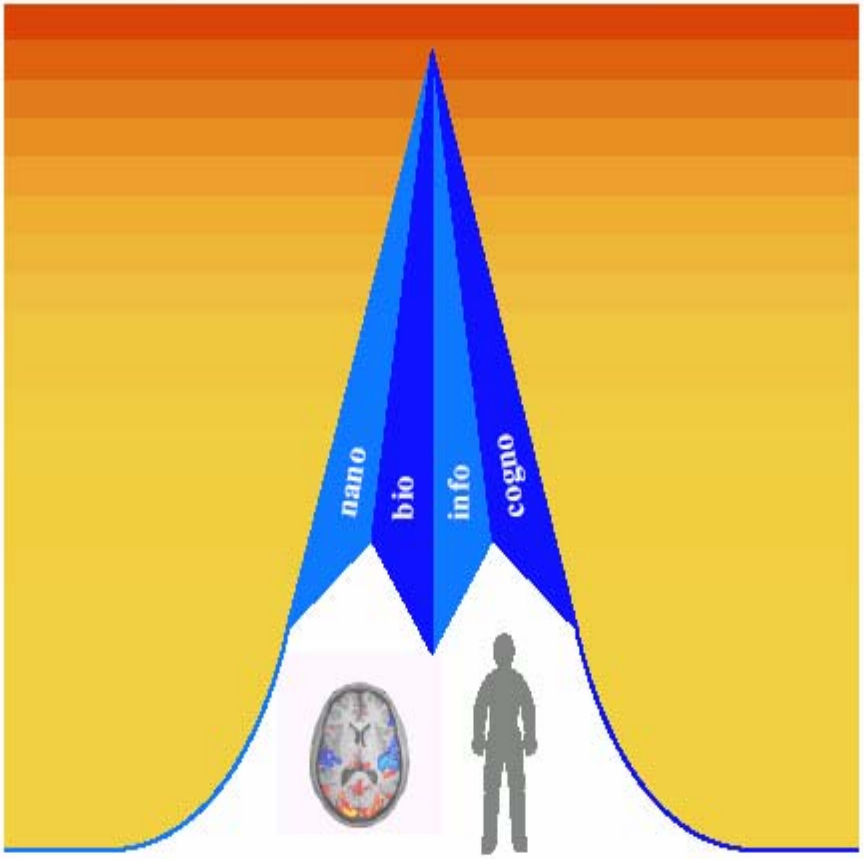
Nano-shop: 3d building at the nanoscale

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

Nano-informatics: libraries for integrating databases

After 2020

- <u>NT convergence with bio, info and cogno</u>, and <u>bifurcation of nanosystem paradigms</u>
  - evolutionary
  - engineered molecular design and guided hierarchical selfassembling
  - robotics based
  - biomimetics
  - ? new carrier of information instead of electron charge
  - ? “productive” nanostructures
  - ? extending human potential
  - ? collective cognitive capabilities

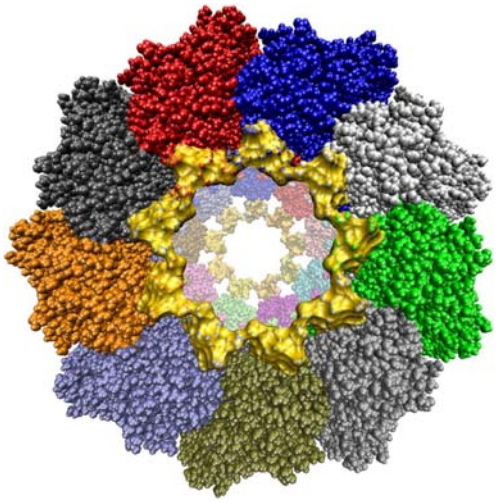


CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

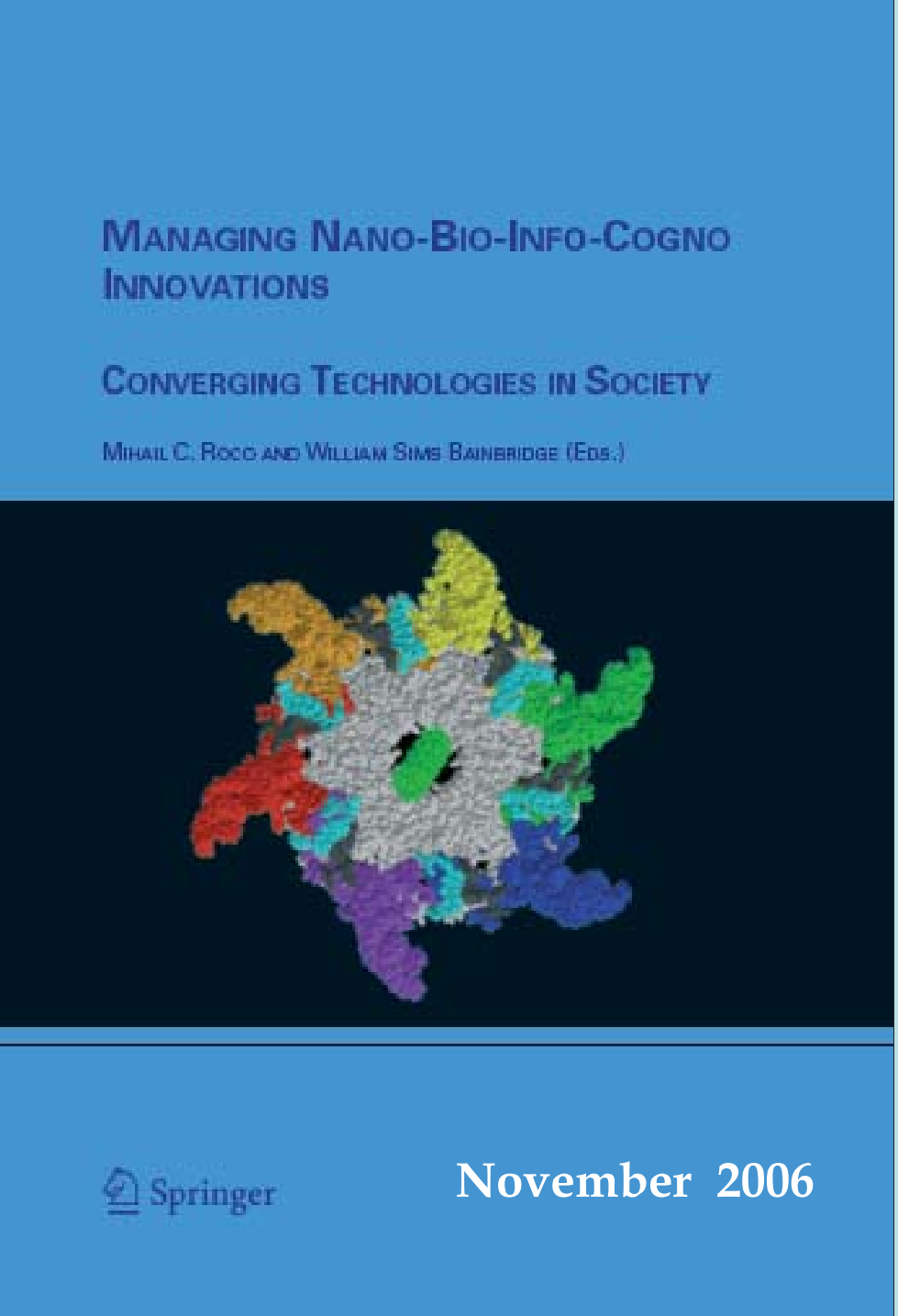
June 2002

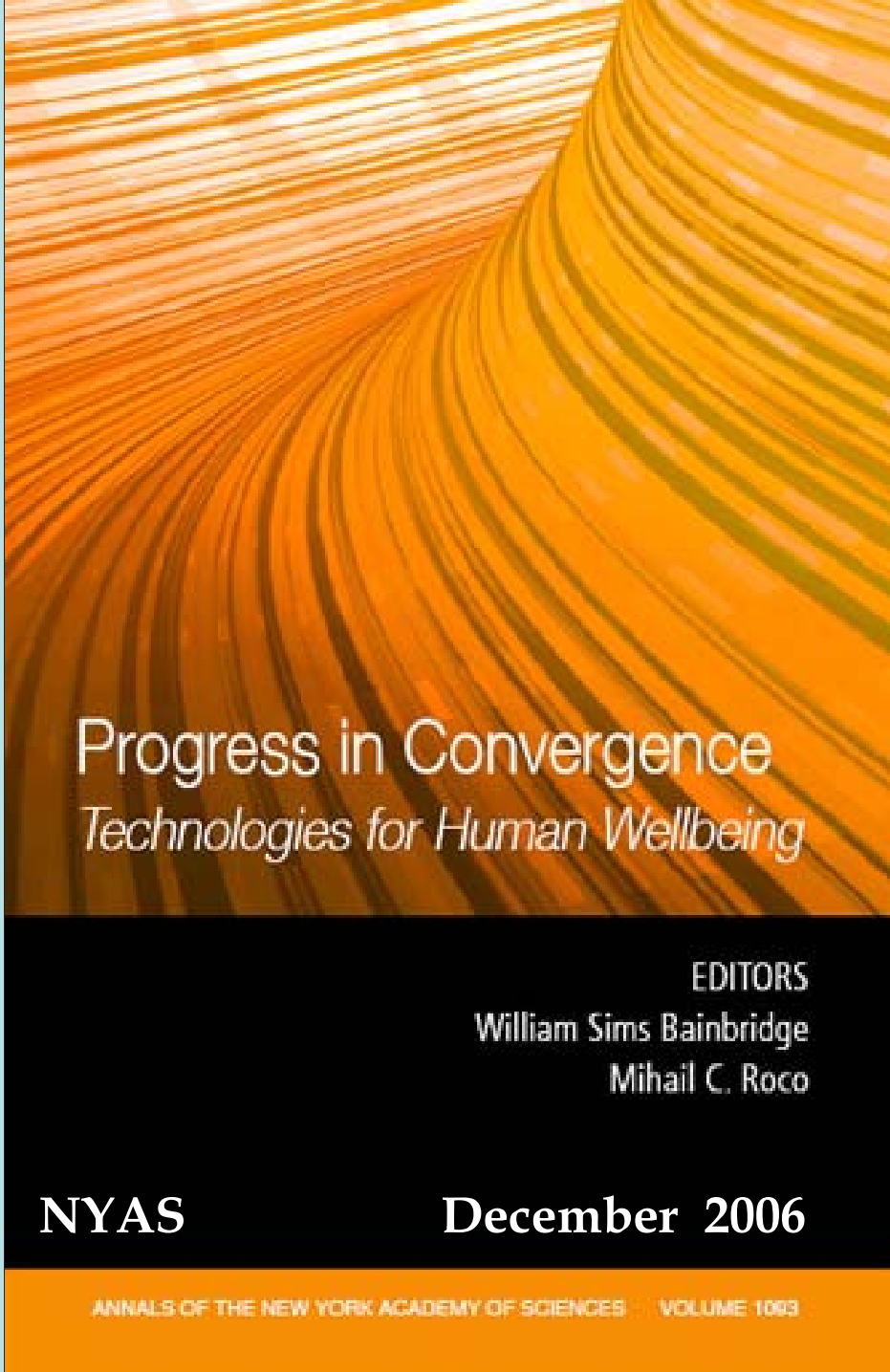
Workshop, Dec. 2001
www.nsf.gov/nano
Kluwer Acad. Publ, 2003

Coevolution of Human Potential and Converging New Technologies



In: Annals of the New York, Academy of Sciences, Vol. 1013, 2004
(M.C. Roco and C. Montemagno)


Managing Nano-Bio-Info-Cogno Innovations
Converging Technologies in Society
Mihail C. Roco and William Sims Bainbridge (Eds.)
Springer
November 2006


Progress in Convergence
Technologies for Human Wellbeing
EDITORS
William Sims Bainbridge
Mihail C. Roco
NYAS
December 2006
ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
VOLUME 1093

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

What is needed for development of nanotechnology products in the U.S.?

- Needs for R&D and production of tools at the nanoscale (experimental, simulation)
- Nanomanufacturing with special focus on automation, use of special qualification and advanced infrastructure, integration of emerging technologies
- Systems nanotechnology – look to nanoscale interactions, collective behavior and complex systems, for revolutionary products and biomedical applications
- Nanoinformatics
- Stimulate innovation and partnerships as part of nanotechnology governance
- Technological education in nanotechnology

Five ways nanotechnology is changing academia

1. *Reverse the pyramid of learning:* learning first (earlier) unifying concepts of matter/ biology/ information systems

2. *More basic science and engineering:* increased opportunities for discovery and innovation

3. *Brings together disciplines and departments and colleges*: Convergence - NT, biomedical, electronics and cognition

4. *New organization models in university:* nanoscale interdisciplinary laboratories (this lab), "horizontal" and "universal" information system, closer with industry (NRI)

5. *Global governance*: collaboration and competition, multi-stakeholders, long-term planning, responsible development

Several Background References for Societal Implications of Nanotechnology

- "Societal Implications of Nanoscience and Nanotechnology", Kluwer, now 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)
- "Nanotechnology–Unifying and transforming tools", AIChE J. (Roco, 2004)
- "Environmentally Responsible Development of Nanotechnology", Environmental Science and Technology (Roco, 2005)
- "Nanotechnology's Future", Scientific American, August 2006, (Roco, 2006)
- "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)

Reserves

Notes on responsible nanotechnology: What is needed more now?

- Monitoring of incidental nanoparticles dispersed in air, water, soil and biosystems
- Predictive modeling and simulation of interactions of nanomaterials with environment and human body
- Research and focus on common resources: water, food and energy
- First generation of nanoproducts: need for predictive methods to make connections between structure and toxicity
- Second generation of nanoproducts: anticipatory approaches are needed
- International governance methods