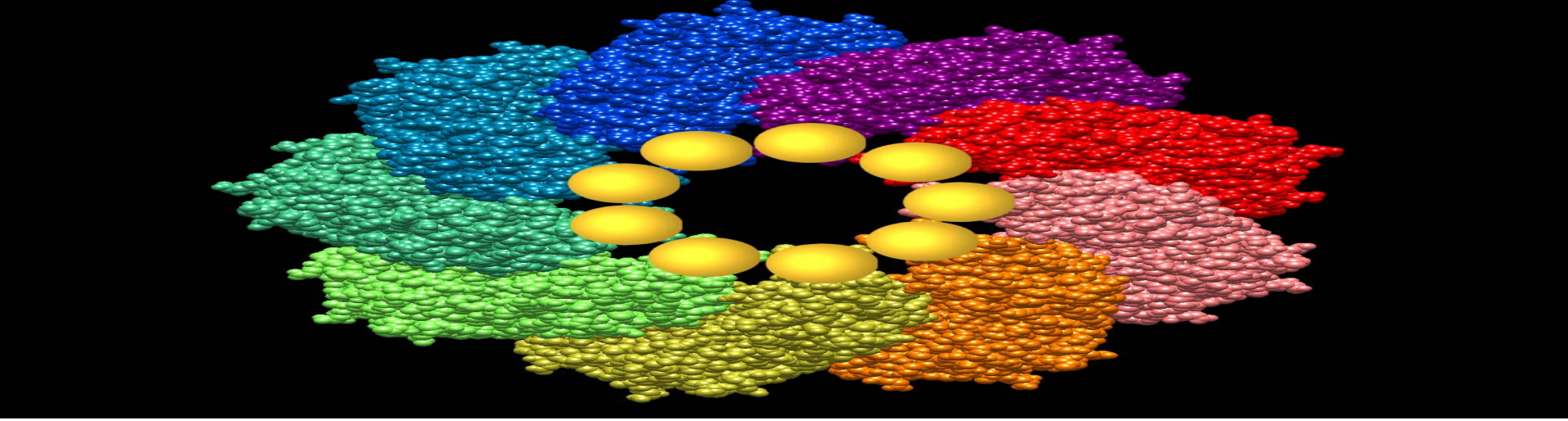
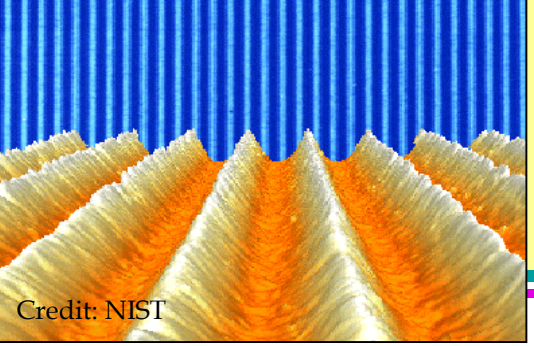


New Frontiers for Nanotechnology

M.C. Roco
National Science Foundation and
National Nanotechnology Initiative

- **Nanotechnology motivation and timeline (1990-2020)**
- **Outcomes at five years of NNI**
- **New frontiers and long-term planning**

University of Virginia, 2006



Nanotechnology

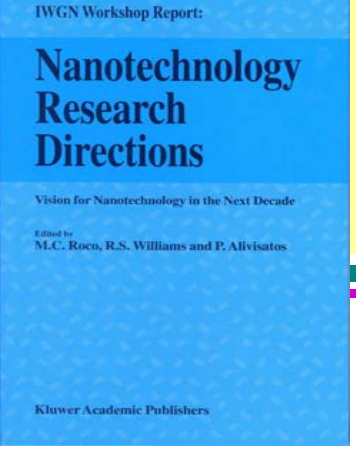
Definition on www.nano.gov/omb (2000)

IWGN Report: Nanostructure S&T Kluwer, 1999

- **Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 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 contributions that were not possible before.**

  - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain
  - the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions
  - integration along length scales, and fields of application



NNI - Why nanotechnology is important?

A. Reaching at the atomic/molecular foundation of matter at the natural threshold between discontinuous and continuous behavior, where first level organization of atoms/molecules defines fundamental behavior

B. It has broad societal implications

Improved knowledge, technology, quality of life

C. Higher purpose goals than development of NT

- More basic science and education
- Higher efficiency processes and novel products
- Molecular medicine
- Extend the limits of sustainable development

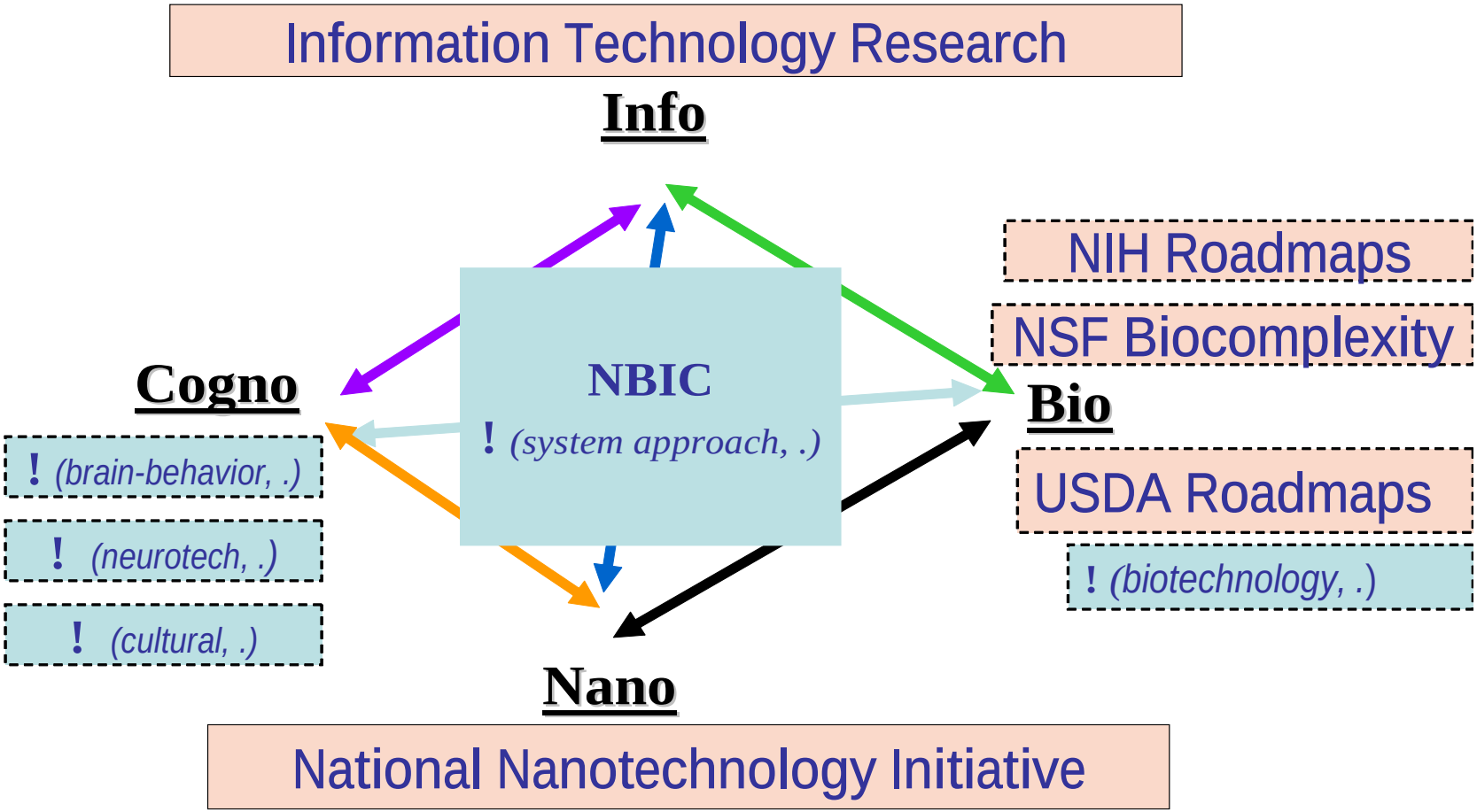
D. At the core of converging new technologies

(nano-bio-info-cogno)

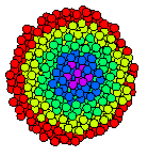
The Context: **CONVERGING NEW TECHNOLOGIES** *NANO – BIO – INFO – COGNO*

The "Push" | *The "Pull"*

Existing | *Needs*



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



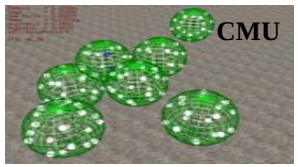
1st: Passive nanostructures (1st generation products)

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

~ 2000

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

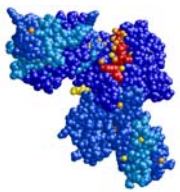
~ 2005



3rd: Systems of nanosystems

Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

~ 2010



4th: Molecular nanosystems

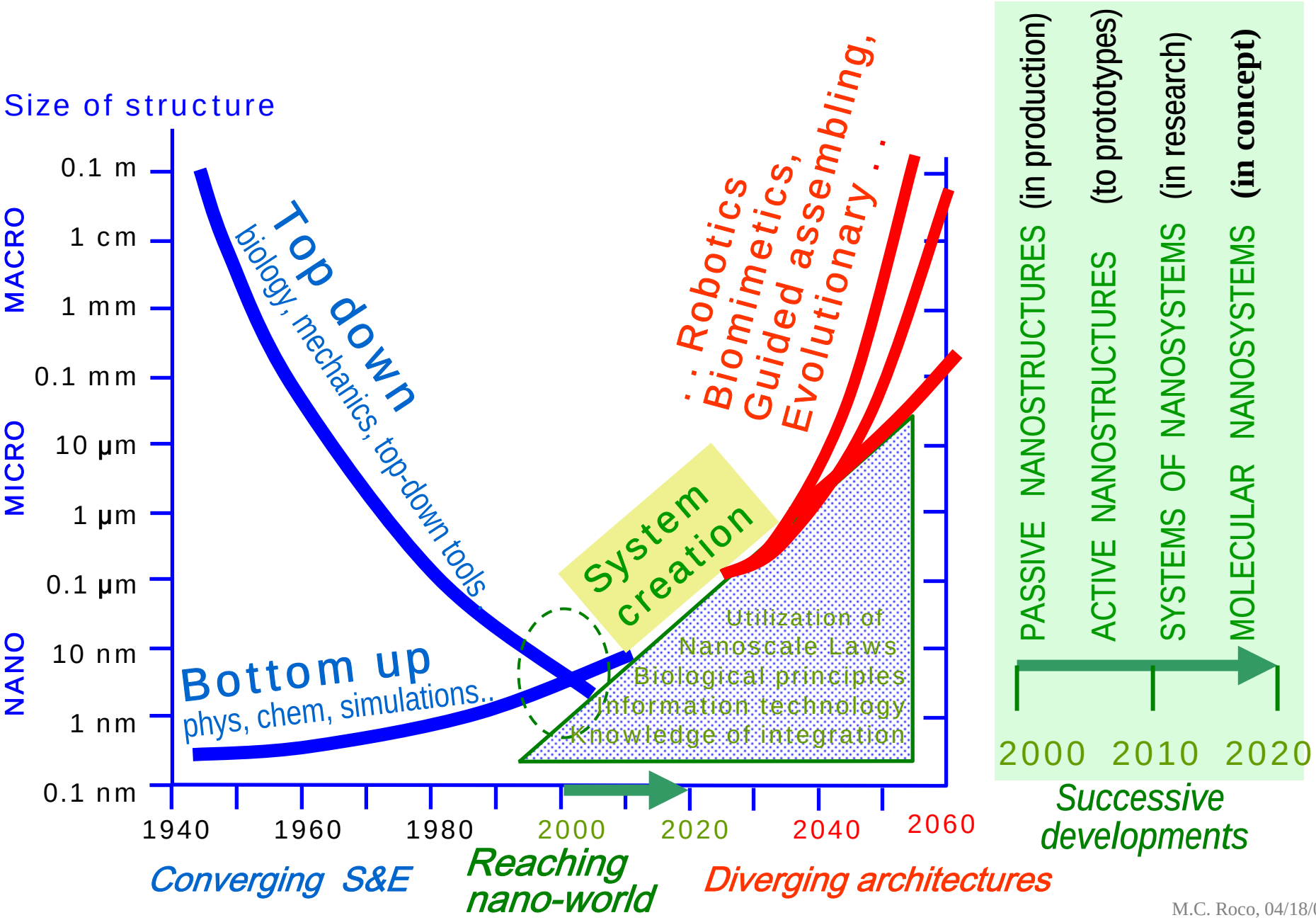
Ex: molecular devices 'by design', atomic design, emerging functions

~ 2015-2020

New R&D challenges

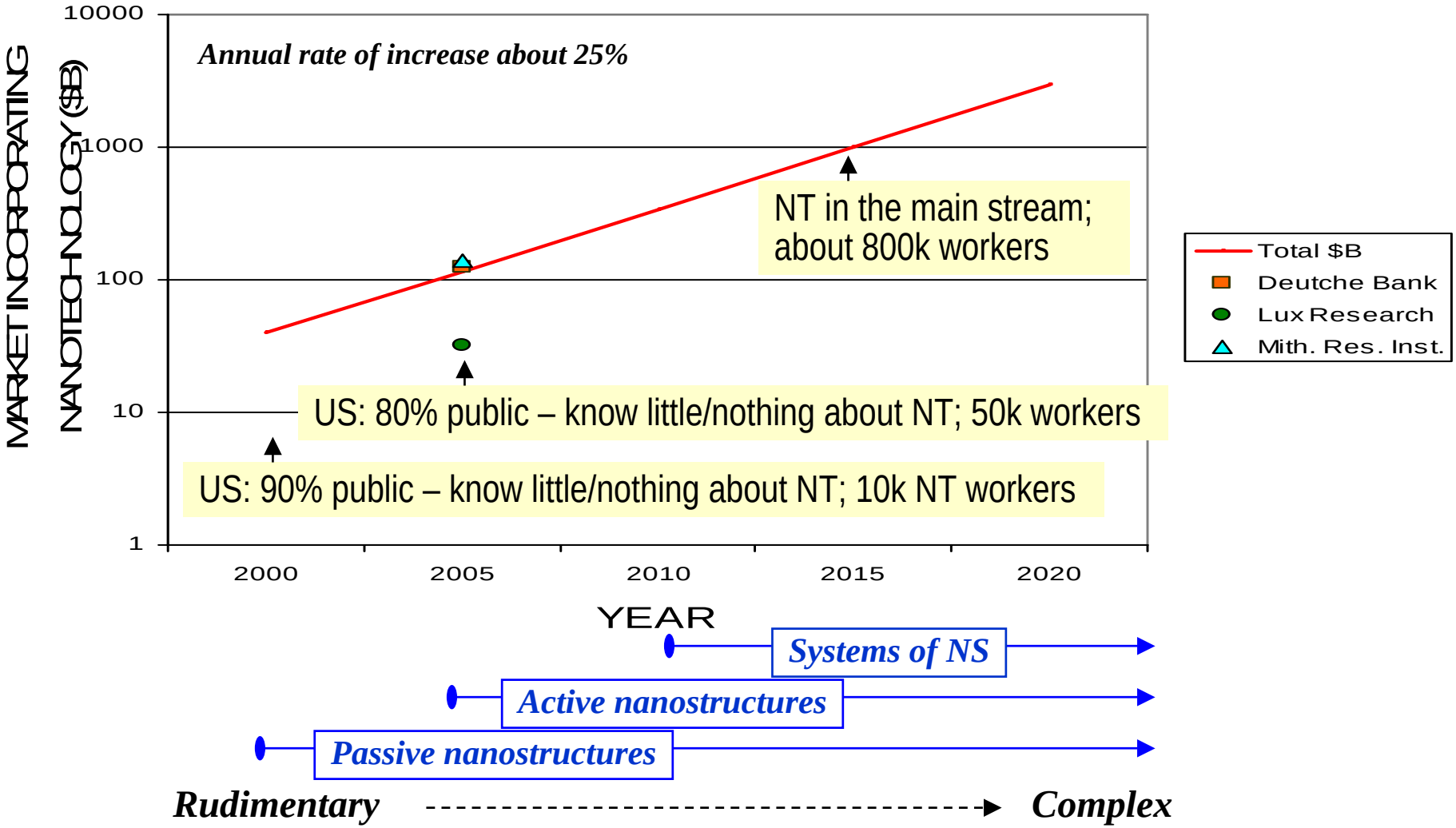
AIChE Journal, 2004, Vol. 50 (5), M. Roco

Reaching nano-world and system creation



M.C. Roco, 04/18/06

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



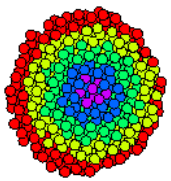
Defining Nanomanufacturing

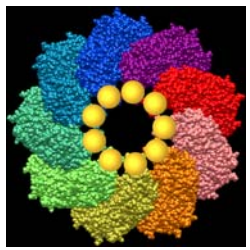
- Fragmentation
- Patterning
- Restructuring of bulk
- Lithographie, ..

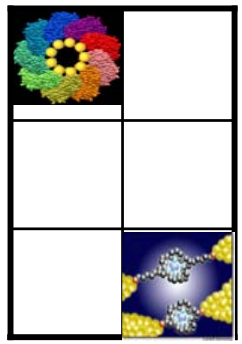
- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

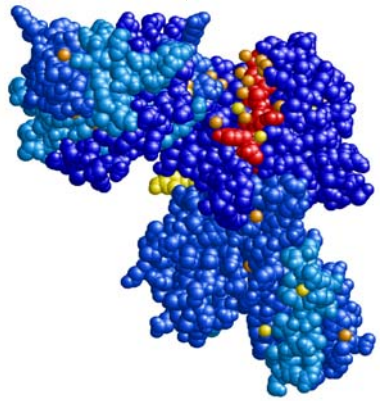
- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration..

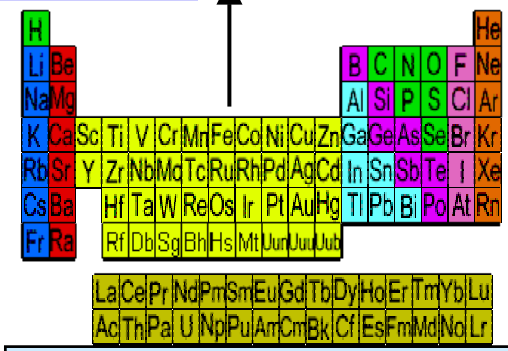








Assembling



- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

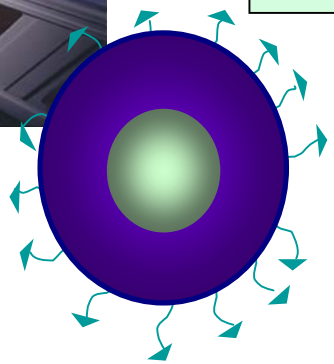
- Eng. molecules as devices,
- Quantum control,
- Synthetic biology..

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

Example 1st generation – platform for passive nanostructures

Aircraft Engines

Healthcare



Nanotechnology Platform

NanoTubes and NanoRods

NanoParticles

NanoCeramics

NanoStructured Metal Systems

Hybrid Materials

Water

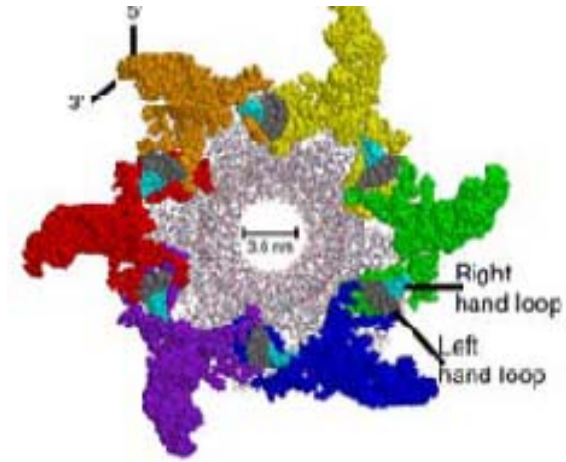
Energy

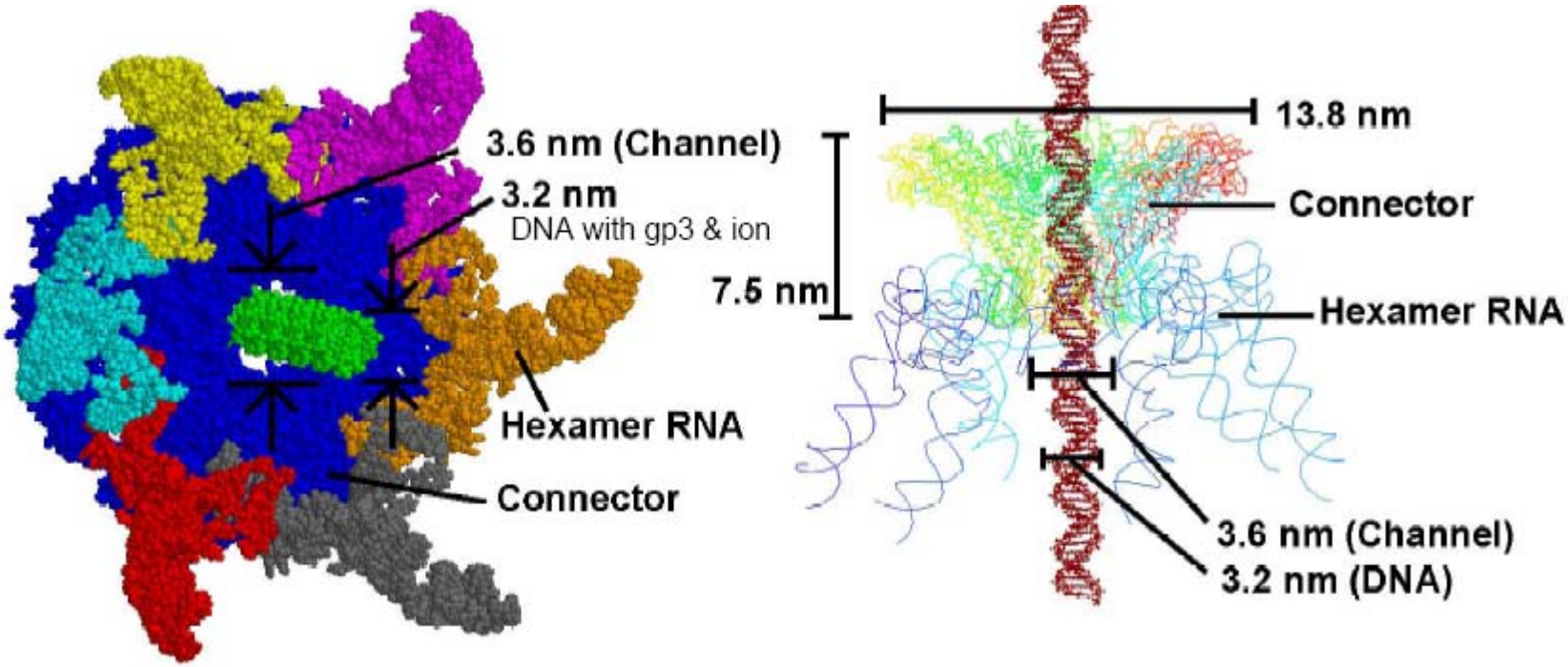
Nanotechnology at General Electric

Example 2nd generation - active nanostructure:

Construction of a Viral Nanomotor Driven by a Synthetic RNA

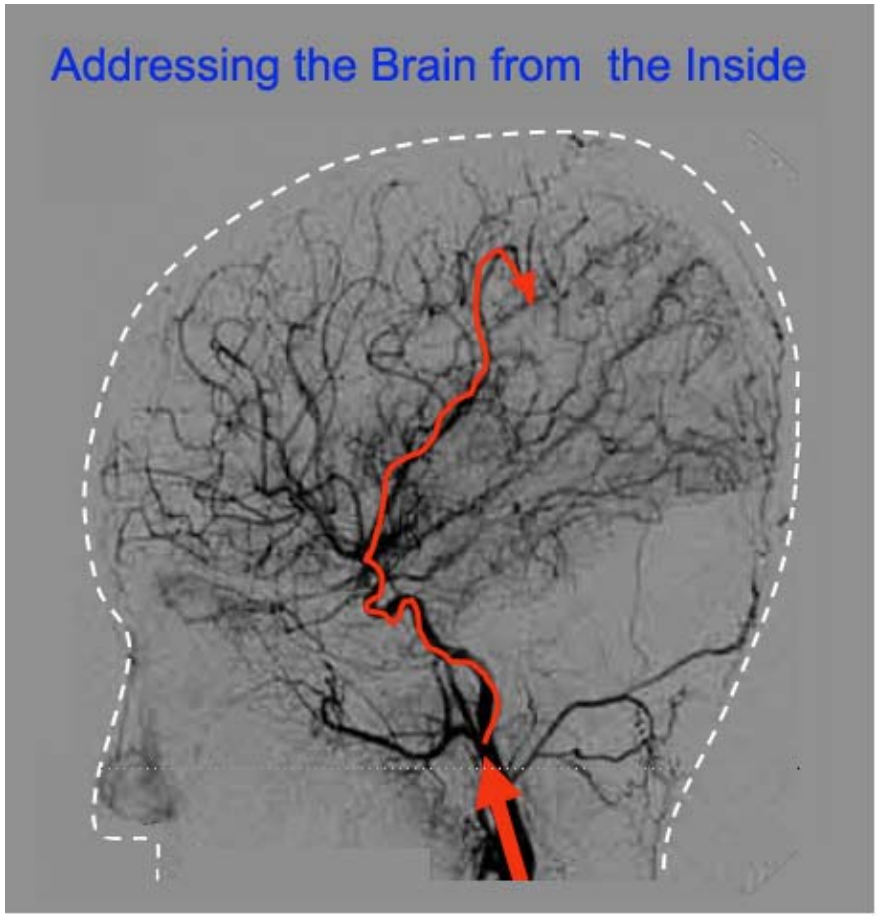
P. Guo, Molecular Virology, Purdue University, 2004





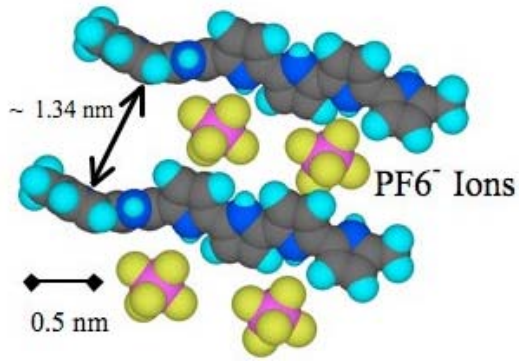
Example 3rd Generation: Neuro-vascular Central Nervous Recording/ Stimulating System: Using Nanotechnology Probes

R.R. Llinás, NYU School of Medicine
I. Hunter, MIT, Bioengineering



J. Nanoparticle Research, 2005, Issue 2

Nanostructured polymeric wires, Conducting biocompatible, biodegradable and with guidance



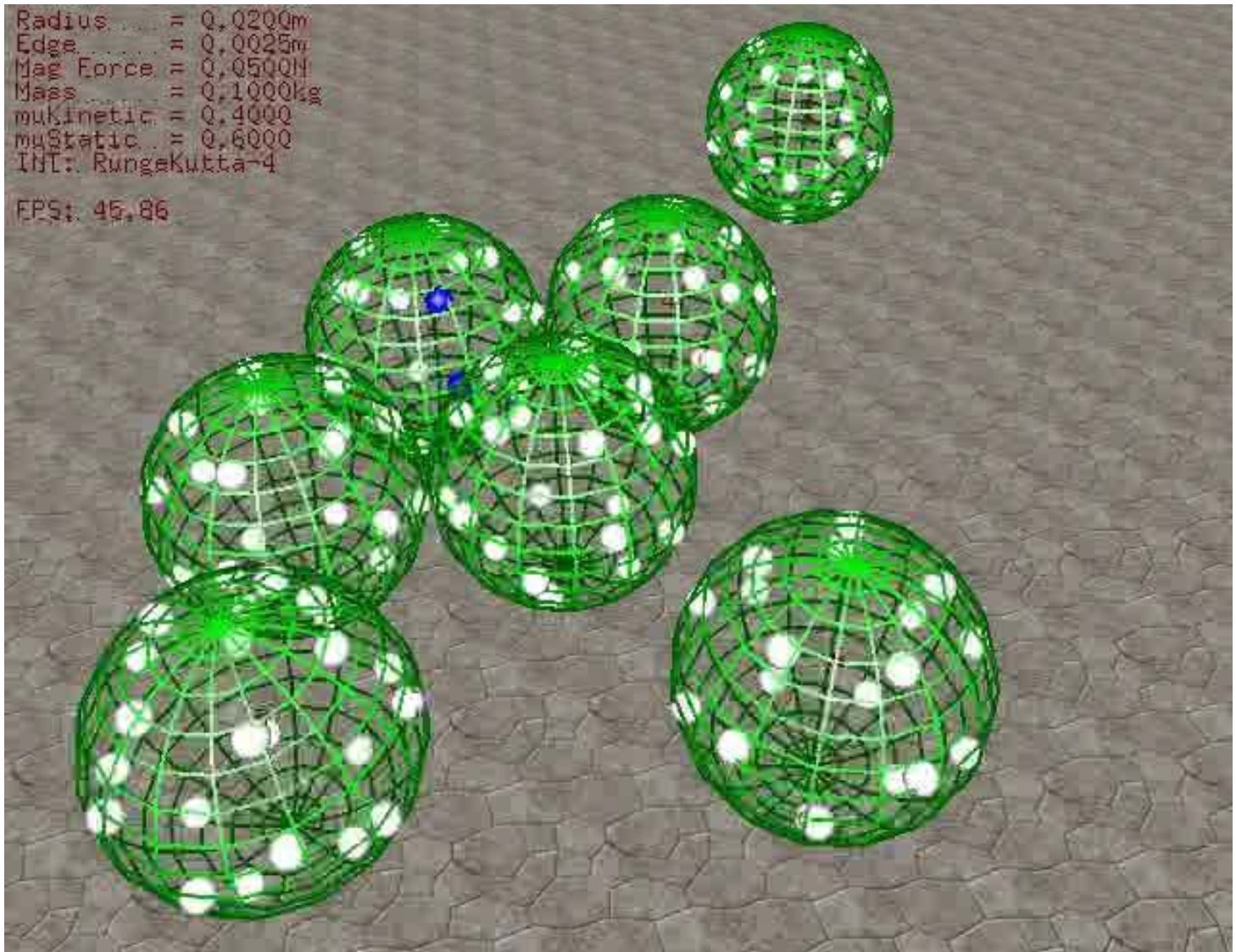
Several goals:

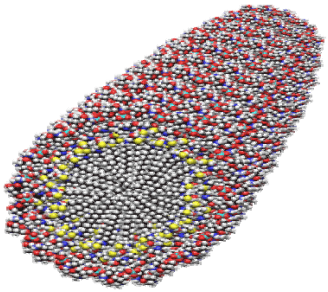
- neuro-to-neuron interaction
- simultaneous multiple probes for describing the system
- treatment Parkinson disease

Example 2nd generation - nanosytems:

Miniature Micro/Nano-Robots-II: "Claytronics"

(Seth Goldstein, CMU)

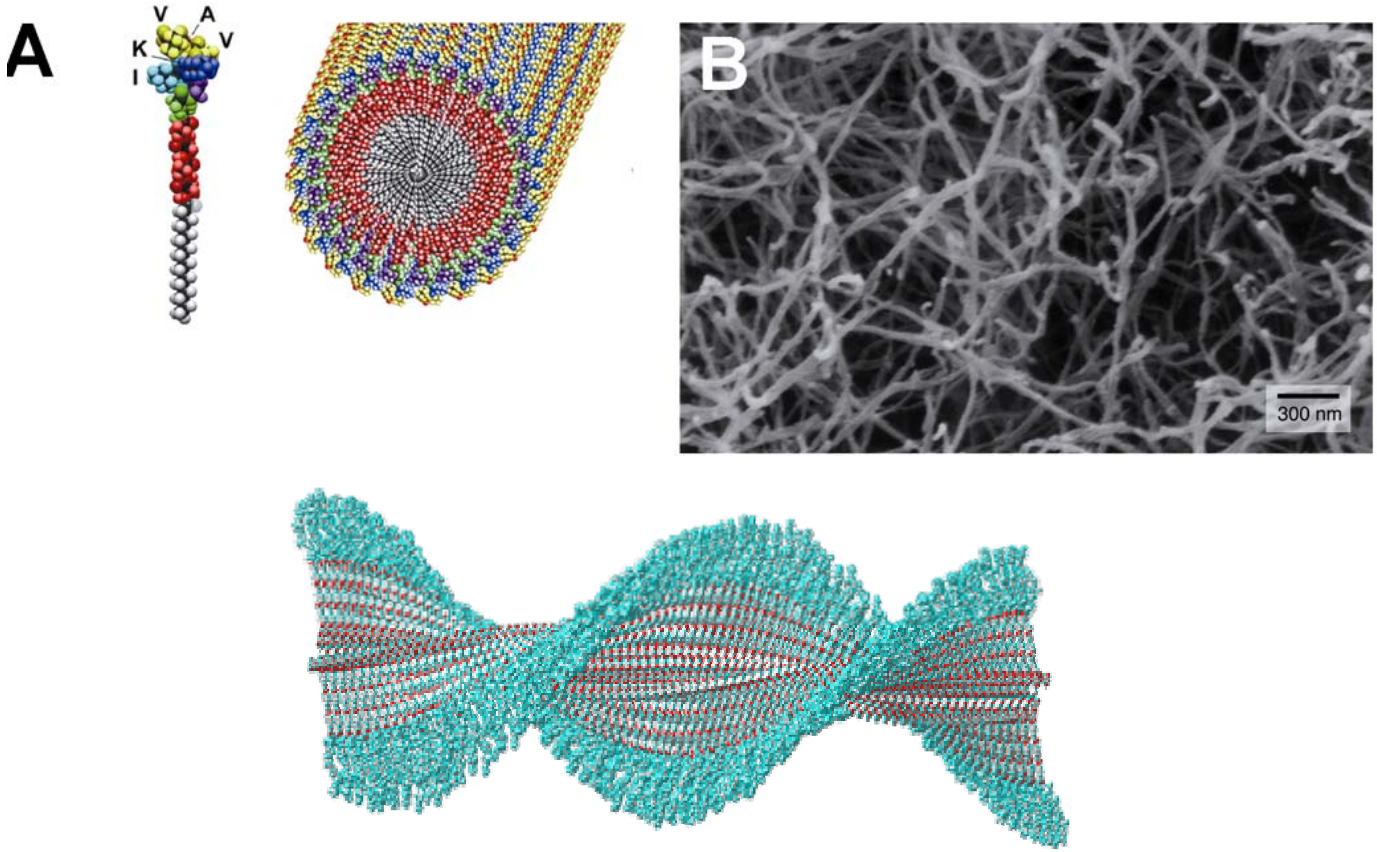




Example 4th generation – molecular nanosystem:

Designing molecules for hierarchical selfassembling

EX: SAMUEL I. STUPP, *Northwestern University*

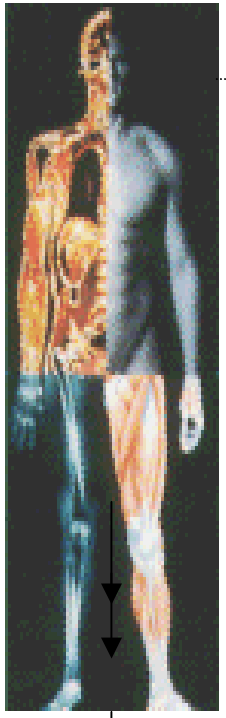


Application: biomaterials for human repair, reactive filters, others

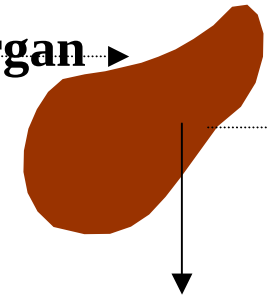
Examples of levels for intervention of nanobiotechnology

4 generations of products for human life extension

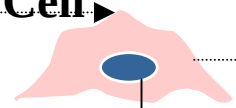
Human



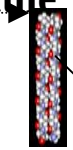
Organ



Cell



Molecule



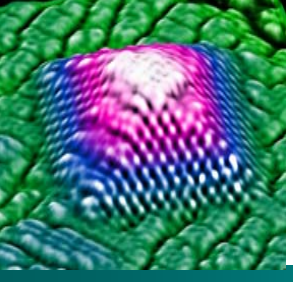
- **(1st)** Joint replacement
- Non-invasive and invasive diagnostics for rapid patient monitoring
- Cognitive-assist devices
- Targeted cancer therapies

- **(2nd)** Sensors for in vivo monitoring
- Localized drug delivery
- Neural stimulation
- Cardiac therapies
- Artificial organs

- ***(3rd)*** *Improved cell-material interactions*
- *Scaffolds for tissue eng.*
- **(4th)** Genetic therapies
- Cell ageing
- Stem cell therapies

- *Localized drug delivery*
- *Fast diagnostic techniques*
- Gene therapy devices
- Self-assembly structures

(NBIC Report, 2002)

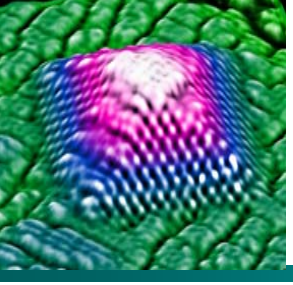


NATIONAL NANOTECHNOLOGY INITIATIVE - *from vision to the investment strategy*

- Timeline (Preparing NNI) -

- March 1991 "Nanoparticle Synthesis and Processing" (NSF program)
- Nov. 1996 Nanotechnology Group (bottom-up)
- March 1998 Functional Nanostructures; Partnership in nanotechnology (NSF in collaboration with other agencies)
- Sept. 1998 NSTC establishes Interagency Working Group of Nanoscience and Engineering (IWGN)

- March 1999 OSTP/CT presentation on NNI, Indian Treaty Room
- May-Sept. 1999 Congress hearings; Three publications NSTC/IWGN; Nanotechnology R&D planning in six agencies IWGN planning for NNI
- Oct. – Dec. 1999 OMB review – NNI the only new topic recommended PCAST – Letter to the President supporting NNI OSTP and WH Approval
- Jan. 2000 NNI announced by the President in Jan 2000



NATIONAL NANOTECHNOLOGY INITIATIVE - *from vision to the investment strategy*

- Timeline FY 2001-2005 -

- Feb.–Dec. 2000 - WH, Congress review and approve FY 2001 NNI
  6 agencies (NSF, DOD, DOE, NIH, NASA, NIST)
  Concerns about applicability; "Societal Implications" workshop

- FY 2001 14 agencies (+ EPA, DOT, DOTr, DOS, DOC-TA, DOJ, USDA, IC); $490M
  NSET signs MOU to establish NNCO ; White Hose support to NNI
  International reaction: programs in > 30 countries (now > 60)
  20 states and regional alliances begin to invest (now > 22)

- FY 2002 16 agencies (+FDA, NRC) ; $737M
  Outcomes: R&D, Education, Patents, Industry growth; EHS aspects

- FY 2003 17 agencies (+ DHS); 2 Bills in Congress for FY2004-2008; $942M
  CBAN established, Research directions workshops

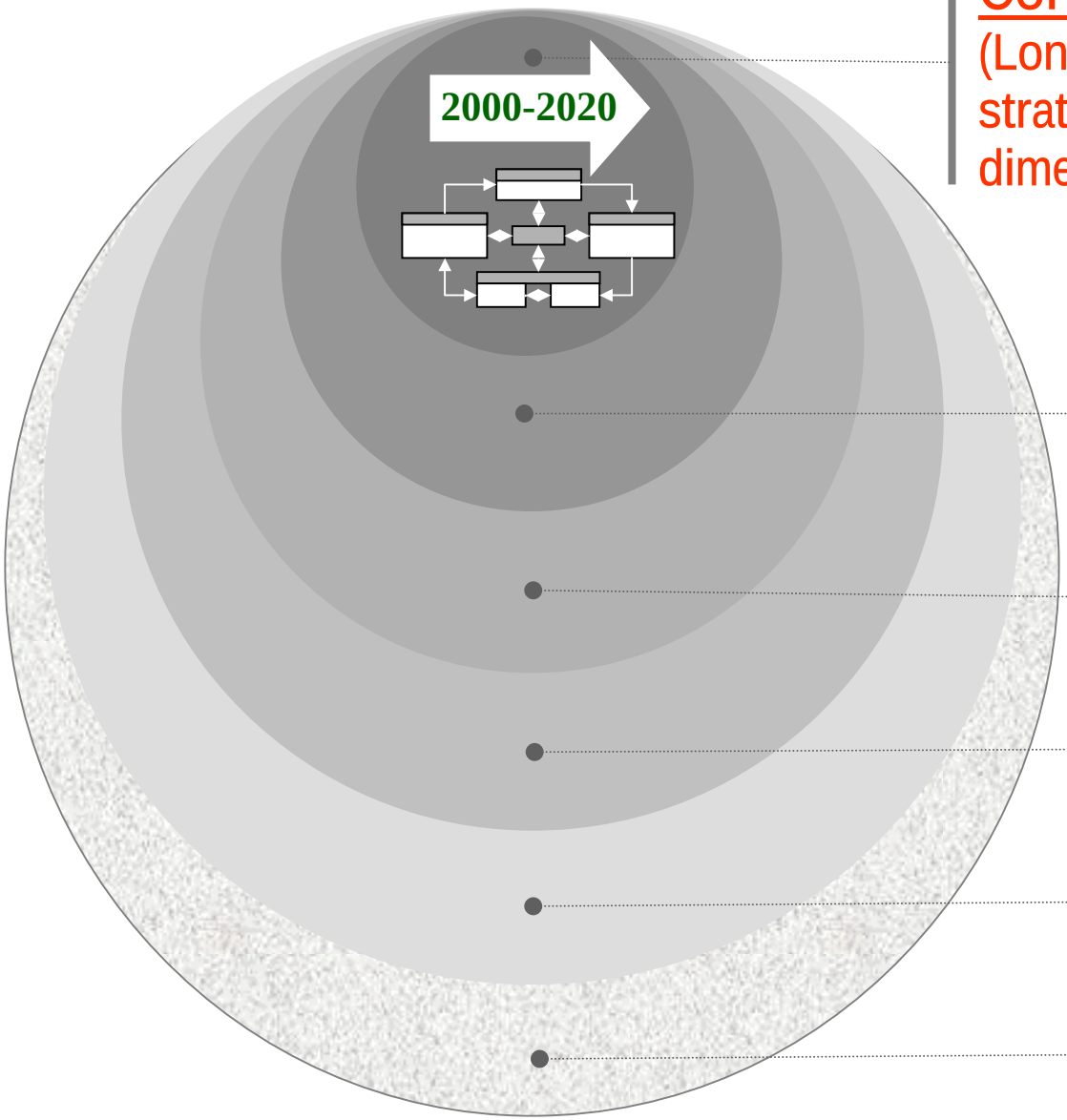
- FY 2004 22 agencies (+ NIOSH, CPSC, ITC, USPTO, DOC-BIS); The Law $1,094M
  Infrastructure development; Strategic Plan II (Dec. 2004)

- FY 2005 24 agencies (+ USDA-FS); New frontiers for nanotechnology $1,231M

The Long-term View

- NNI was designed as a science project (2000-2020)
  2 years long-term planning without dedicated funding in 1997-1999.
  Reports prepared for: long-term view ("NT Research Directions"), definitions and international benchmarking ("Nanostructure S&T"), science and engineering priorities, societal implications from the beginning, plan for government agencies, public engagement.
- NNI has exceeded the usual borders of academic science and engineering projects by involving almost all industries, health care R&D, the public and civil organizations, and international community in only 5 years.
- NNI has been the first national initiative in the U.S. initially motivated by the need for basic research and knowledge creation
- Main questions: 1980- could measure size? 1990- scientific interest? 2000 – promise is real? 2005 – challenges for better and safer NT?

NANOTECHNOLOGY GOVERNANCE OVERVIEW



Core Governance Process
(Long-term view, several investment strategies, addressing societal dimensions, risk governance)

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

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

Social Climate
(Perceived authority of science, civil involvement)

Political Context

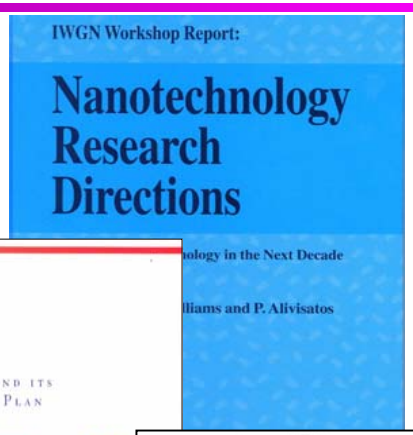
International Interactions

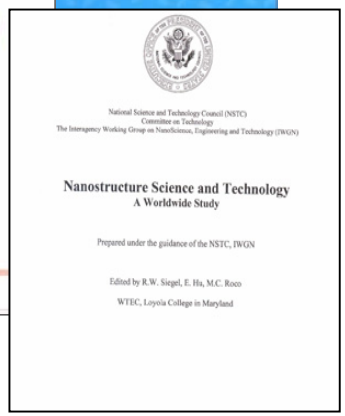
Defining the vision for the *first strategic plan (I)*

National Nanotechnology Initiative

1999-2000

1999:
10-year
vision

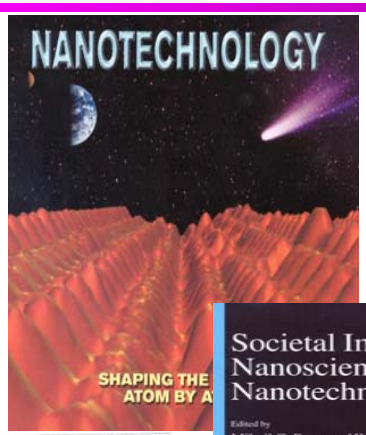




Government
plan

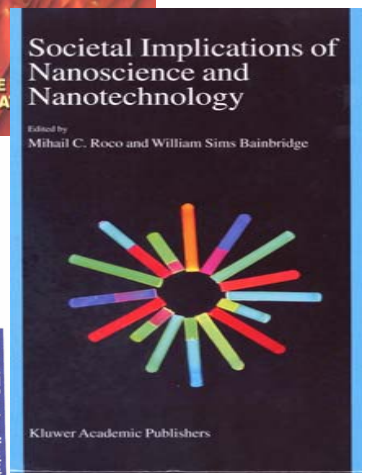
Reports

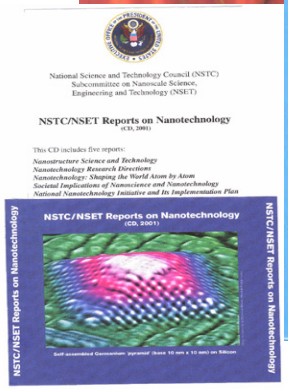
Worldwide
benchmark



Brochure for
public

Societal
implications





Focus on Knowledge Creation (same principles, phenomena, tools, architectures) to support innovation in various areas of relevance

Planning with Feedback: after each 5 years, 1 year, 1 month (2001-2005); and various levels: national / NSET, agency (25), R&D program

NNI: Key Investment Strategies
(2001 - 2005)

- Long-term planning, part of coherent S&T evolution
- Focus on interdisciplinary fundamental research (‘horizontal’) + transition to technological innovation (“vertical’)
- Address broad humanity goals and other societal aspects
- Prepare the nanotechnology workforce as a key component
- Policy of inclusion and partnerships
  Interdisciplinary, Interagency collaboration, Public engagement
- Transforming strategy for competitive advantage; “bio-inspired” approach; consider the full architecture and interactions
- Risk governance for the societal dimensions

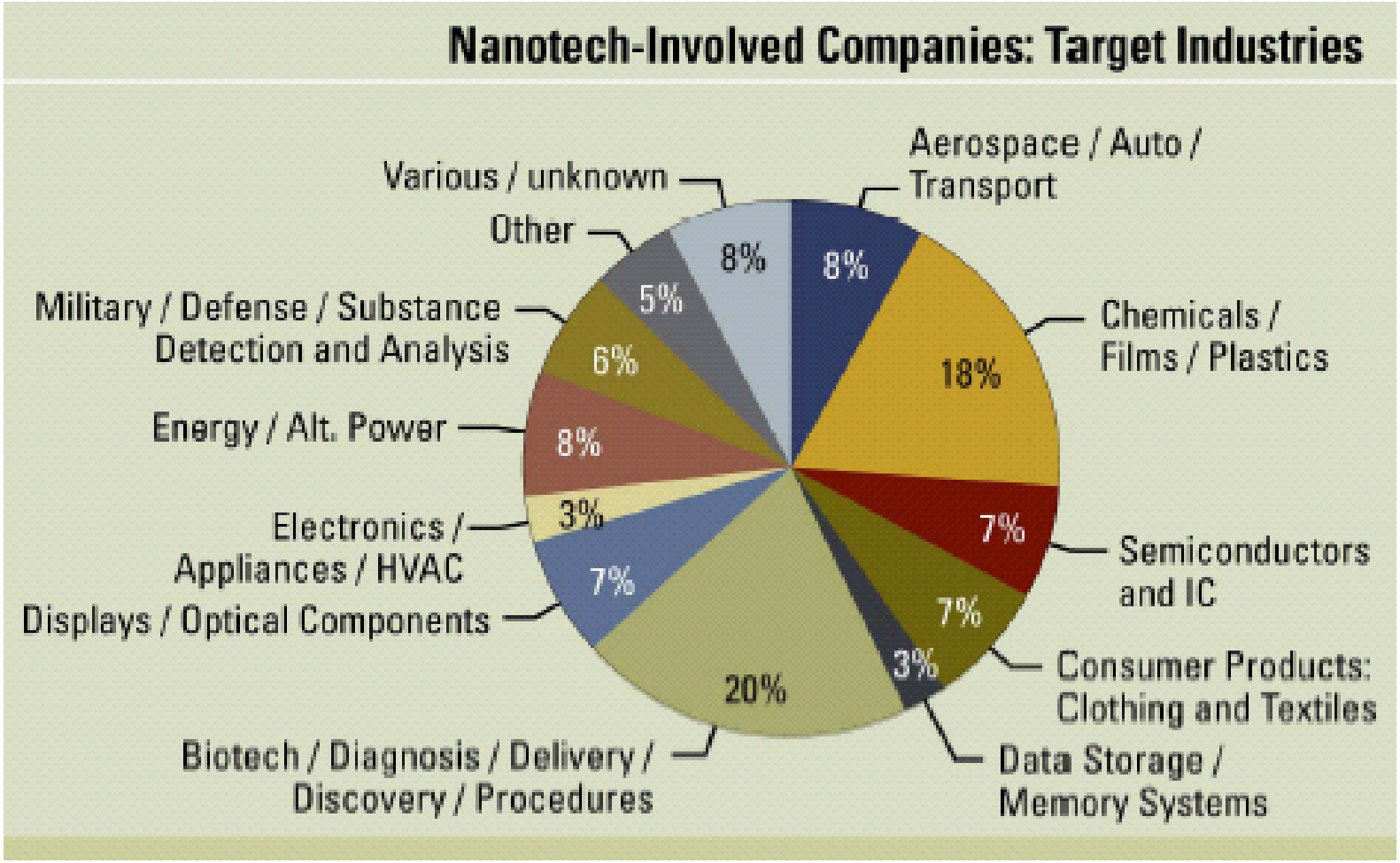
NNI Vision: Systematic control matter on the nanoscale will lead to a revolution in technology and industry

- 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

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

Develop metrics 1999, check progress 2005, to satisfy first criteria 2015

Rudimentary nanostructures in the First Generation of products: broad based impact



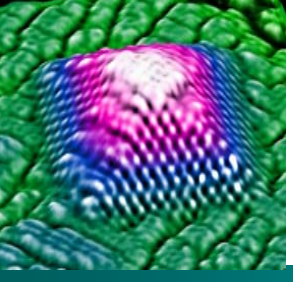
Source: *Small Times Media* (2004)

NATIONAL NANOTECHNOLOGY INITIATIVE

First NNI strategic plan (2001-2007): R&D funding by Agency

Fiscal year (all in million $)	*2000* Actual	*2001* En./Actual	*2002* En./Actual	*2003* En./Actual	2004 En../Actual	2005 En./Actual	2006 En/Est	2007 Req
NSF	97	150 /150	199 /204	221 /221	249 /256	305/334	344/344	373/
DOD	70	110 /125	180 /224	243 /322	222 /291	276/257	230/336*	345/
DOE/BES+FS	58	93 /88	91.1 /89	133 /134	197 /202	211/210	207/207	258/
HHS/NIH+NIOSH	32	39 /39.6	40.8 /59	65 /78	70 /106	89/145	147/175	173/
NASA	5	20 /22	35 /35	33 /36	31 /47	35/45	32/50**	25/
DOC/NIST	8	10 /33.4	37.6 /77	66 /64	62 /77	53/75	75/76	86/
EPA	-	/5.0	5.0 /6	5 /5	5 /5	5/5	5/5	9/
DHS/TSA	-		2.0 /2	2 /1	2 /1	1/1	3/2	2/
USDA/CREES+FS	-	/1.5	1.5 /0	1 /1	10 /2	5/3	11/5	5/
DOJustice	-	/1.4	1.4 /1	1.4 /1	1.4 /2	1/2	2/1	1/
Congressionally-directed		/464	/ 697	/ 862	/ 989	/1078 /	/1191	
To DOD and NASA		/25	/40	/80	/103	/150	/*100,**10	/
TOTAL	270	422 /489	600 /737	770 /942	849 /1092	982/1228	1054/1301	1277/
Average annual rate: 38		+82%	+50%	+28%	+16%	+ 13%	+6%	

- Industry, state and local organizations: about 2 times NNI budget in 2004
- 2004 NNI budget: 65% to academia; 25% - R&D labs; 10% - industry (7% SBIR)
- NNI as part of the U.S. Federal R&D ~ 0.25% (2000) to 1% (2005)



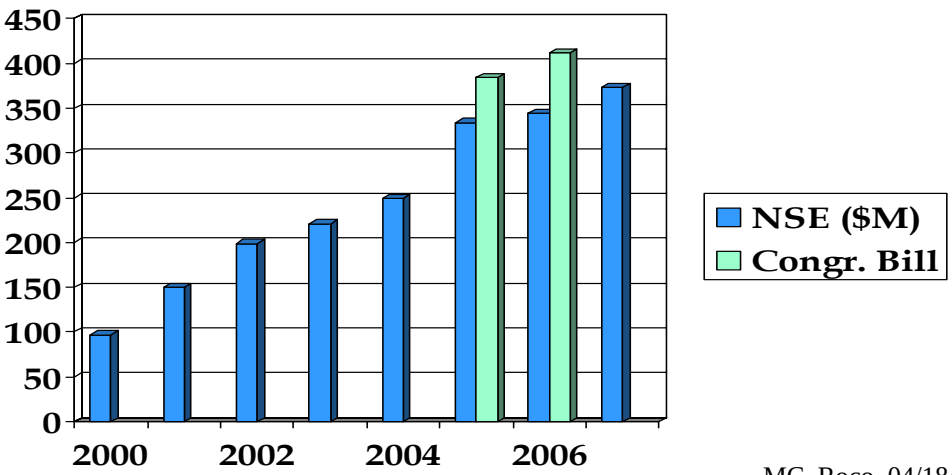
NSF - a pioneer at the international level in Nanoscale Science and Engineering (NSE)

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

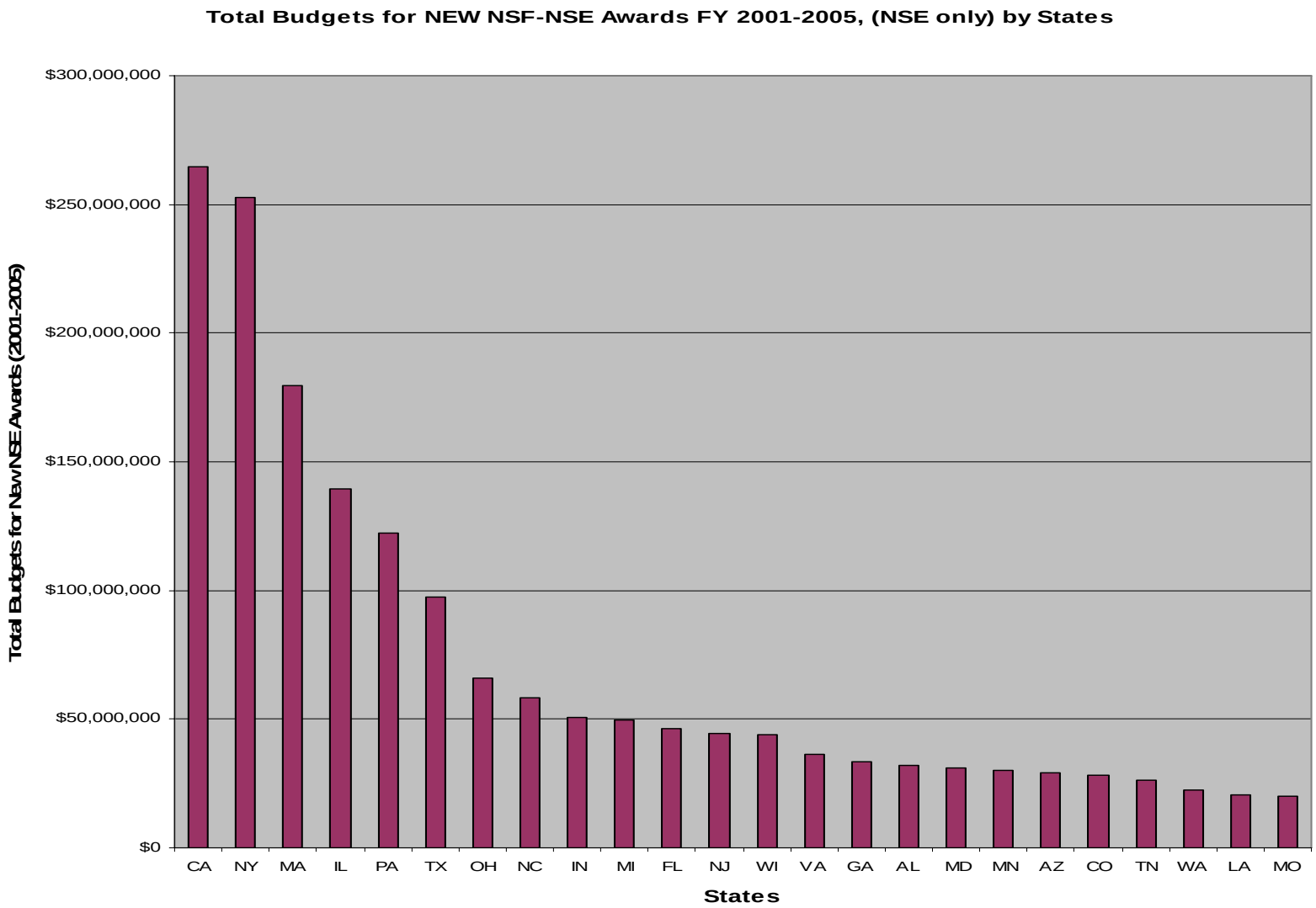
FY 2005: ~ **1/4 of Federal** and **1/12 of World Investment**

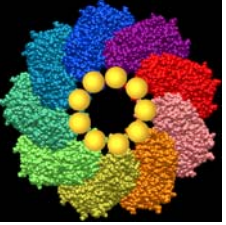
- **Fundamental research**: Biotechnology, Novel nanostructures and phenomena, Device and system architecture, Beyond CMOS, Environmental Processes, Multiscale modeling, Nanomanufacturing; Societal implications and Improving human performance (8 themes)
- **Establishing the infrastructure**: over 3,000 active projects; 23 large centers, 2 user facilities (NNIN, NCN), multidisciplinary teams
- **Training and education** - 10,000 students and teachers

Fiscal Year	NSF	Law 03
2000	$97M	
2001	$150M	
2002	$199M	
2003	$221M	
2004	$254M	
2005	$334M	$384M
2006	$344M	$412M
R. 2007	**$373M**	



Total budget for NEW NSF-NSE awards for FY 2001-2005 by states





NNI Accomplishments (1)

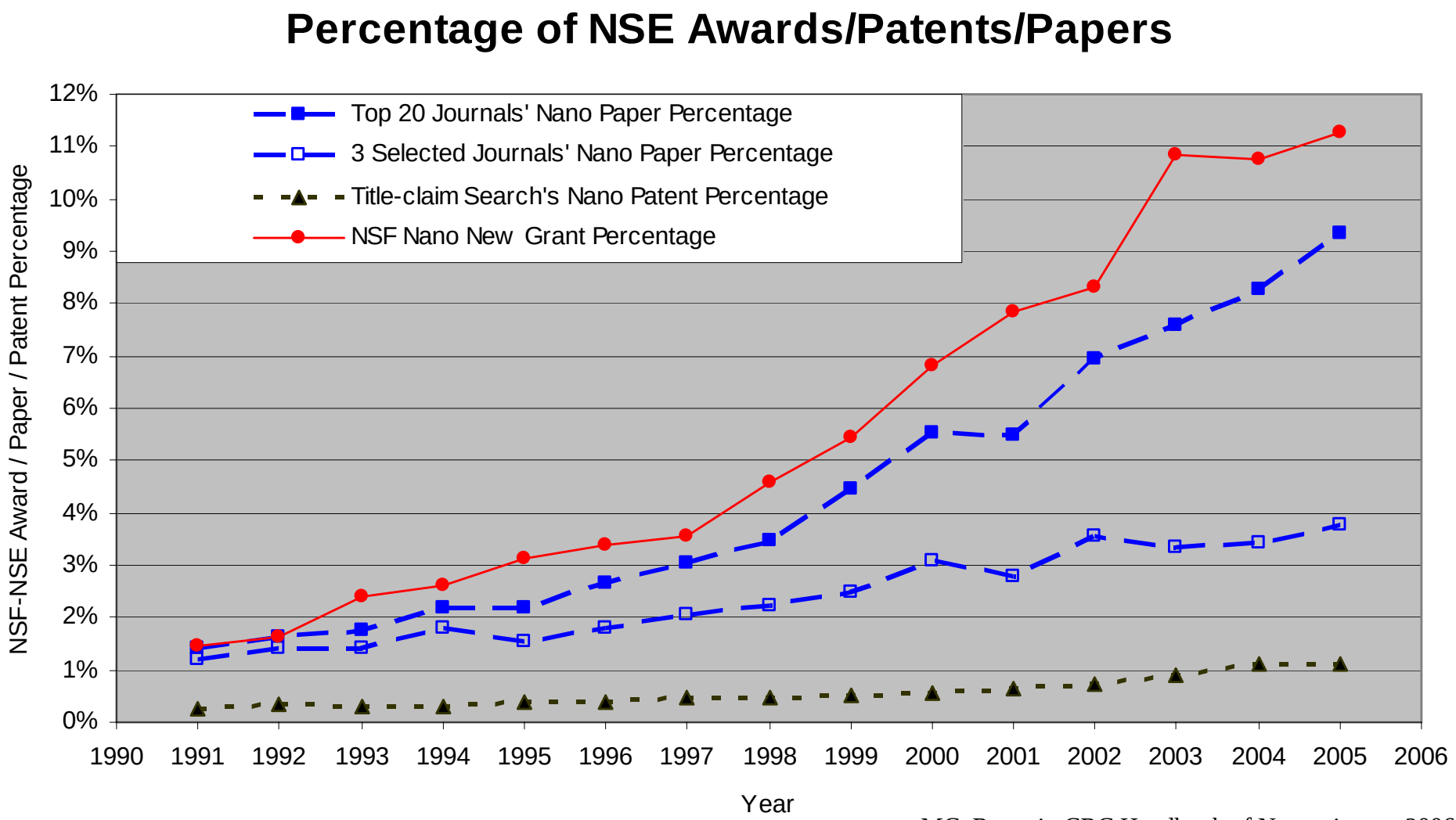
- Developed foundational knowledge for control of matter at the nanoscale:
  over 3000 active projects in > 500 universities, private sector institutions and gov. labs in all 50 states
- "Created an interdisciplinary nanotechnology community" [1]
- R&D / Innovation Results: With ~25% of global government investments, the U.S. accounts worldwide for
  ~ 50% of highly cited papers,
  ~ 60% of USPTO patents[2], and
  ~70% of startups[3] in nanotech. Small Times reported ~ 1645 US nanotech companies in March 2005
- Infrastructure:
  over 59 new large nanotechnology research centers, networks and user facilities; about 8,000 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 - from the beginning, about 10% of 2004 NNI; addresses environmental and health, safety, and other societal and educational concerns; NSET SC leadership thru NEHI WG
- Nanotechnology education and outreach - impacting over 10,000 graduate students and teachers in 2004; expanded to undergraduate and high schools, and outreach; create national networks for formal and informal education
- Leadership: The U.S. NNI has catalyzed global activities in nanotechnology and served as a model for other programs.

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



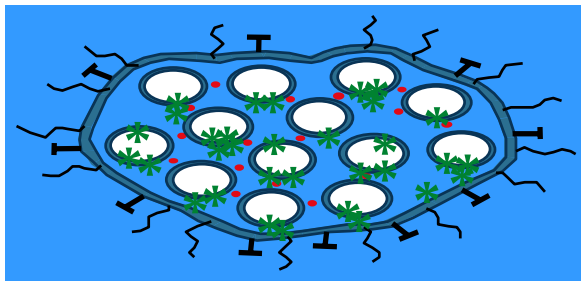
MC. Roco, in CRC Handbook of Nanoscience., 2006

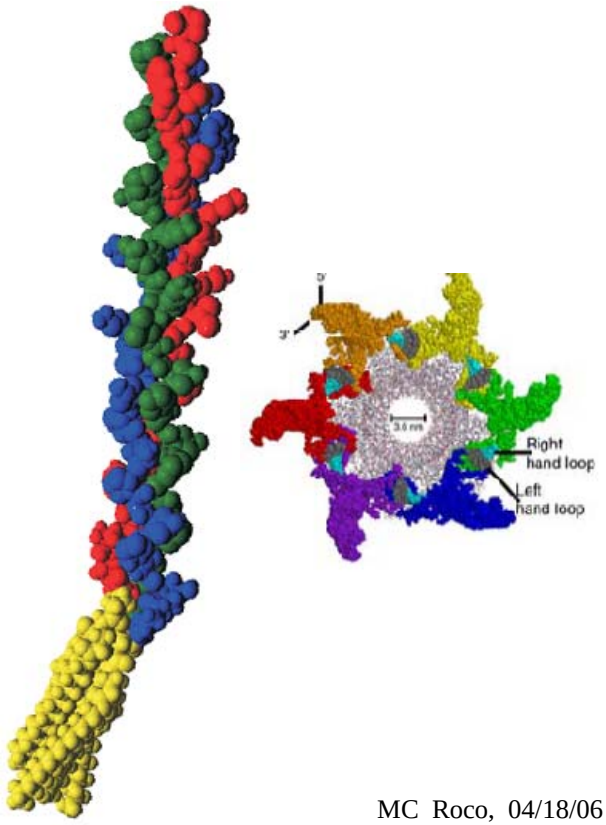
Example:

Synthesis and control of nanomachines

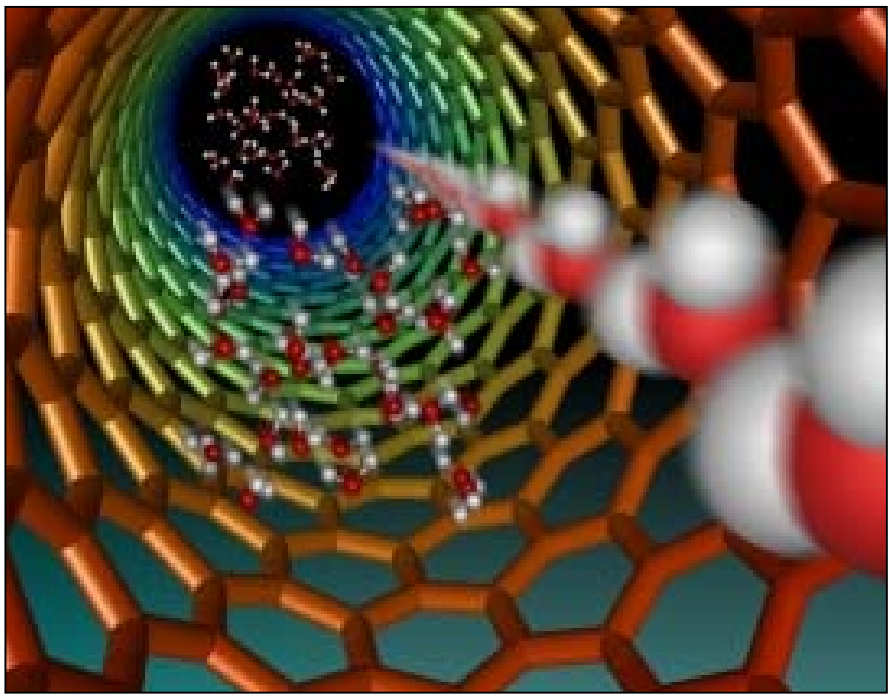
(examples NSE in 2004, www.nseresearch.org - 300 projects)

- **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)
- **Combinatorial engineering of nanomachi** with application to membranes and filters (U. Penn.
- **Nanoengineering surfaces** for probing viral adhesion (UC Davis)





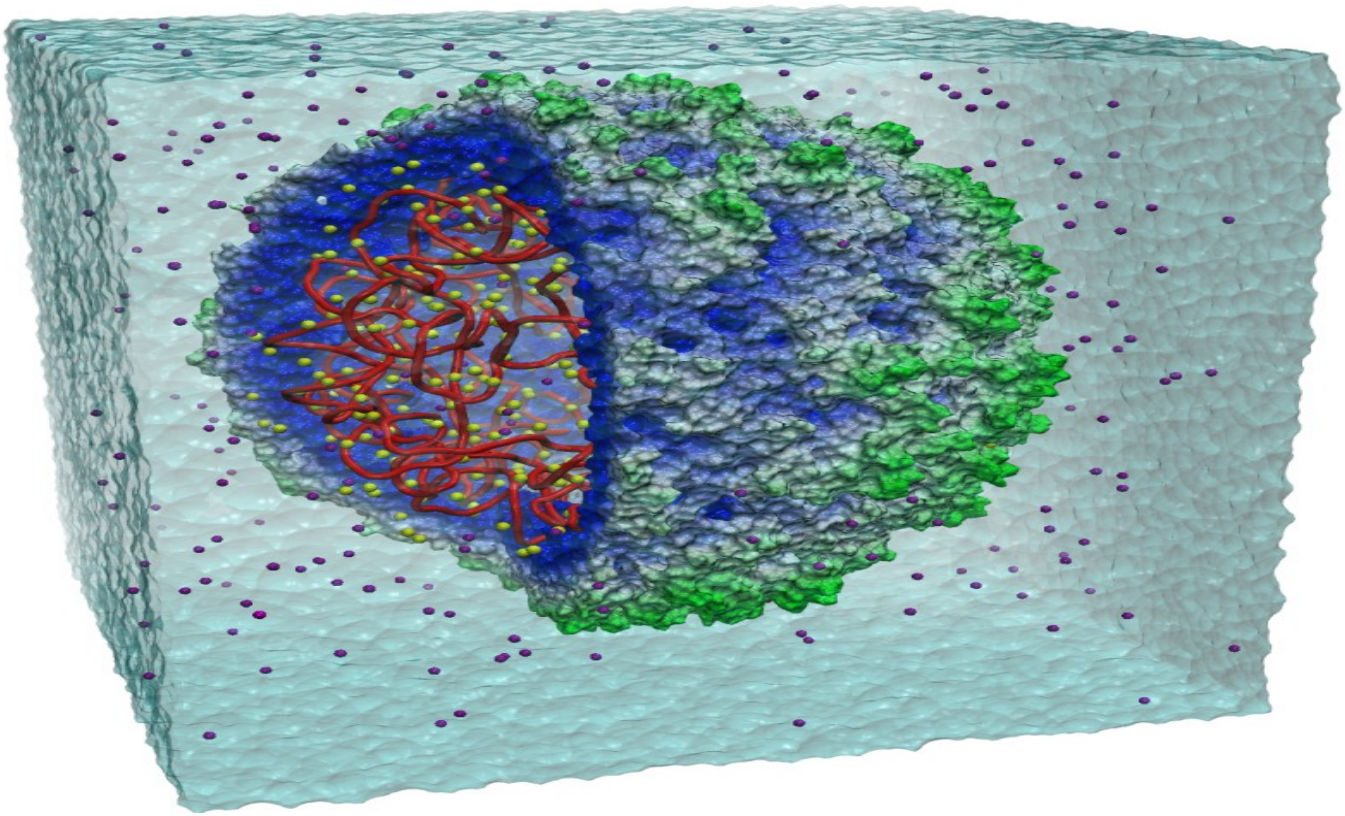
Novel Membranes Researchers at the University of Kentucky have fabricated membranes from billions of aligned carbon nanotubes. The surfaces of the membranes are almost friction-free, allowing fluids to flow at nearly 100,000 times the speed predicted by fluid-flow theory. Highly efficient nanotube-based filters may one day contribute to the purification of products ranging from industrial chemicals and pharmaceuticals to dairy production. (ENG)



In this illustration, water is shown flowing through carbon nanotube membranes at a rate up to 100,000 times faster than models predict.

NSF Press Release 06-049
Supercomputer Maps One Million Atoms of a Complete Virus in First Simulation of a Life Form

Virtual virus takes 100 days on supercomputer, 35 years on a desktop, for 50 ns simulation



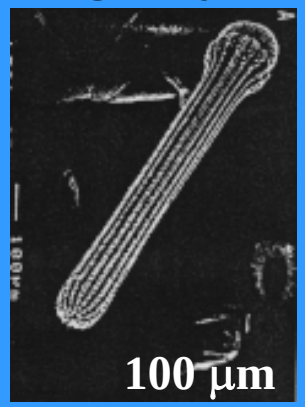
Credit: *University of Illinois at Urbana-Champaign's Theoretical and Computational Biophysics Group, 2006*

Microbes and higher organisms direct the formation of complex structures in controlled biomineralization

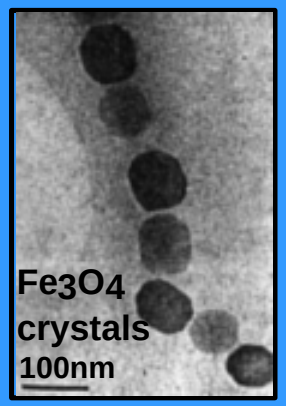
- Biologically-mediated crystallization of inorganic ions produces nanophase structures as single crystals and composites with remarkable properties that fulfill specific functional needs

- Recent advances offer opportunities to decipher mechanisms by linking molecular interactions to surface processes and nanoscale controls on crystal morphology

$CaCO_3$ sea urchin single crystal



Fe_3O_4 microbial nanocrystals



$CaCO_3$ coccolith crystal com

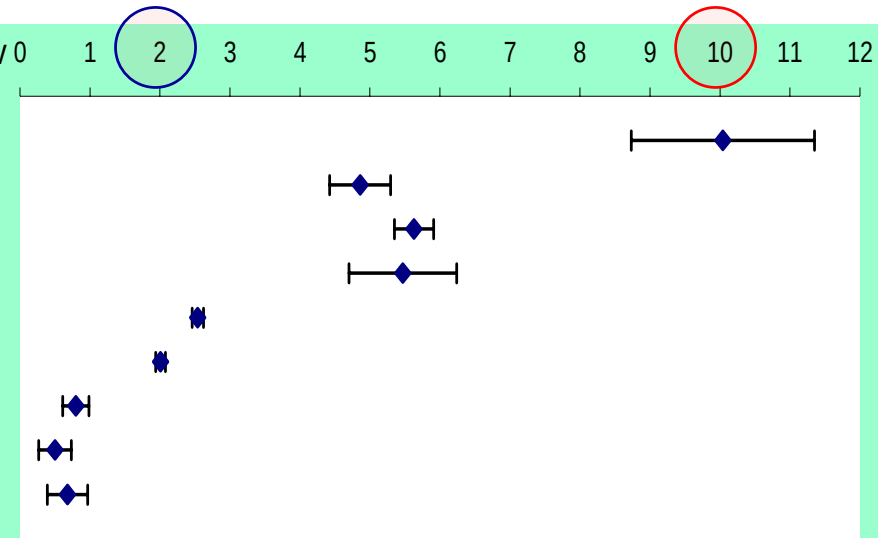
1 µm

Number of citations of Nanoscale Science and Engineering patents

(analysis NSF sponsored research and USPTO patents)

Group	N	Mean	StDev	95% CIs based on pooled StDev Lower	Upper
NSF	307	10.04	23.6	8.731	11.349
IBM	2756	4.86	15.7	4.423	5.297
Top10	6650	5.63	22.38	5.349	5.911
UC	894	5.47	29.59	4.703	6.237
US	78227	2.54	12.29	2.458	2.622
EntireSet	108378	2.01	10.94	1.940	2.080
Japan	14837	0.8	7.89	0.612	0.988
European	9560	0.5	4.99	0.265	0.735
Others	6385	0.68	6.64	0.393	0.967

Pooled StDev = 11.70

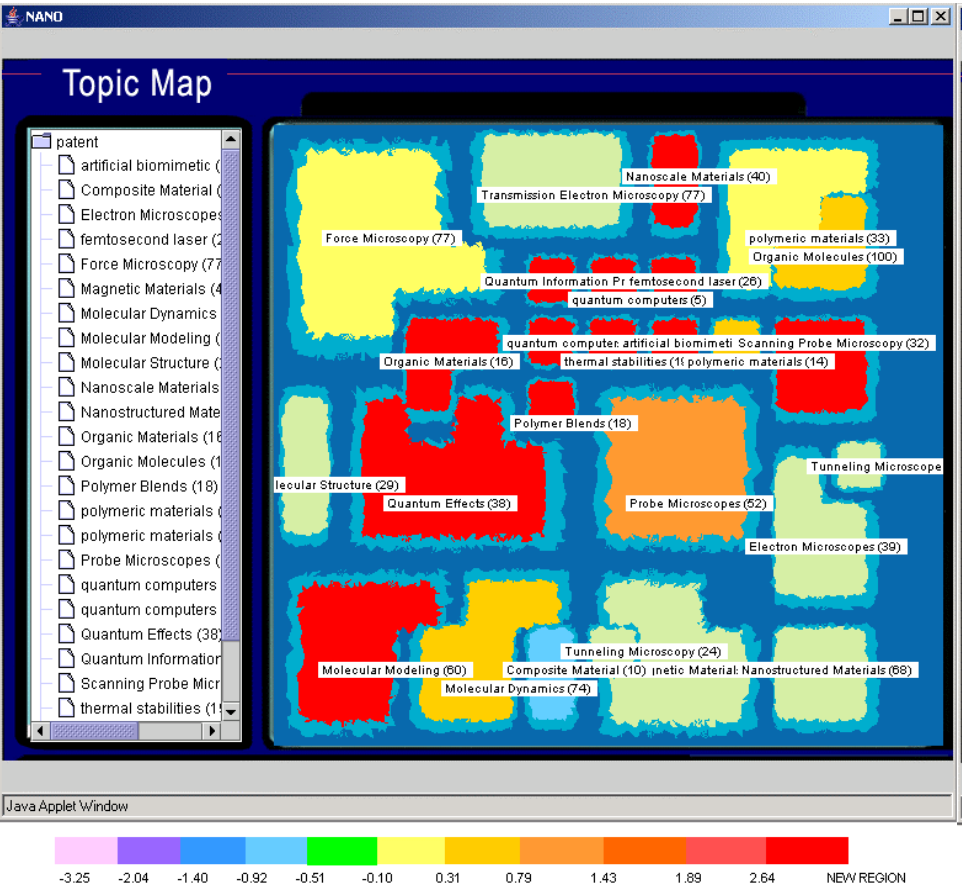


NSF Principal Investigator's patents had significantly higher number of cites measure than most other comparison groups. It shows the relevance of fundamental research for nanotechnology development.

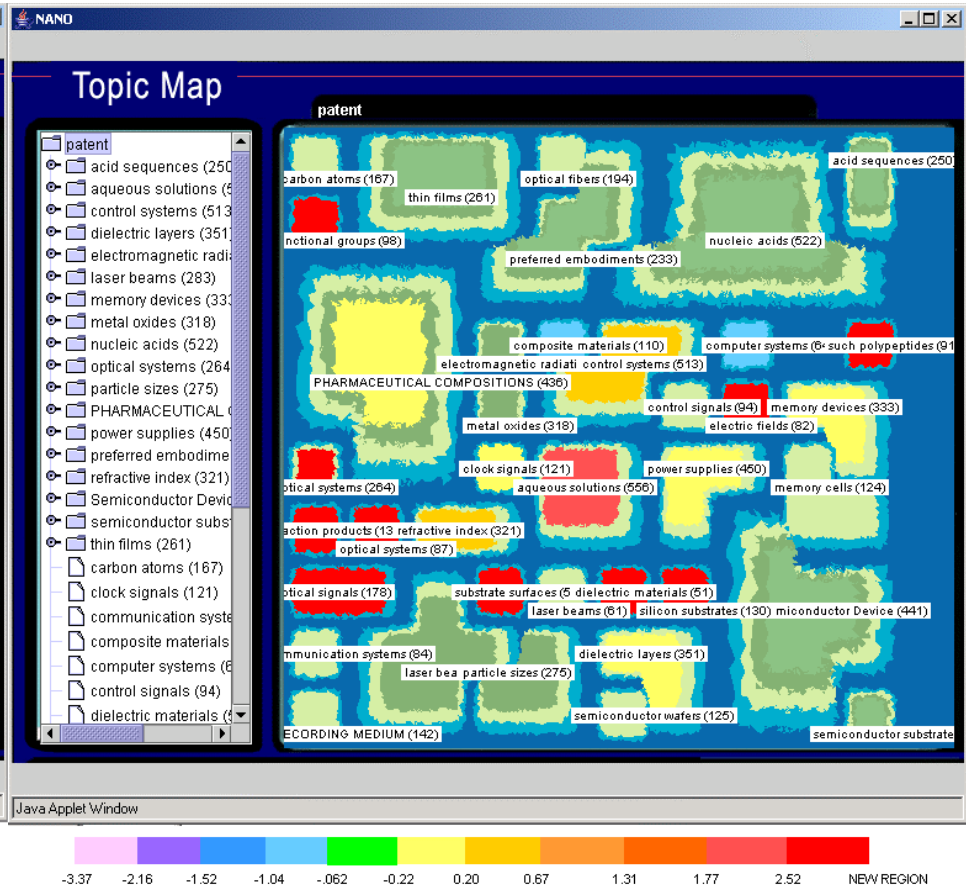
(from J. Nanoparticle Research, 2005, Issue 7(3))

NSE content map analysis
grant – patent topic association

NSE Grant Content Map (2001-2002)



NSE Patent Content Map (2001-2002)



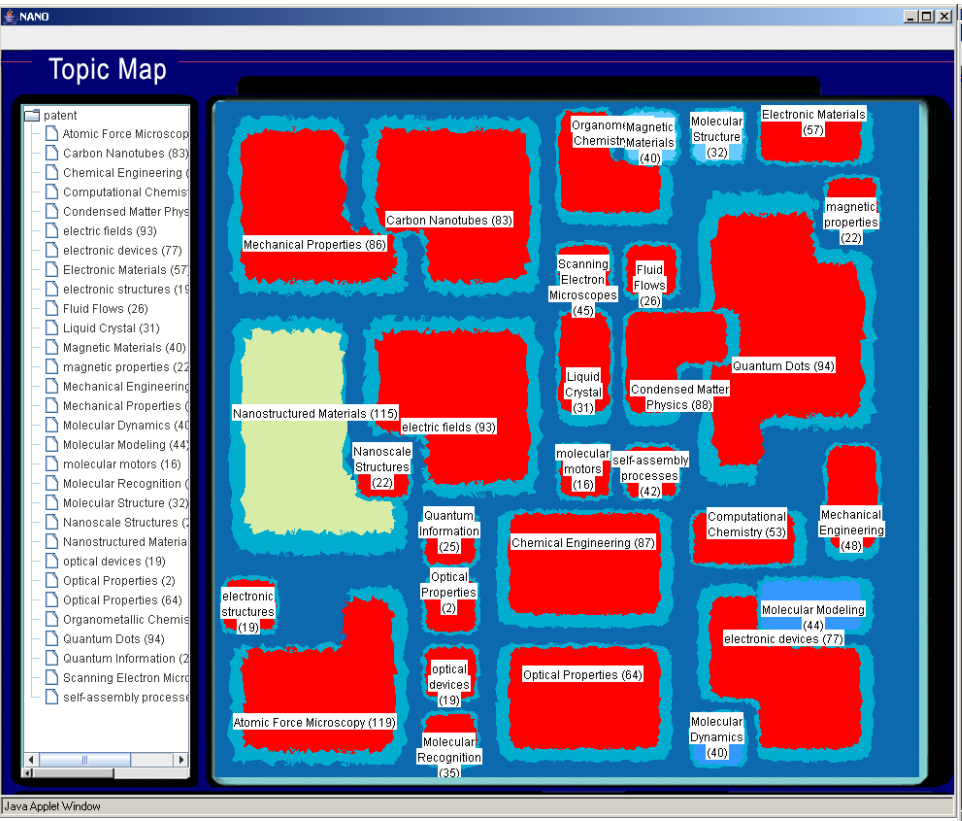
*

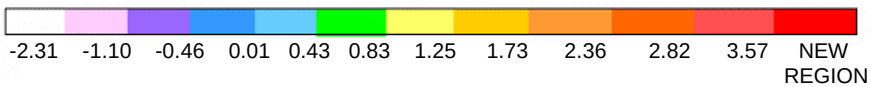
Region color indicates the relative growth rate (red – highest rate)

(source: NSF sponsored research)

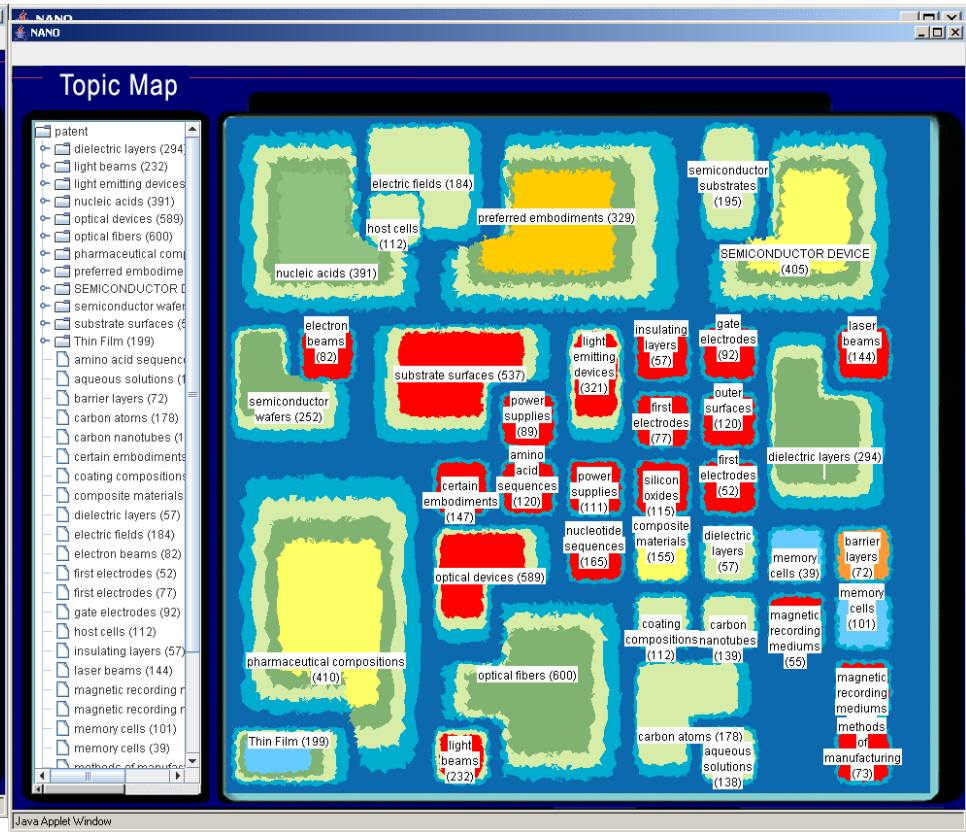
NSE content map analysis
grant – patent topic association

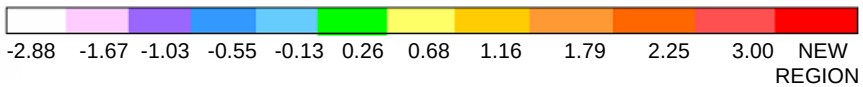
NSE Grant Content Map (2003-2004)





NSE Patent Content Map (2003-2004)





Region color indicates the relative growth rate (red – highest rate)

(source: NSF sponsored research)

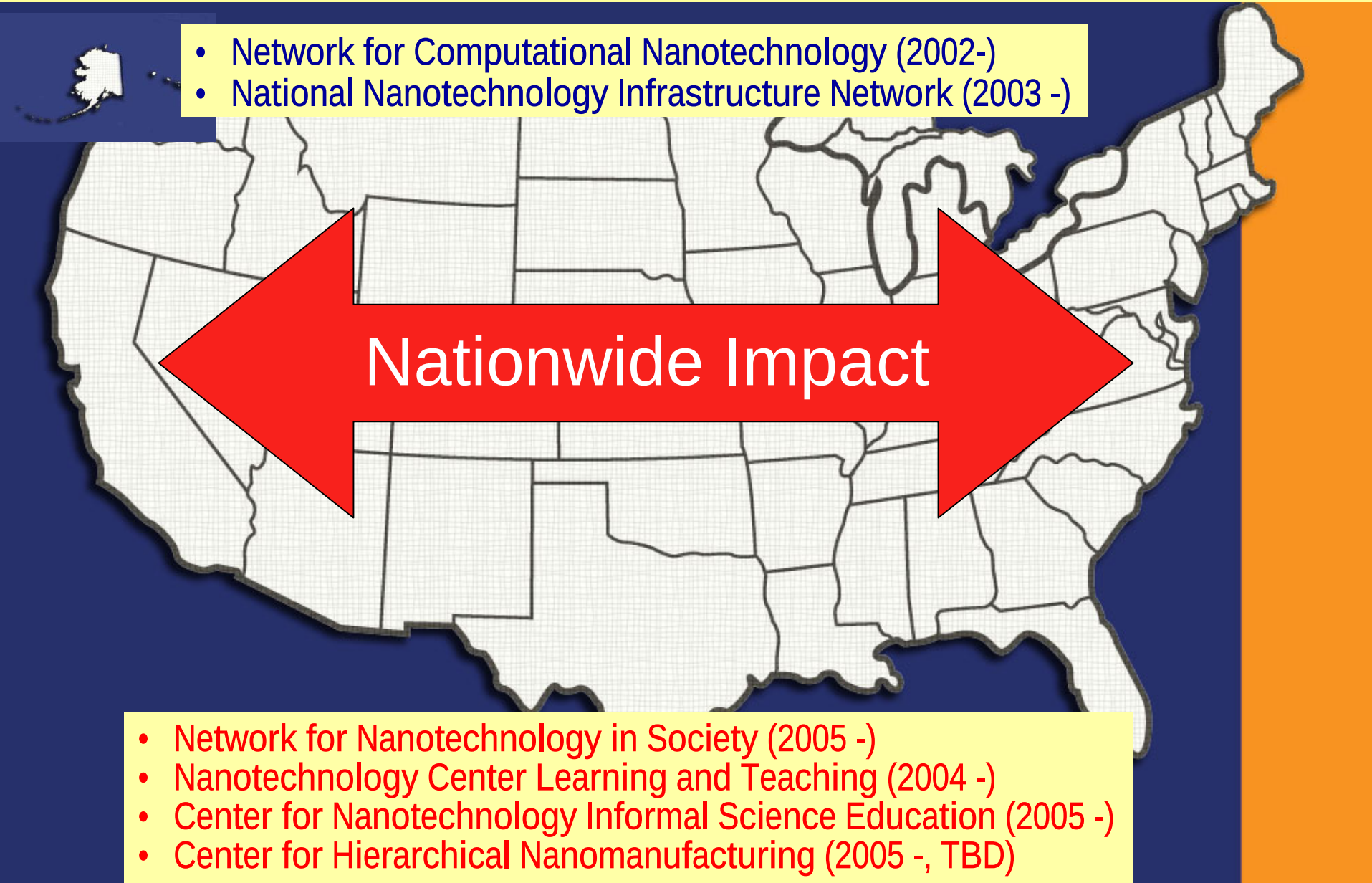
Outcomes of 2001-2005: R&D Networks and User Facilities

- **Network for Computational Nanotechnology** (NCN)
  - **7** universities (Purdue as the central node)
  - Nanoelectronic device simulation/modeling
- **National Nanotechnology Infrastructure Network (NNIN)**
  - 13 universities with user facility (Cornell as central node)
  - Development measuring & manufacturing tools
  - Education and societal implications
- **Oklahoma Nano Net (EPSCoR award)**
- **DOE network for large scale facilities**
- **NASA academic research network**
- **NIH centers of excellence in nanotechnology**

59 new centers and networks created by NNI since 2001:

24 NSF, 3 DOD, 5 DOE, 4 NASA (academic), 2 NIST, 21 DHHS

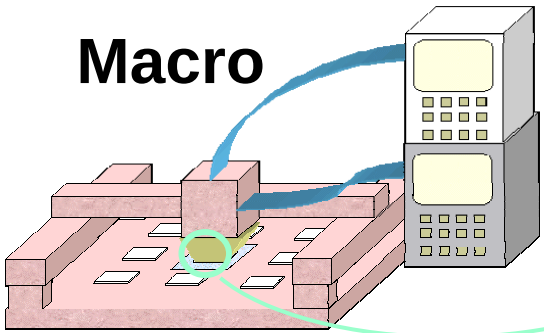
Six NSF networks/centers with national outreach

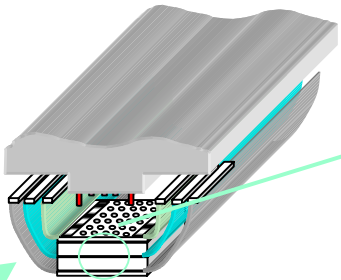


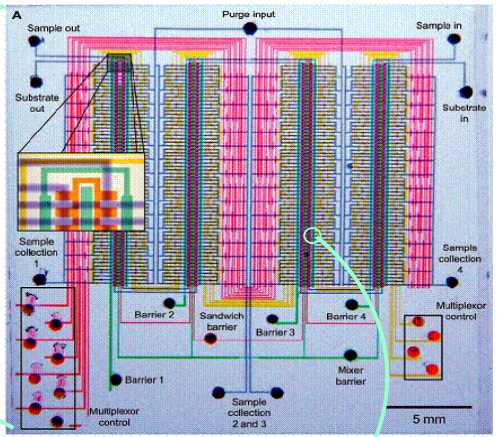
- Network for Computational Nanotechnology (2002-)
- National Nanotechnology Infrastructure Network (2003 -)

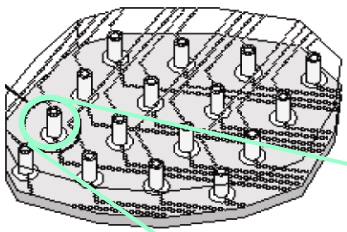
- Network for Nanotechnology in Society (2005 -)
- Nanotechnology Center Learning and Teaching (2004 -)
- Center for Nanotechnology Informal Science Education (2005 -)
- Center for Hierarchical Nanomanufacturing (2005 -, TBD)

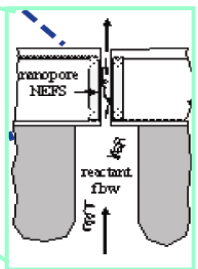
Example: Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, UIUC, NCSU, Caltech











Nano

Goals - control of composition at nanoscale

- placement of nanostructures in 3D
- knowledge of the state of matter at nano

Research Thrusts

Micro-Nano Fluidic Network Toolbit

Process Sensing and Control

Manufacturing Systems

DOE Nanoscale Science Research Centers

Summer '03

Center For Nanophase Materials Sciences at ORNL

Spring '05

Center For Functional Nanomaterials at BNL

Spring '04

Molecular Foundry at LBNL

Spring '04

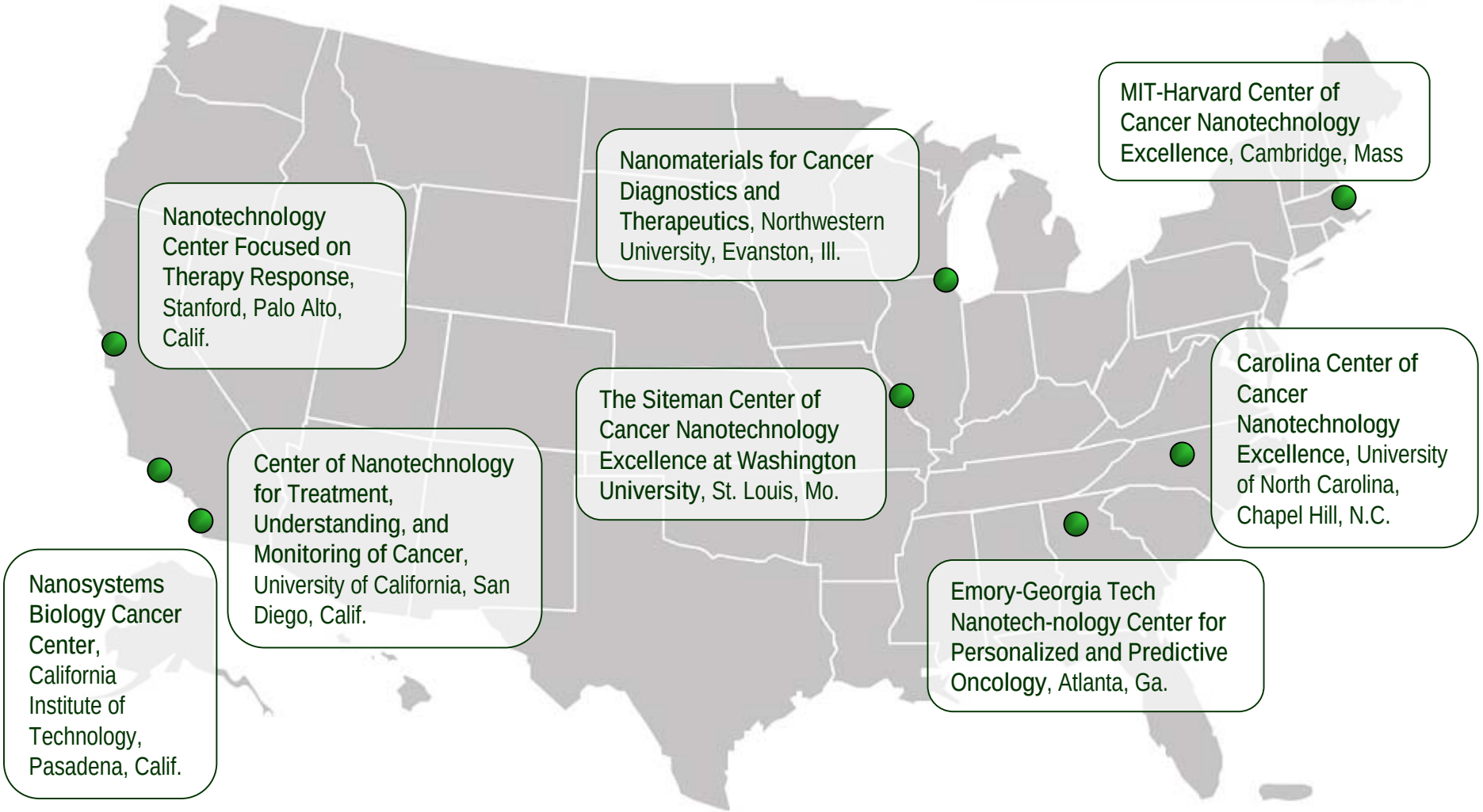
Center for Nanoscale Materials at Argonne

Spring '04

Center for Integrated Nanotechnologies

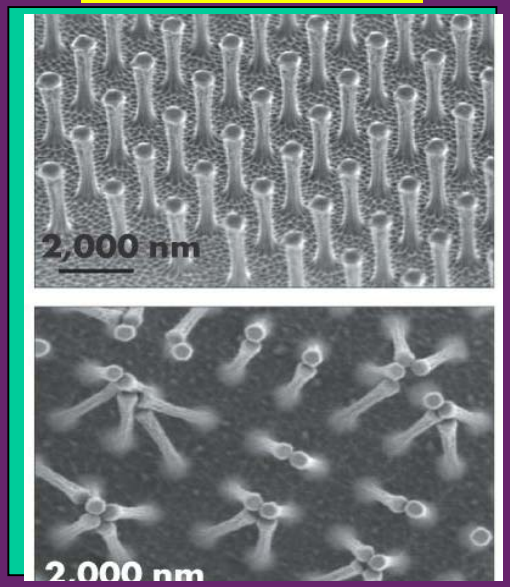
Cancer Centers of Nanotechnology Excellence (8 established in October 2005)

NCI Alliance for Nanotechnology in Cancer



Nanotechnology Informal Science Education Network

Center for
NISE Research
Exploratorium
San Francisco



- **Visualization Lab**
- **Resource Center**
- **Research and Evaluation**
- **Professional Development**
- **Public Website**

Center for Public
Engagement
Museum of Science
Boston

- **Network Media**
- **Forums**
- **Network Administration**

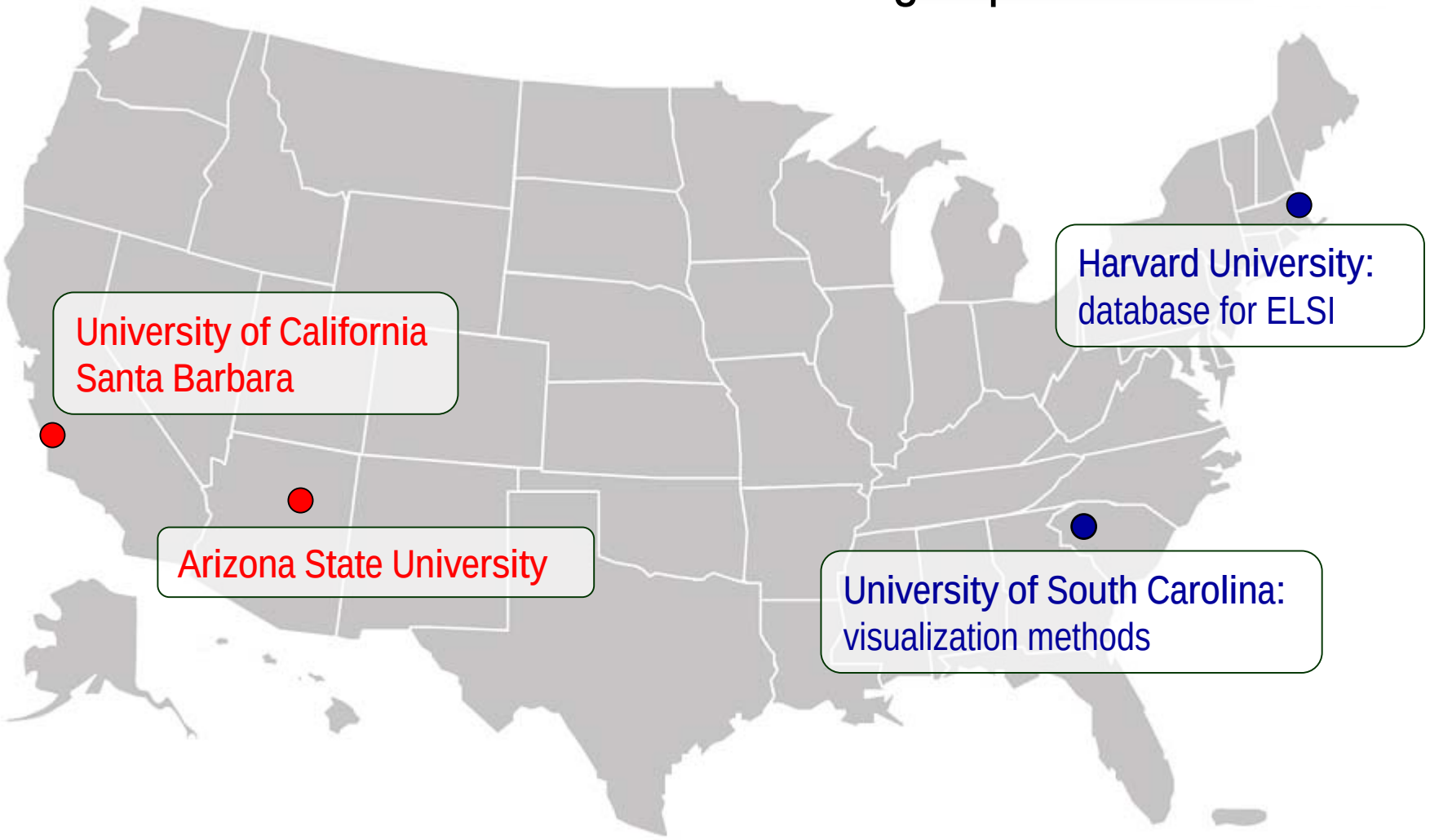
Center for
Exhibits & Programs
Science Museum of
Minnesota

- **Exhibit and Program Packages**

NSEC: Nanotechnology in Society

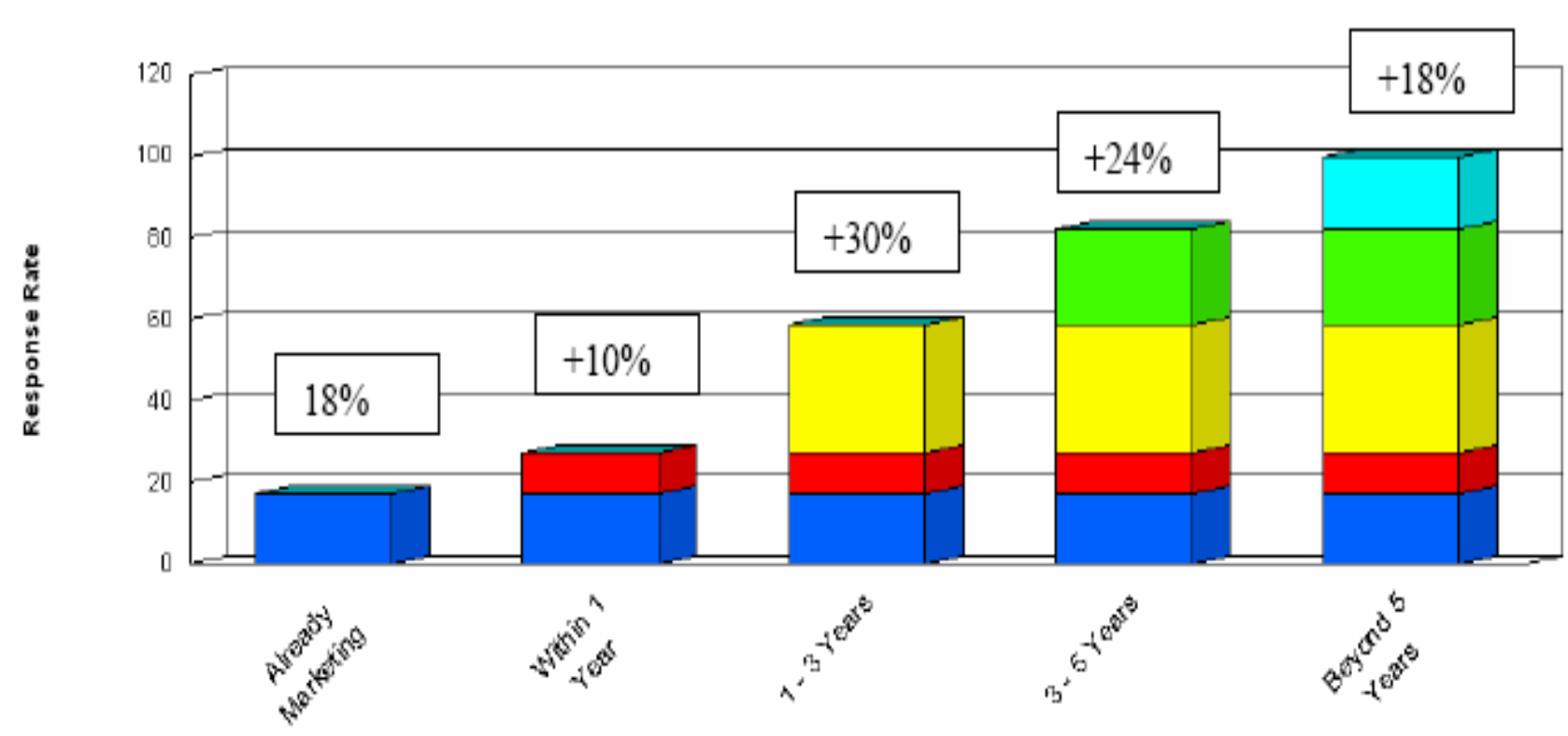
Four nodes established in September 2005:

● 2 centers and ● 2 small-groups



To address Ethical, Legal and other Social Issues related to Nanotechnology

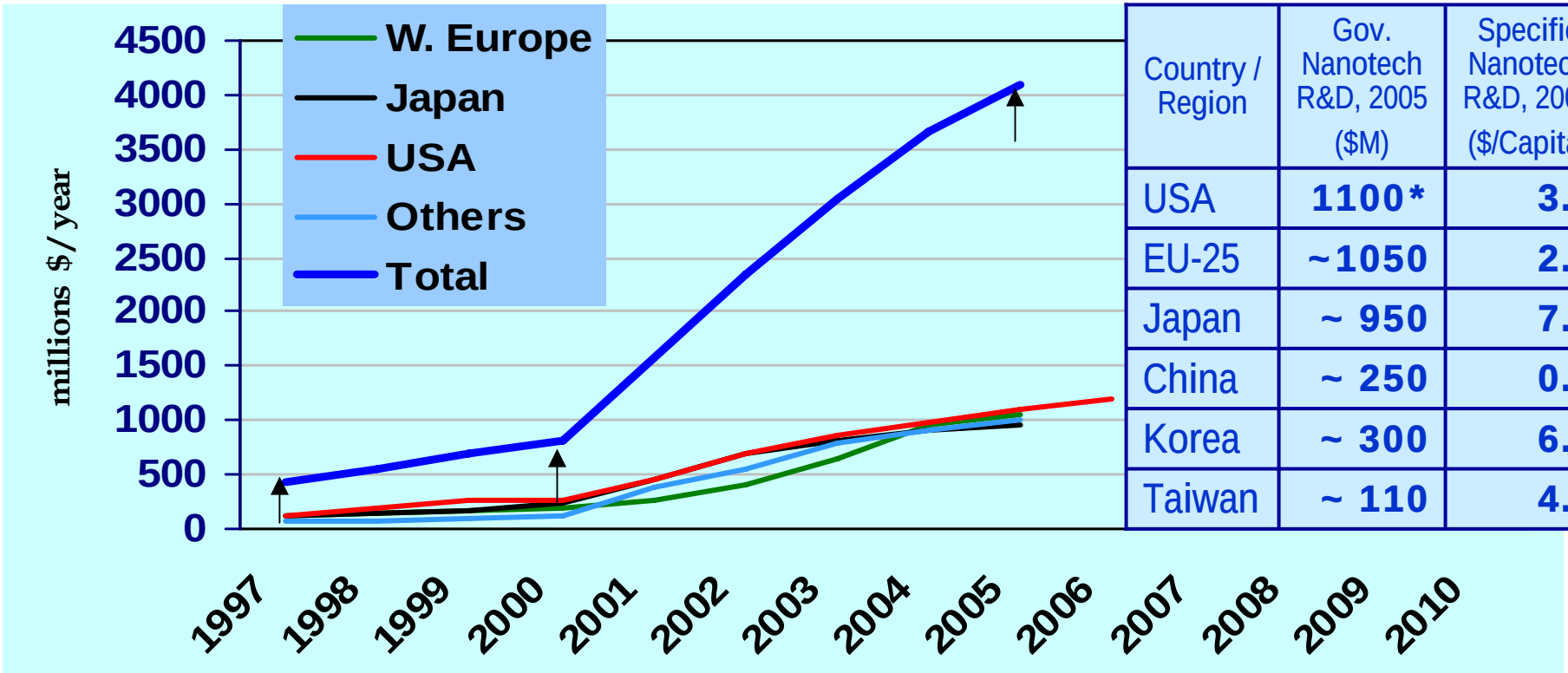
2005 NCMS Survey on nanotechnology in manufacturing industry (594 companies)



Commercialization timelines indicate many new nanoproducts introductions in 2007-2011, and the high level of expectation in long-term (Jan 2006)

Context – Nanotechnology in the World

Past government investments 1997-2005 (est. NSF)



Country / Region	Gov. Nanotech R&D, 2005 ($M)	Specific Nanotech R&D, 2004 ($/Capita)
USA	1100*	3.7
EU-25	~1050	2.3
Japan	~ 950	7.4
China	~ 250	0.2
Korea	~ 300	6.2
Taiwan	~ 110	4.7

Seed funding (1991 -)

NNI Preparation (vision / benchmark)

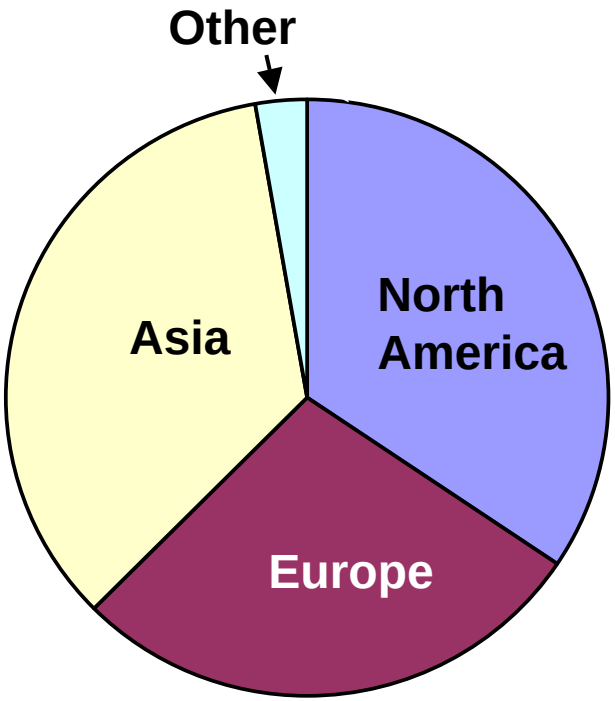
1st Strategic Plan (passive nanostructures)

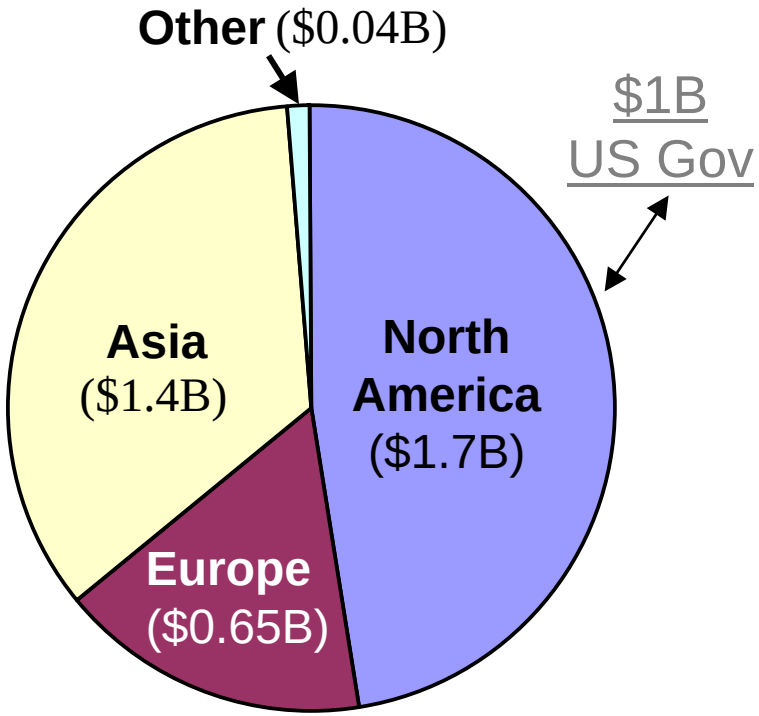
2nd Strategic Plan (active ns. & systems)

Total government expenditure in FY 2005 – about $4.1 billion

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

Where do we stand?
Global R&D investments in 2004 (Total = $8.6 billion)





Public (National, regional, state)

Focused on long-term research

Total = $4.6 B

(less than $0.5 B in 1997, NSF survey)

Private (Corporate + VC)

Focused on 1st Gen. R&D applications

Total = $4 B (Lux Research)

(less than $0.1 B in 1997)

Source: Lux Research & NSF

Comprehensive national programs on nanoscience and nanotechnology (over $100M/yr)

Begins national interagency planning

Begins funding for societal implications

Preparation of NNI

Broad definition, 10 year vision, worldwide study, investment plan

U.S. NNI
(announced January 2000)

Japan
(announced April 2001)

South Korea
(announced Nov. 2001)

EC-15
(March 2002)

Germany
(May 2002)

Taiwan
(Sept. 2002)

China
(2003)

UK
(July 03)

1996	1987	1988	1999	2000	2001	2002	2003

M.C. Roco,, 04/18/06

Technological Comparison

Europe, Japan, U.S.

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

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

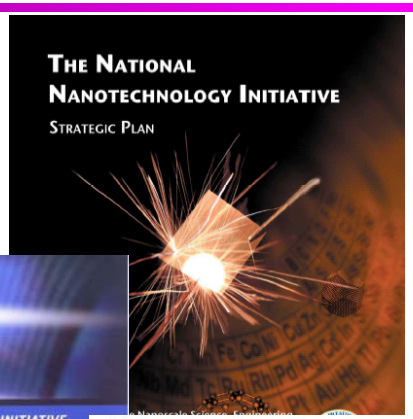
MC. Roco, 10/17/05

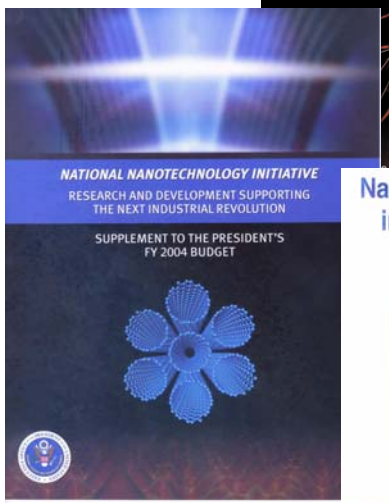
Defining the vision for the second strategic plan (II)

National Nanotechnology Initiative

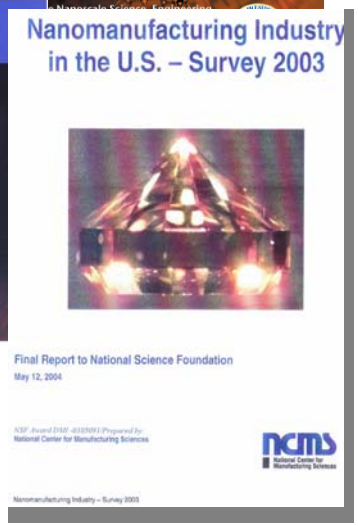
2006-2010

2004:
10-year
vision/plan



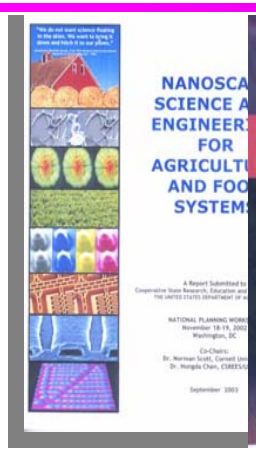


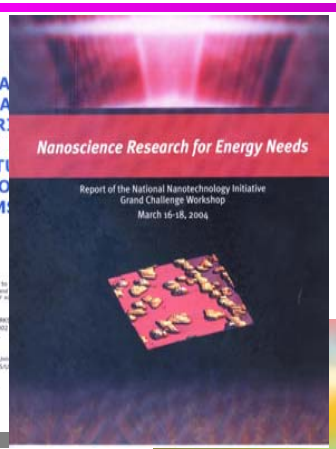
Government
Plan (annual)



Survey
manufacturing

Agriculture
and Food

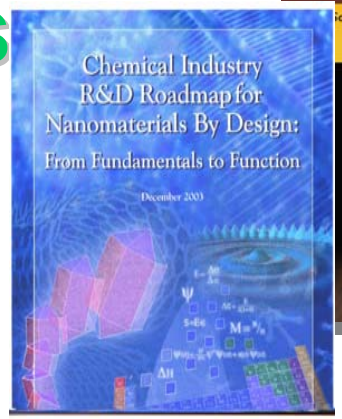




Energy

Societal
Implications
2004

Reports



Other topical reports
on www.nano.gov

Dec. 2004: <u>Update 10 year vision, and develop strategic plan</u>

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

2005 **2015**

Nanoscale visualization and simulation of 3D/m domains

= Micro domains with atomic space and chemistry time resolution

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: artificial organs, 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**
- **Water filtration and desalinization based on nano**
- **Nano-shop: 3d building at the nanoscale**
- **Nano-biomedicine: towards artificial organs**
- **Nano-informatics: libraries for integrating databases**

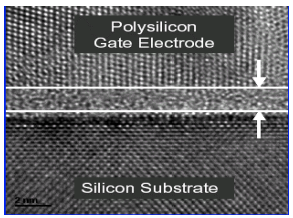
Challenge 2015: Transistor beyond/integrated CMOS under 10 nm

- In the 70s, 80s and 90s

  Geometrical scaling was the major driver

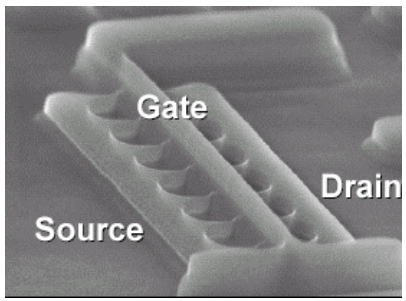
- In the 2003 - 2012 period (industry target)

  Use of novel physical phenomena to extend performance by equivalent scaling are the major drivers. Examples (2004):



1.2 nm gate oxide is ~5 Silicon atom layers thick

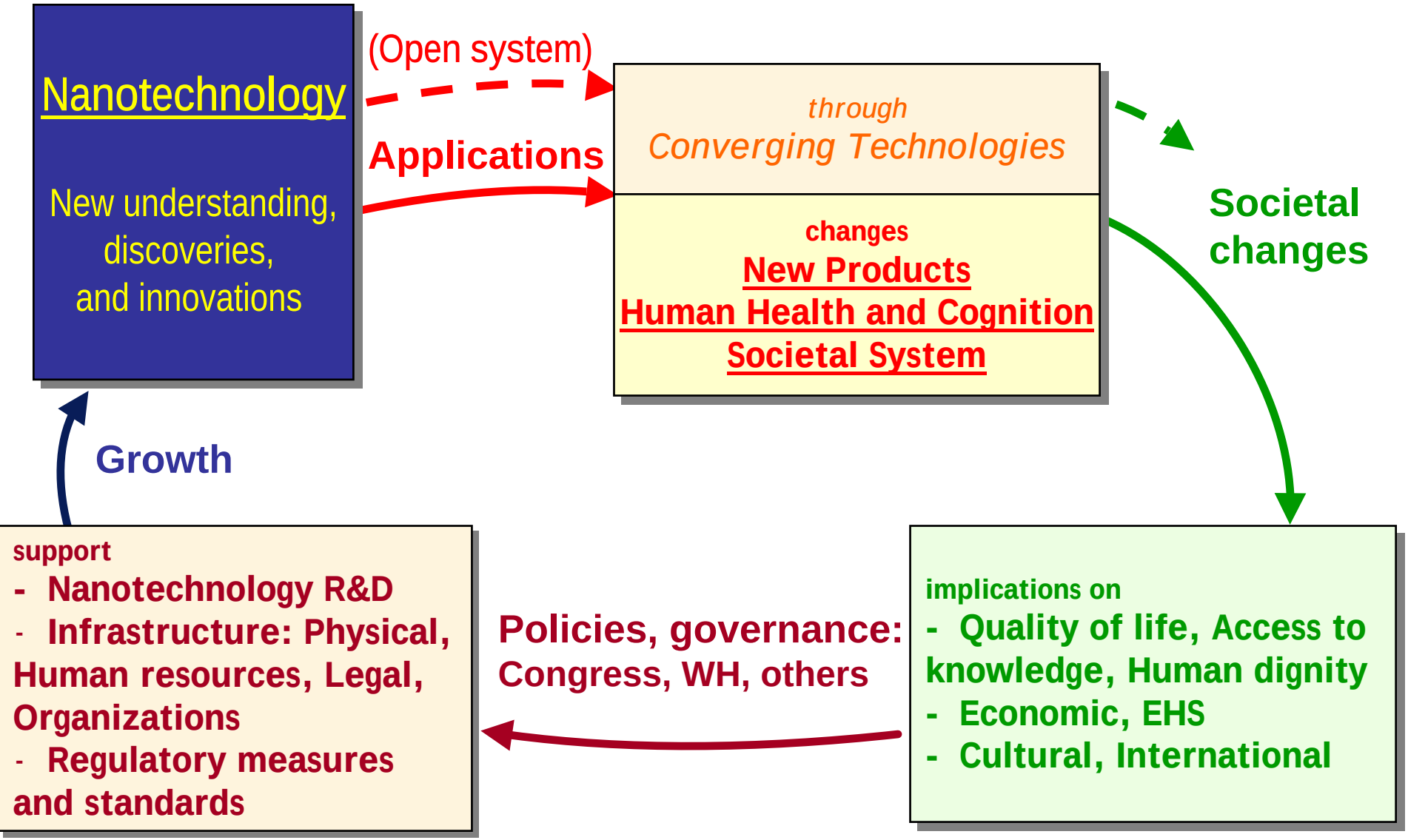
"Strained Silicon" - Separating the Silicon Atoms for Faster Electron Flow



Tri-gate Transistor

In addition, to explore beyond CMOS:

- **New carriers instead of electron charge**
- Integrate CMOS with other nanodevices; non-equilibrium
- New system architectures
- Integration with applications



Nanotechnology in Society

J. Nanoparticle Research, 7(2), 2005

Transforming and Responsible development of nanotechnology

Reaching at the building blocks of matter for all manmade and living systems, with the nanotechnology platform - makes transforming tools more powerful and unintended consequences more important than for other technologies

Besides the immediate and continuing societal implication issues, the long-term concerns must be addressed

There is a need for an anticipatory and corrective approach in

- **planning, to be both transforming and responsible**
- **in addressing societal implications for each major R&D program or project from the beginning**
- **risk governance at national and international levels**