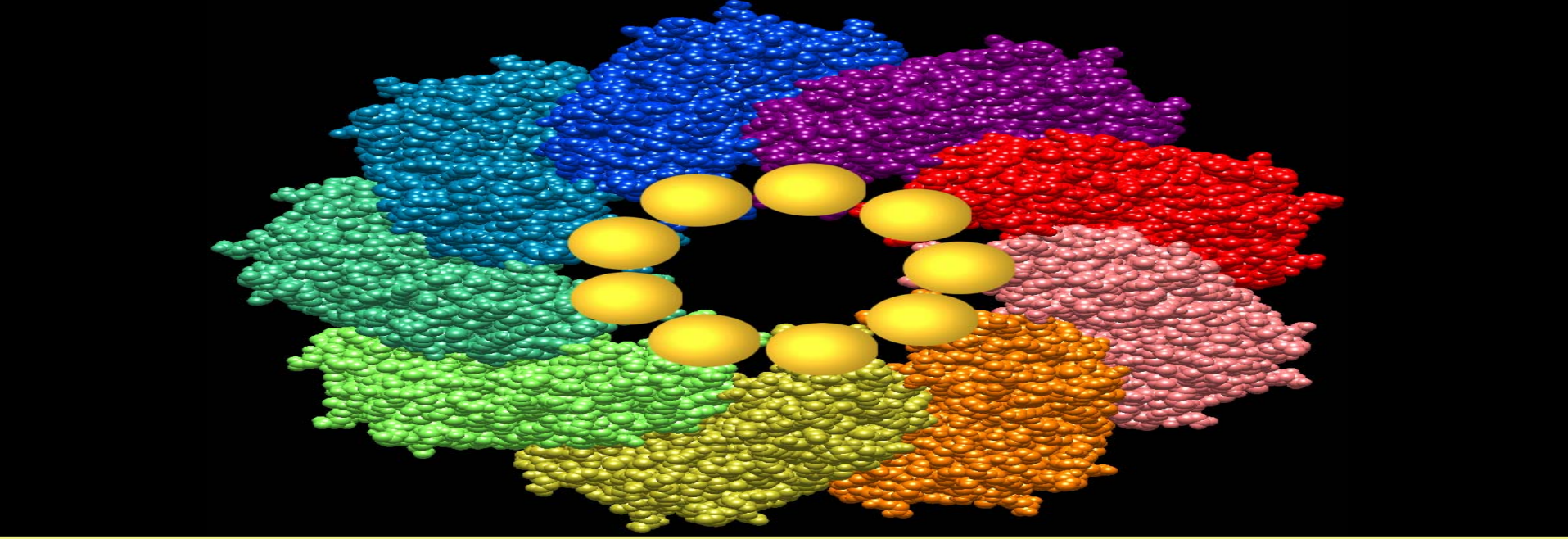


Industries of the 21st Century and Beyond

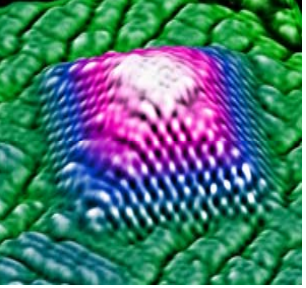
Nanotechnology

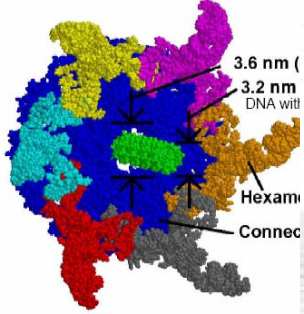
M.C. Roco

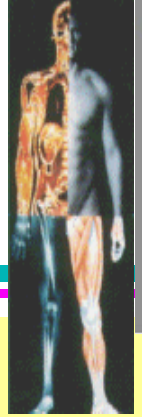
National Science Foundation and

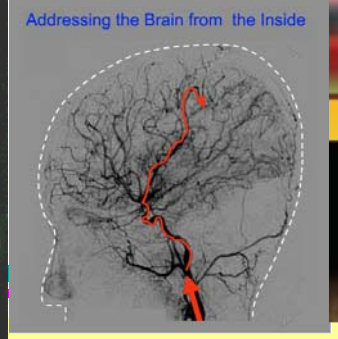
National Nanotechnology Initiative

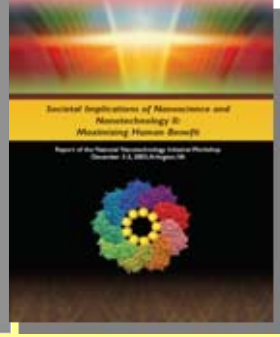
New York, November 2006











TOPICS

A. What is nanotechnology and why it is important?

From new phenomena and structures to applications

B. Four generations of nanotechnology products

Outlook 2000-2020

C. NNI in the international context

New technological and medical frontiers

D. Societal dimensions: benefits and risks

EHS: new findings, standards and regulations,
Education and training
Governance of nanotechnology development

Benchmark

"Nanostructure S&T"

Book Springer, 1999

Part A
WHAT IS NANOTECHNOLOGY
(definition based on international benchmark since 2000)

- **Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure (see http://nano.gov)**

- NNI definition encourages new R&D 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, and restructure matter*** *at the nanoscale* in order to change those properties and functions
  - ***integration along length scales, systems and applications***

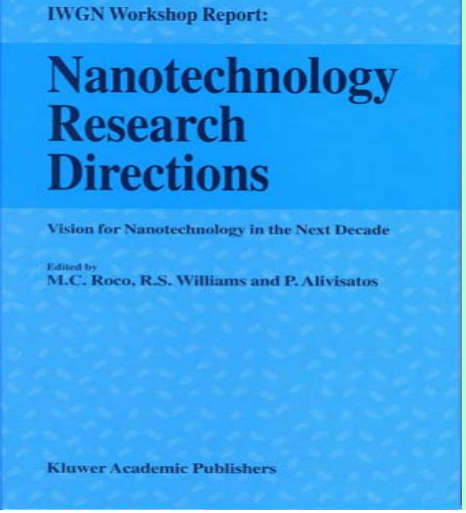
In short

Nanotechnology

is the ***control and restructuring of matter*** at dimensions of roughly 1 to 100 nanometers,

where new phenomena

enable new applications.



WHAT IS SPECIAL ABOUT NANOTECHNOLOGY?

General drivers defined in 2000

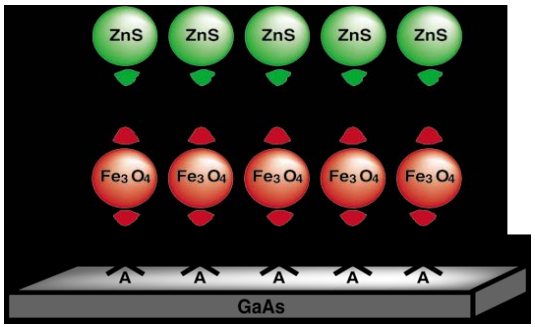
- **Reaches at the basic level of organization of atoms and molecules**, where properties/functions of manmade and living systems are defined

- **Broad technology platform** for industry, biomedicine and environment, with significant societal implications

- **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

Scales: Expanding the limits of knowledge and action

Nanoworld
- natural threshold to atoms / molecules collective behavior



1 to 100 nm

Lowest Limit for Manufacturing

~ 1 m
Human
Scale

Outer space

Over 10,000 km

Highest Limit for Satellites Flight

Smallest Known Size

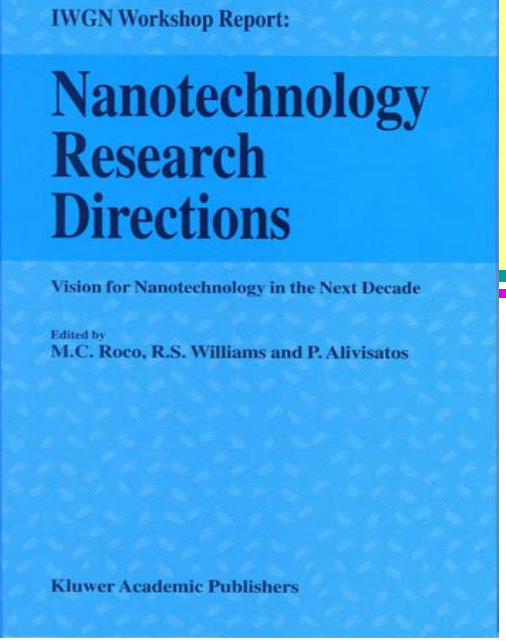
10^{-7}

10^{7}

Largest Known Size

10^{-27}

10^{27}



Why moving into nanoworld ?

A. Intellectual Drive

Miniaturization is of interest

Less space, faster, less material, less energy

More important:

- Novel properties/ phenomena/ processes
- Unity and generality
- Most efficient length scale for manufacturing
- Transcendent effects: at the confluence of steams

B. Broad societal implications
(Ex: worldwide estimations made in 2000, NSF)

- **Knowledge base**: better comprehension of nature, life

- **New technologies and products: ~ $1 trillion/year by 2015**
  (With input from industry US, Japan, Europe 1997-2000, access to leading experts)

  Materials beyond chemistry: $340B/y
  Pharmaceuticals: $180 B/y
  Aerospace about $70B/y
  Electronics: over $300B/y
  Chemicals (catalysts): $100B/y
  Tools ~ $22 B/y; Agric. and food

  Est. in 2000 (NSF) : about $40B for catalysts, GMR, materials, etc.; + 25%/yr
  Est. in 2002 (DB) : about $116B for materials, pharmaceuticals and chemicals

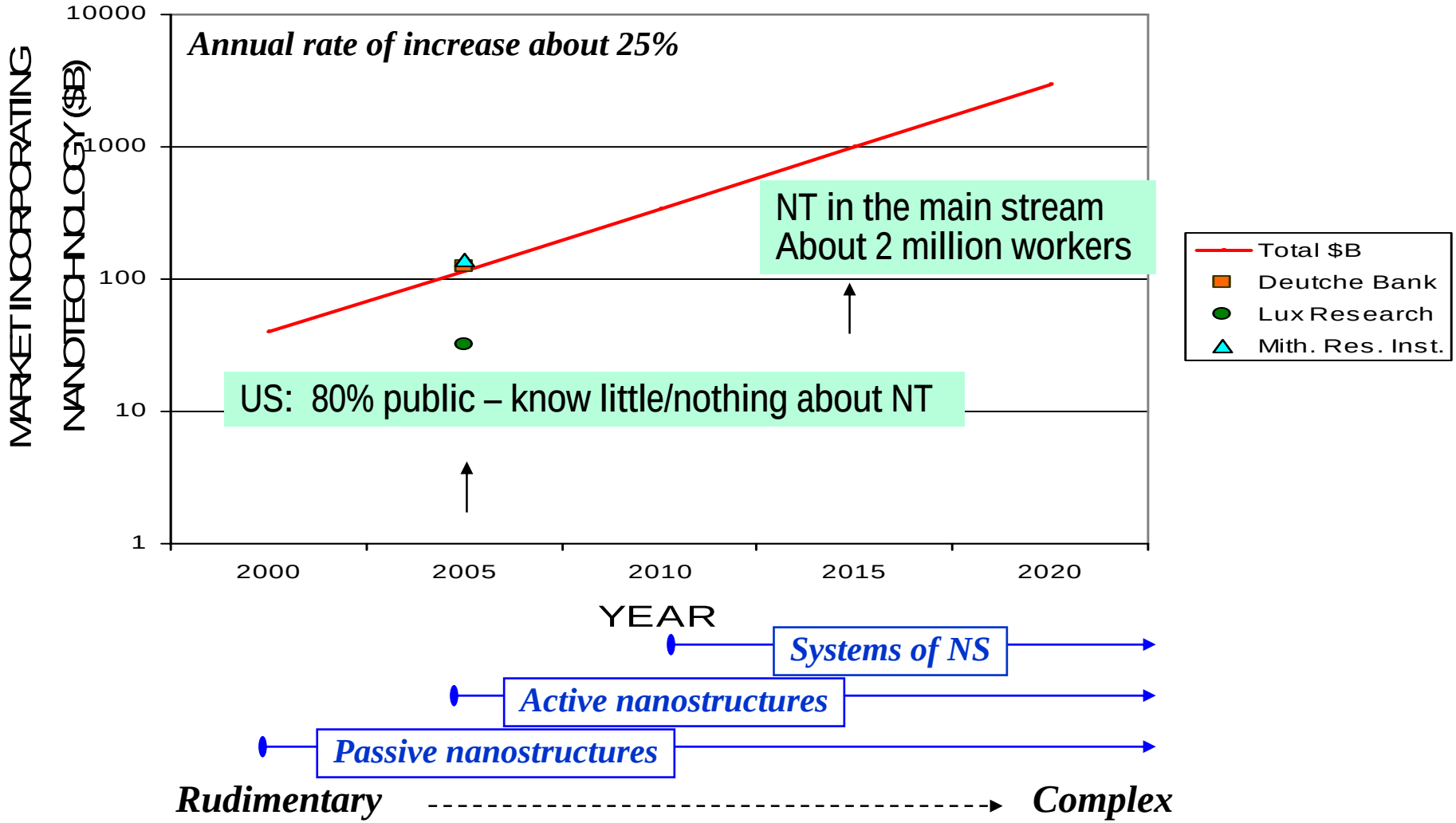
  Would require worldwide ~ 2 million nanotech workers (all ~7M)
  In U.S.: ~ 0.8 million (all with supporting jobs ~ 2.8 million)

- **Improved healthcare**: extend life-span, its quality, physical capabilities

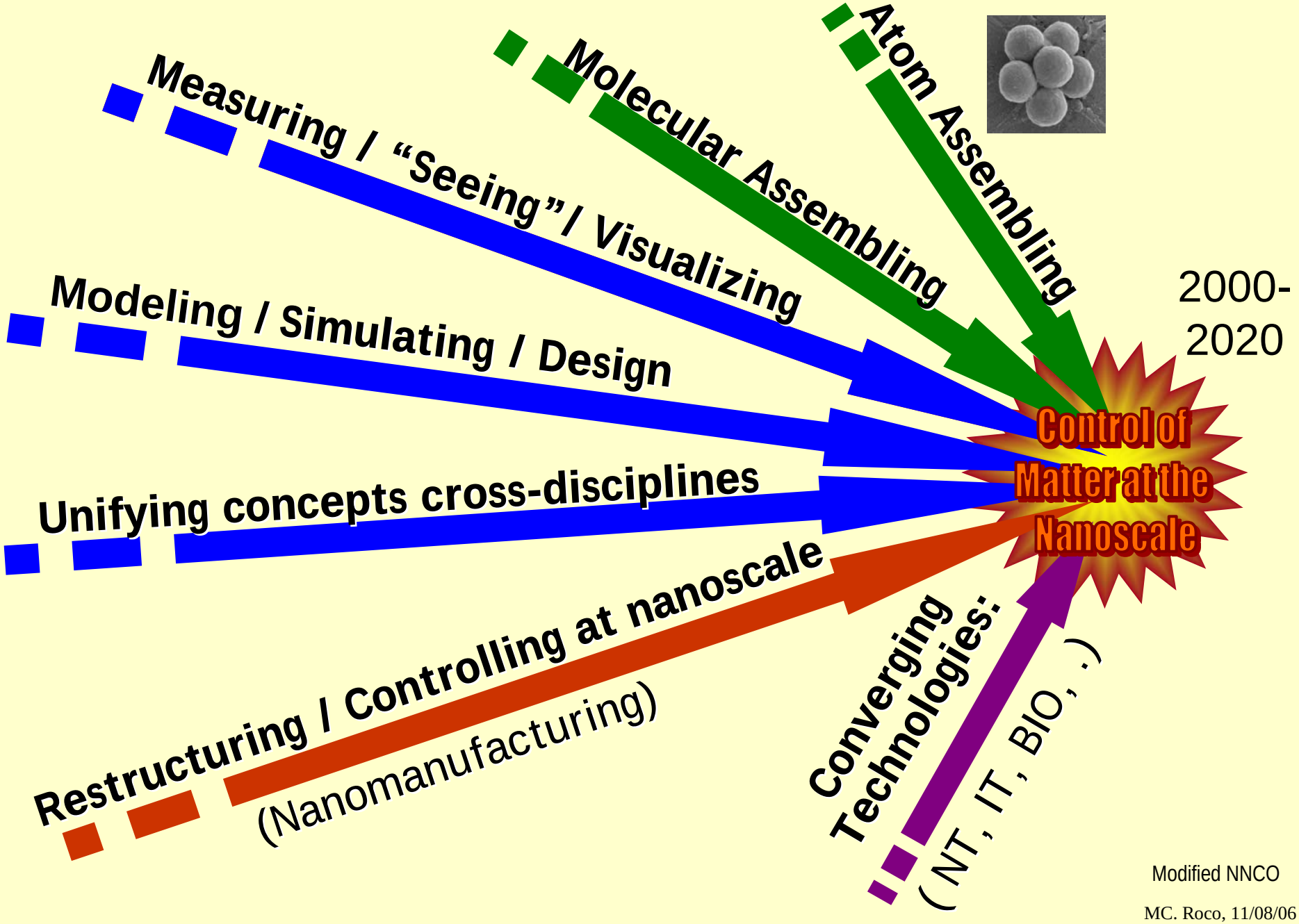
- **Sustainability**: agriculture, food, water, energy, materials, environment; ex: lighting energy reduction ~ 10% or **$100B/y; food - $60B/y by 2015**

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

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



C. Nanotechnology progress: *concurrence of capabilities*

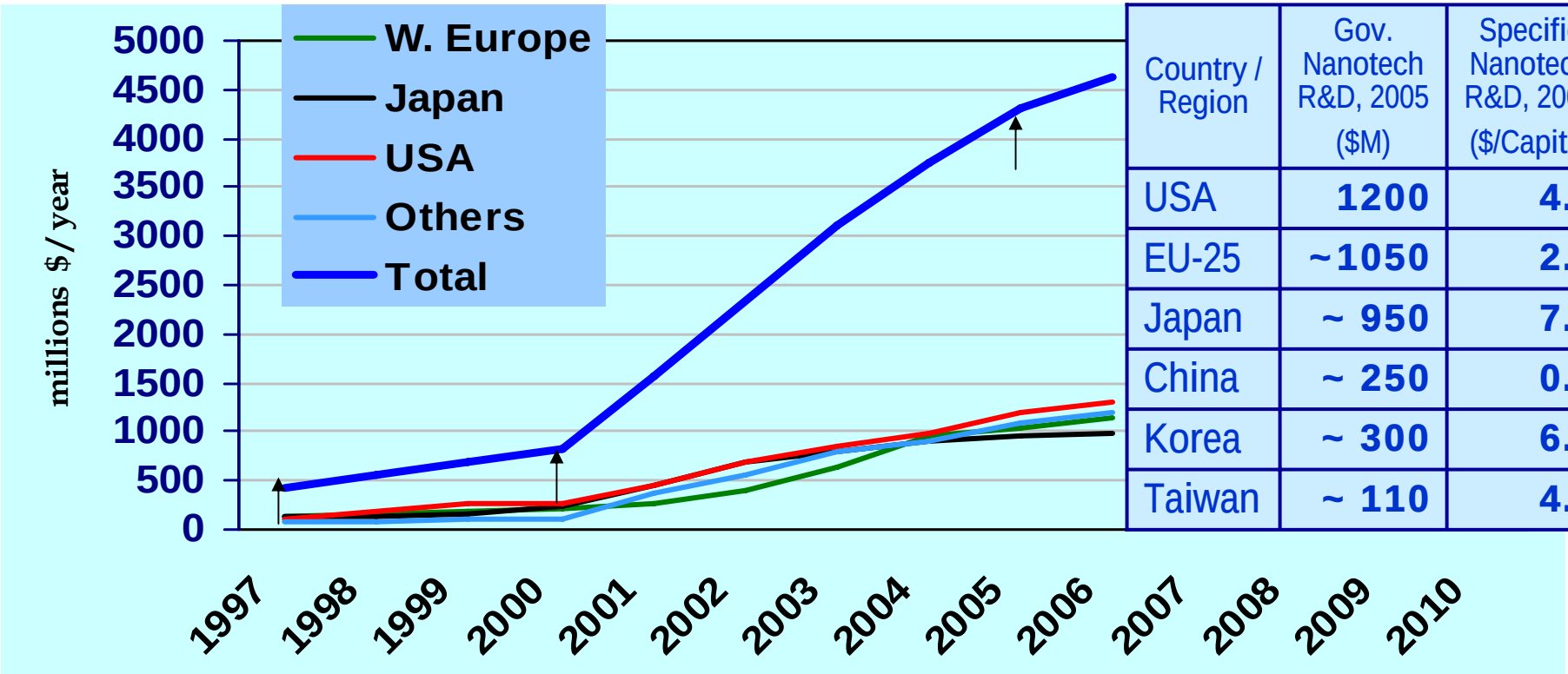


Modified NNCO

MC. Roco, 11/08/06

Context – Nanotechnology in the World

National government investments 1997-2006 (est. NSF)



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

Seed funding (1991 -)

NNI Preparation (vision / benchmark)

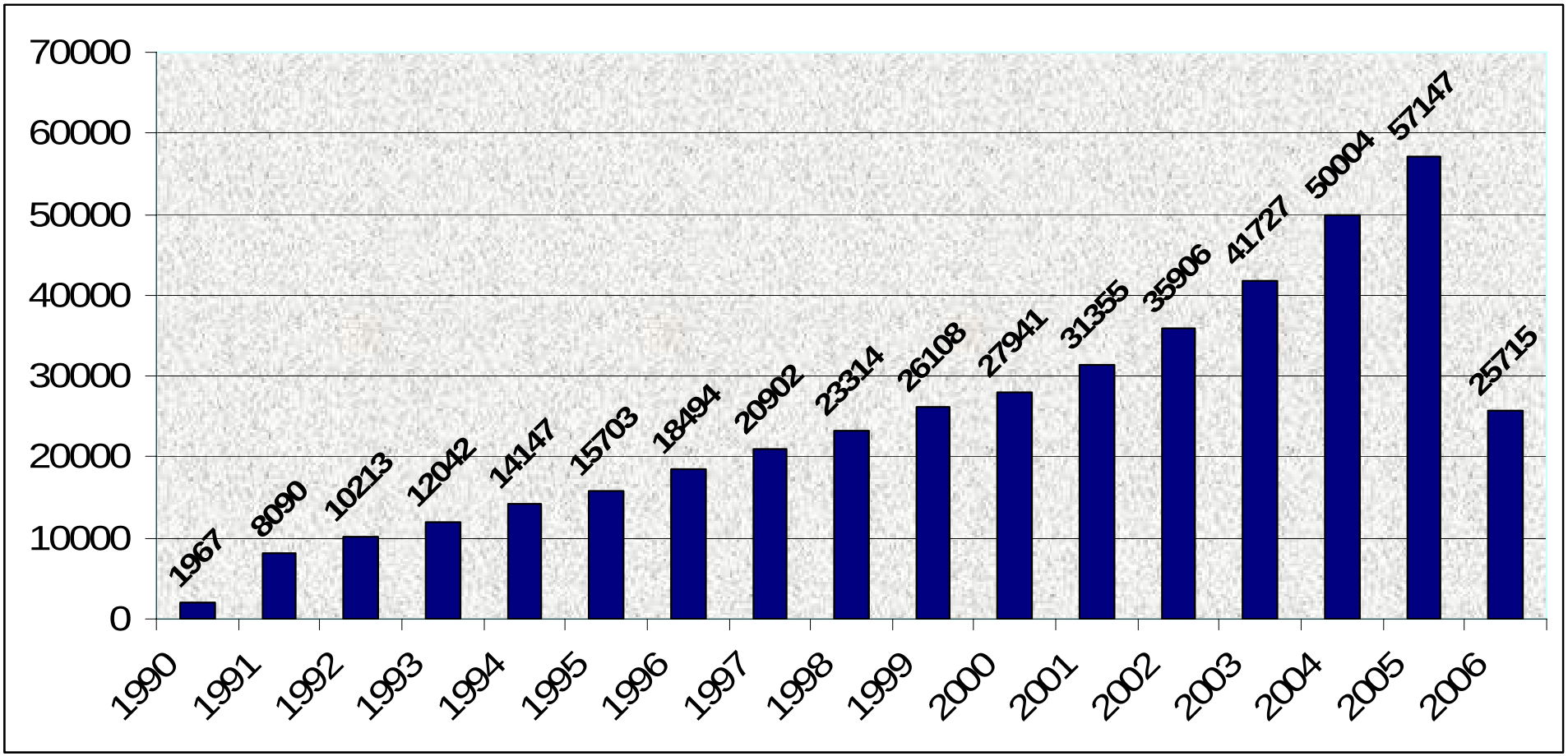
1st Strategic Plan (passive nanostructures)

2nd Strategic Plan (active ns. & systems)

Industry R&D ($5B) has exceeded national government R&D ($4.3B) in 2005

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

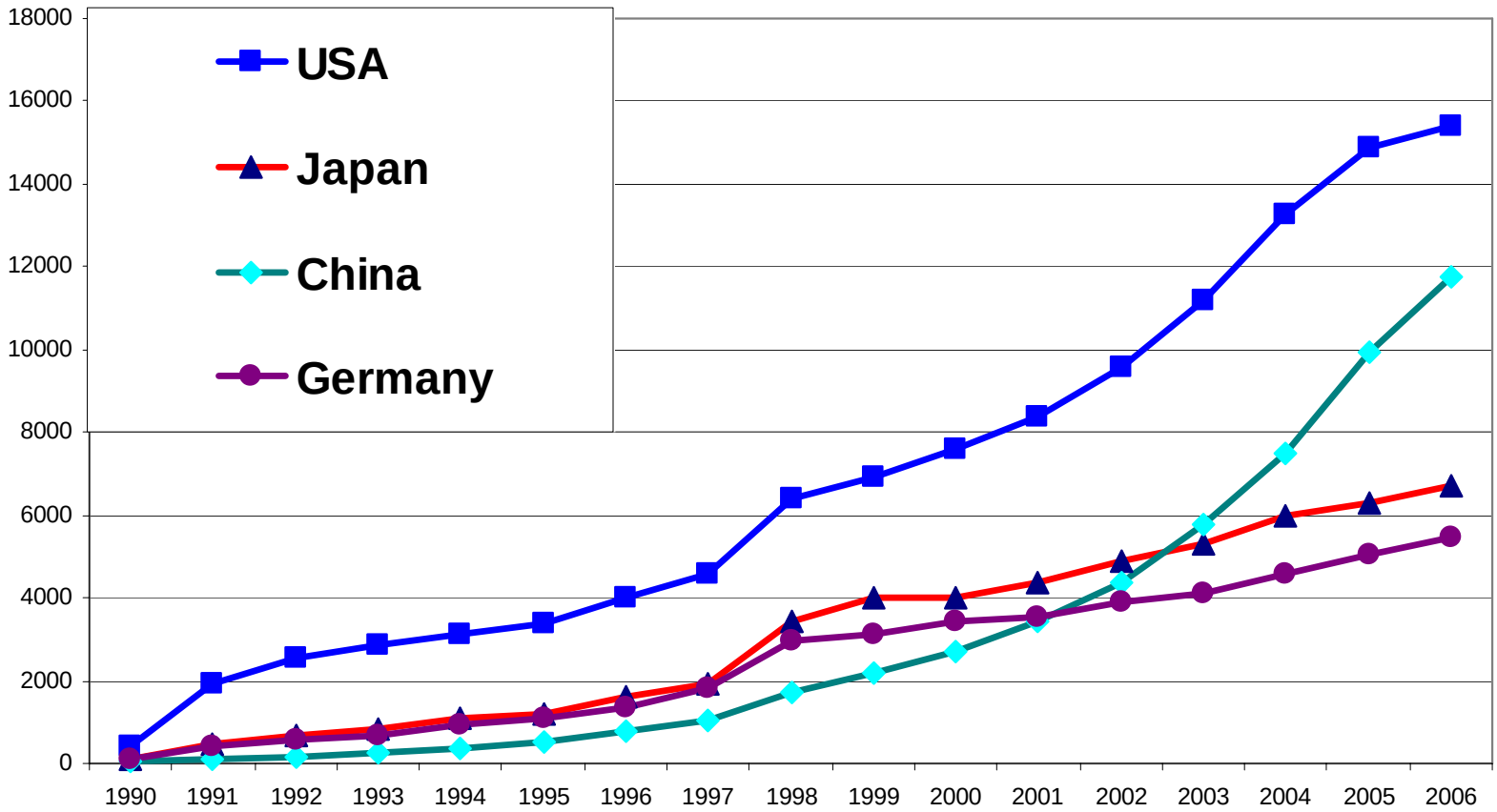
Nano Research Publications, 1990 – 2006 (August), from Web of Science – Science Citation Index



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

Nano publications per year

1990 - 2006 (estimated)



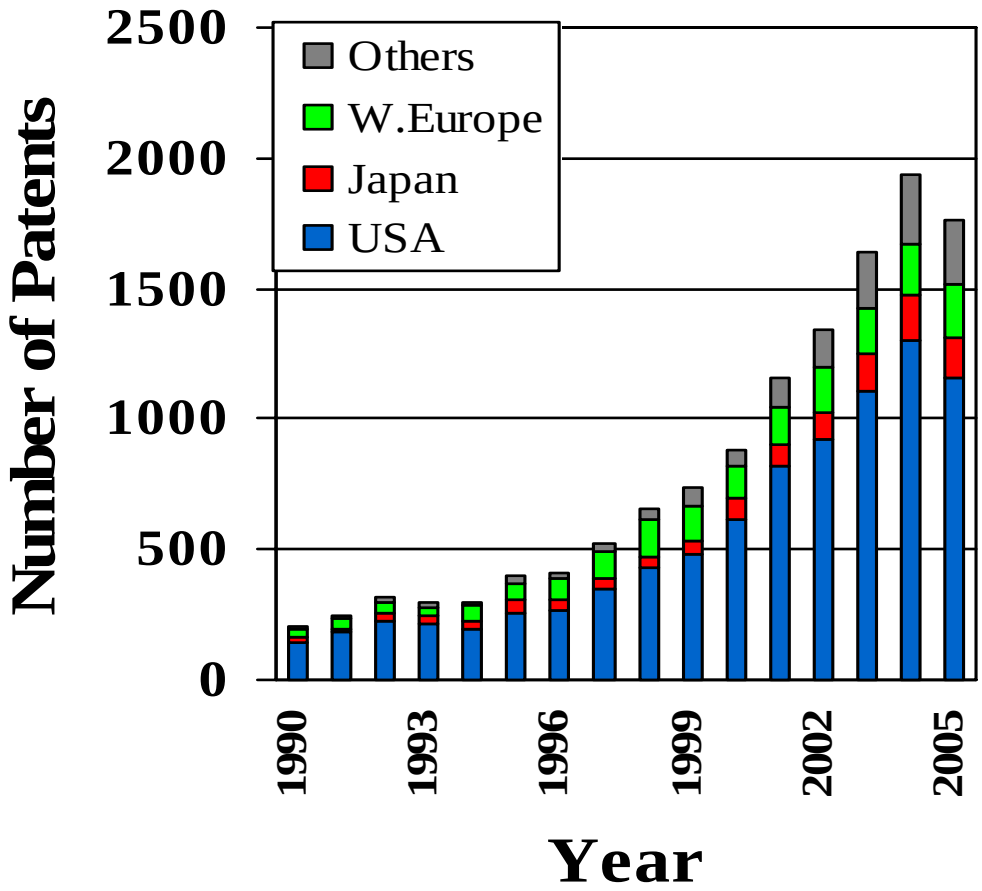
Courtesy: Georgia Tech TPAC / CNS-ASU Analysis of SCI Publication (August 2006)

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

using "Title-claims" search for nanotechnology by keywords

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

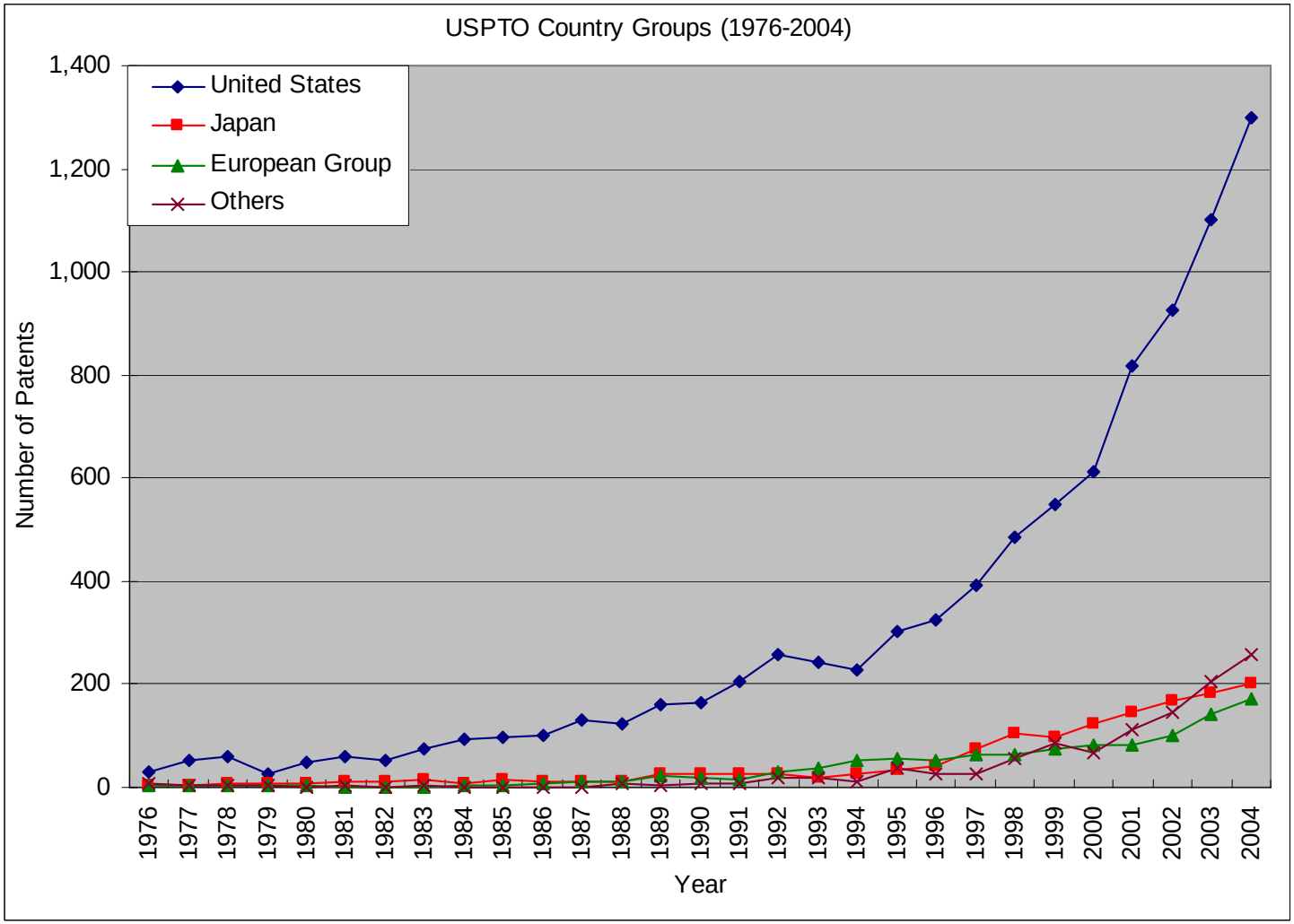
Using "Title-claims" search:
nanotechnology claims



MC. Roco

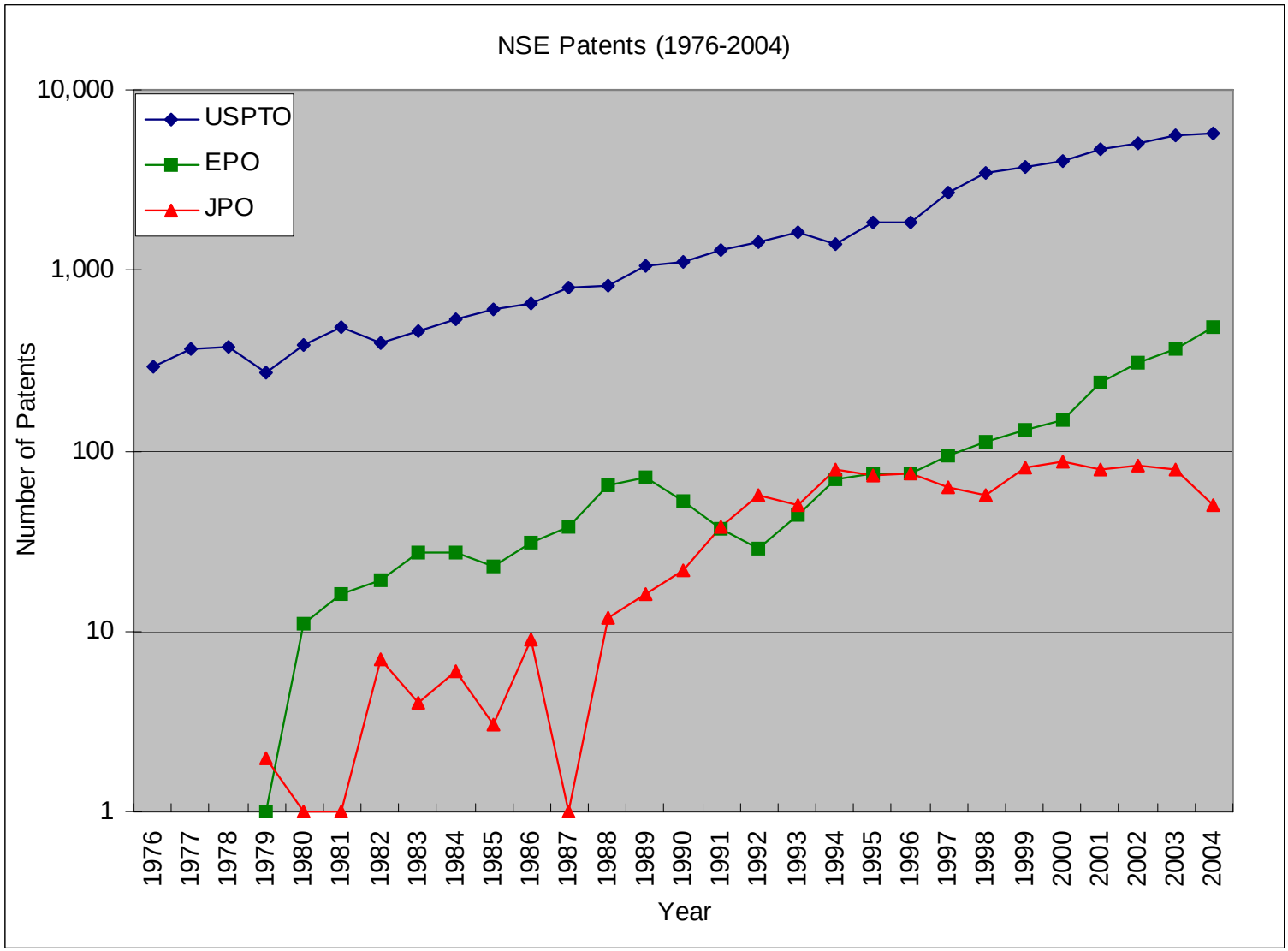
NSE patents at USPTO by country group

Assignee country group analysis by year, 1976-2004 **("title-claims" search)**



Year	United States	European Group	Japan	Others
1976	30	3	3	6
1977	53	3	2	3
1978	58	9	3	3
1979	26	7	2	3
1980	50	9	3	0
1981	61	10	1	3
1982	51	13	1	1
1983	73	15	1	4
1984	93	8	4	0
1985	97	16	2	1
1986	100	11	6	1
1987	132	11	12	0
1988	124	10	10	6
1989	162	28	21	4
1990	164	28	17	7
1991	204	28	14	9
1992	256	26	31	19
1993	244	20	36	18
1994	227	28	51	10
1995	302	33	57	36
1996	325	40	52	27
1997	393	73	62	25
1998	486	103	65	56
1999	548	96	75	85
2000	612	122	81	68
2001	818	147	84	112
2002	926	168	102	144
2003	1,103	182	143	207
2004	1,300	203	172	257
Total	9,018	1,450	1,113	1,115

2004 NSE patents ("title-claims" search) at USPTO (5706), EPO (480), and JPO (50)



	NSE Patents		
Year	USPTO	EPO	JPO
1976	291	0	0
1977	363	0	0
1978	372	0	0
1979	272	1	2
1980	386	11	1
1981	486	16	1
1982	396	19	7
1983	466	27	4
1984	535	27	6
1985	607	23	3
1986	663	31	9
1987	794	38	1
1988	822	64	12
1989	1,059	72	16
1990	1,113	53	22
1991	1,295	37	38
1992	1,445	29	56
1993	1,632	44	50
1994	1,402	69	79
1995	1,853	74	73
1996	1,866	74	74
1997	2,714	95	62
1998	3,430	113	57
1999	3,710	130	80
2000	3,985	147	86
2001	4,656	236	78
2002	5,104	310	83
2003	5,654	365	78
2004	5,706	480	50

Technological Comparison

Europe; Japan; U.S.

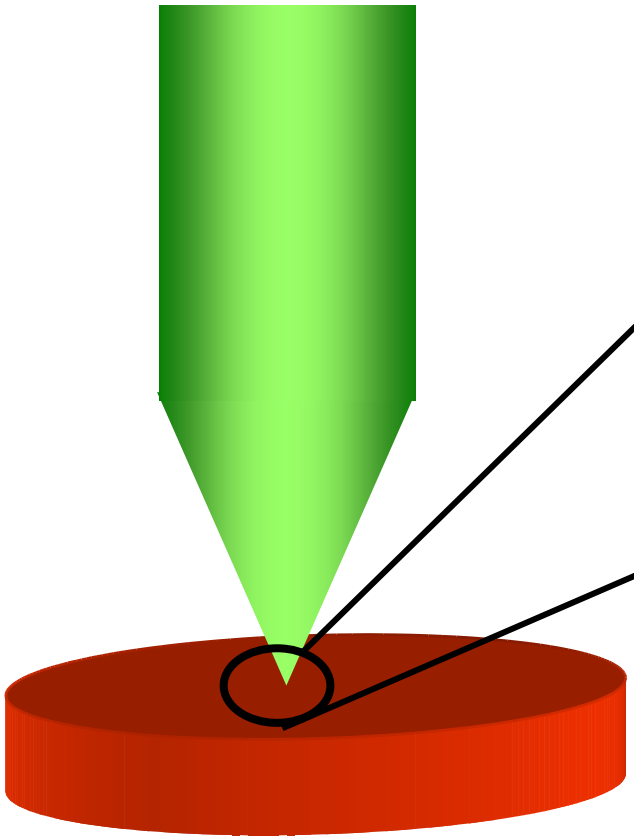
This is an extension in 2004 survey of the WTEC Nanotechnology Workshop's first evaluation in 1999

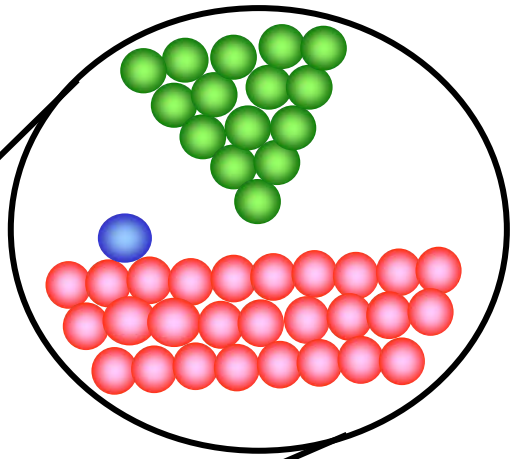
	1	2	3	
Synthesis & Assembly	U.S.	Europe	Japan	BASIC APPROACHES
Biological Approaches & Applications	U.S.	Europe	Japan	
Dispersions and Coatings	U.S./Eur	Japan		R&D for PRODUCTS 1st Generation
High Surface Area Materials	U.S.	Europe	Japan	
Consolidated Materials	Japan	U.S./Eur		
Nanodevices	Japan	U.S./Eur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

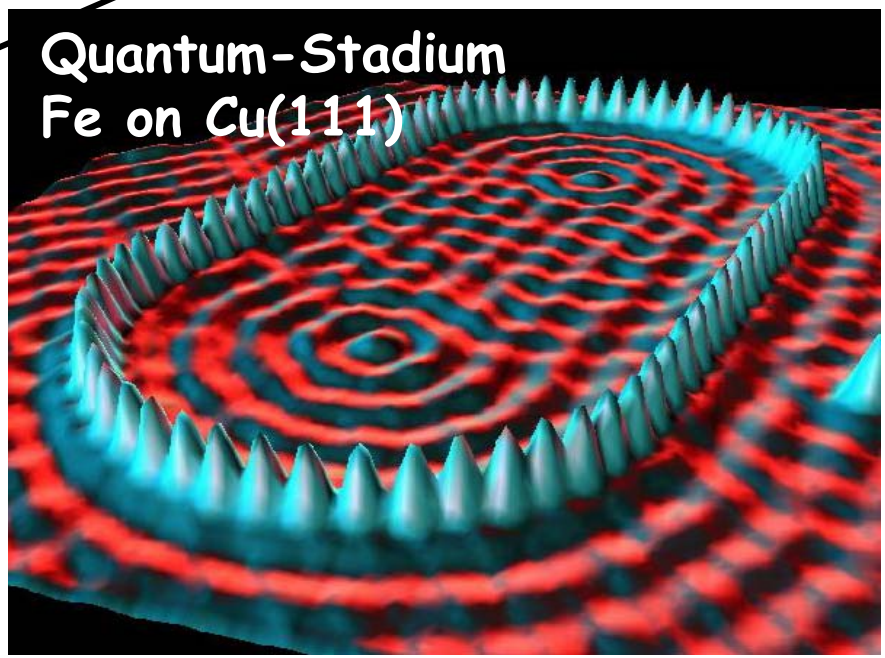
MC. Roco, J. Nanoparticle Research, Vol. 7(6), 2005

Nanotools – key challenge for advancing NT

Scanning Tunneling Microscope







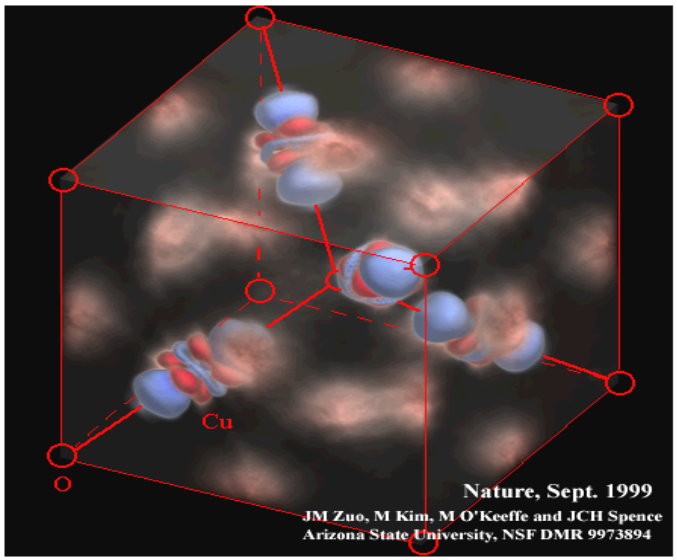
(IBM - Zurich, 1981)

(Point average, slow)

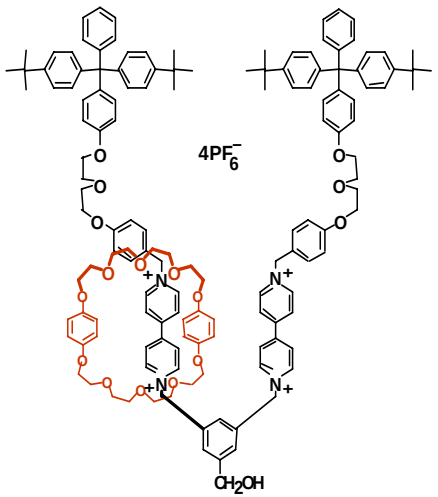
Courtesy: IBM Almaden Lab

“Nanotechnology Research Directions” – the vision
Examples of nanostructures identified in 1999

(a) One nanometer structures

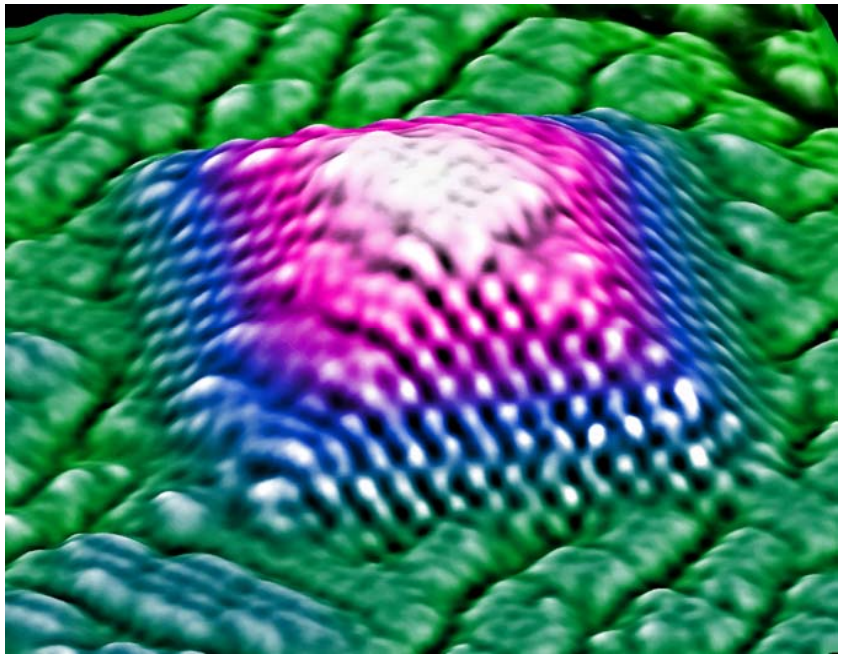


Electron orbitals have been directly observed (L ~ 1nm). For understanding molecular assembling (ASU, 1999)

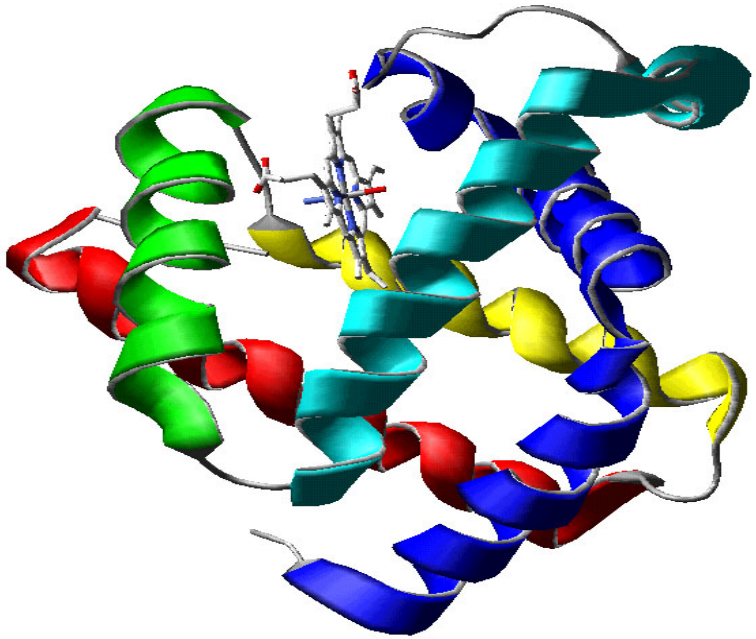


Molecular logic: switches (size ~ 1 nm) (HP, UCLA, Yale, 1999)

(b) 10 nanometer structures

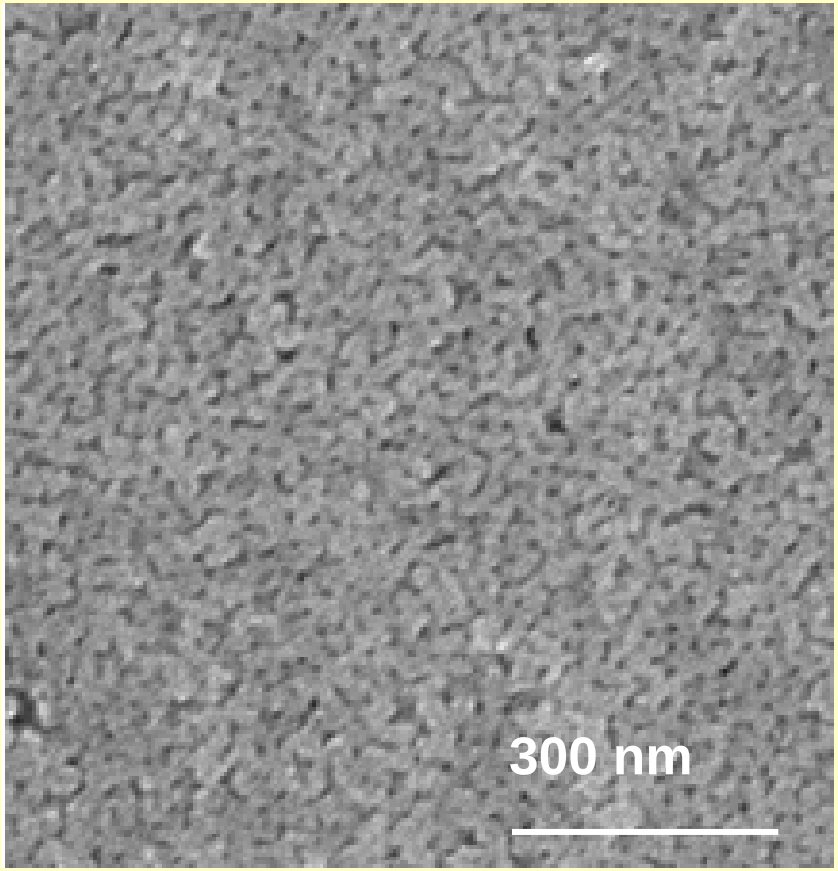


Quantum dot - self-assembled Germanium pyramid (HP, 1999)



Proteins - fold into precisely defined three-dimensional structures (Cornell, 1999)

Example in 2001: **Hypersonic plasma 20 nm particle deposition for hard coatings and patterning on surfaces** (S. Girshick, University of Minnesota)

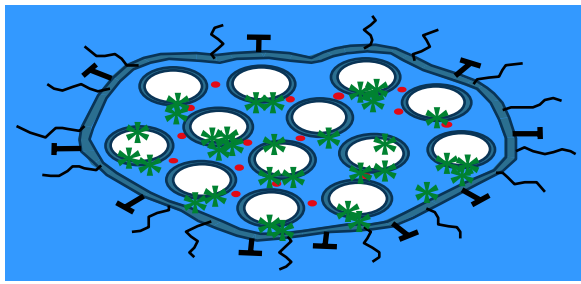


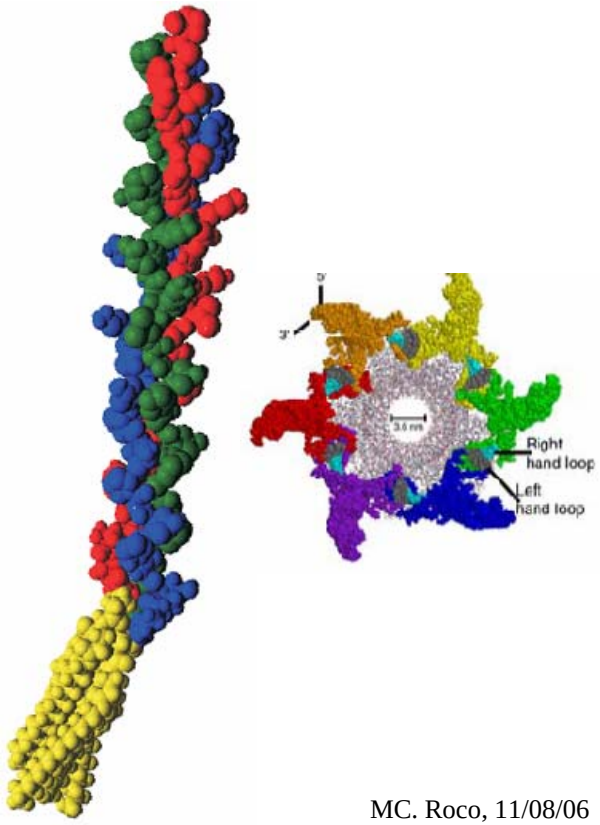
Examples in 2004:

Synthesis and control of nanomachines

(NSF awards, www.nseresearch.org - 350 projects)

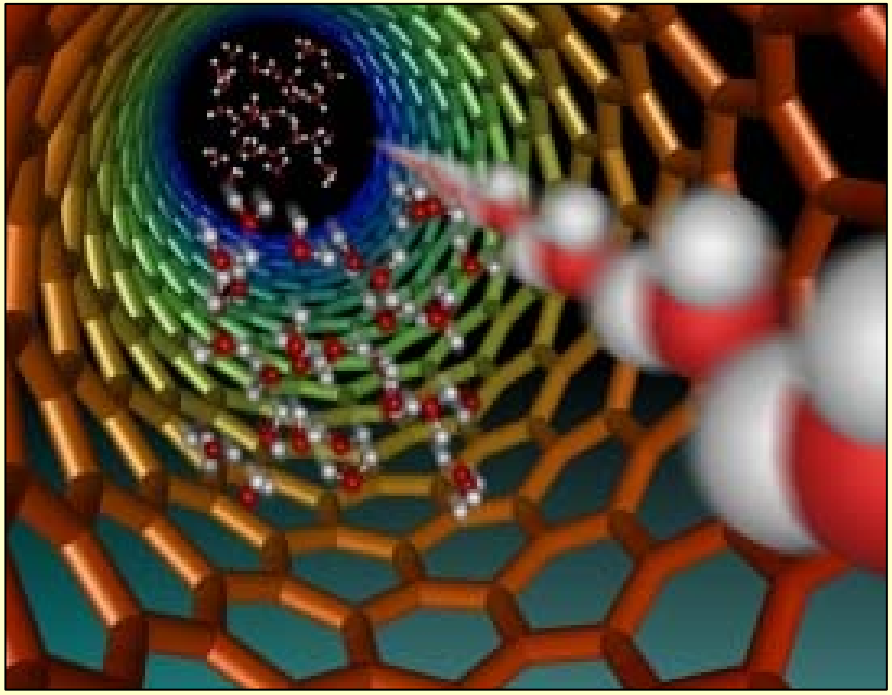
- **Self-assembly processing** of nanoscale bio-materials and devices for micromachines components (UCSB)
- Chemistry to synthesize components of **nano machines to work on surfaces** and b activated by external electromagnetic fields (UCB)
- **Light driven molecular motors** (U. Nevada)
- **Combinatorial engineering of nanomachi** with application to membranes and filters (U. Penn.
- **Nanoengineering surfaces** for probing viral adhesion (UC Davis)





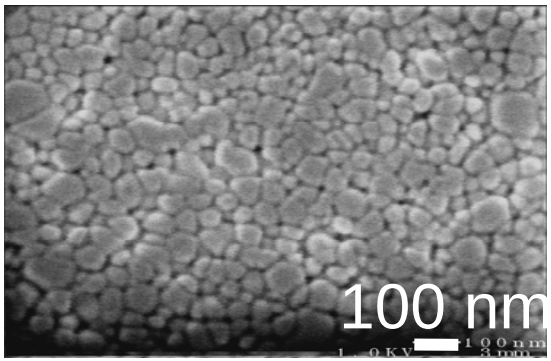
Example new properties (2006):

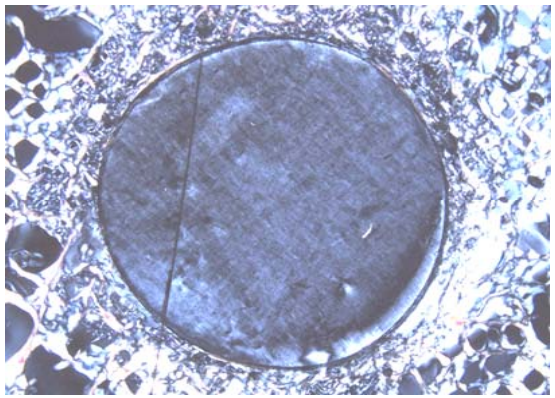
Novel Membranes Researchers at the University of Kentucky have fabricated membranes from billions of aligned carbon nanotubes. The surfaces of the membranes are almost friction-free. The theory has been verified in the same year by SNL



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

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

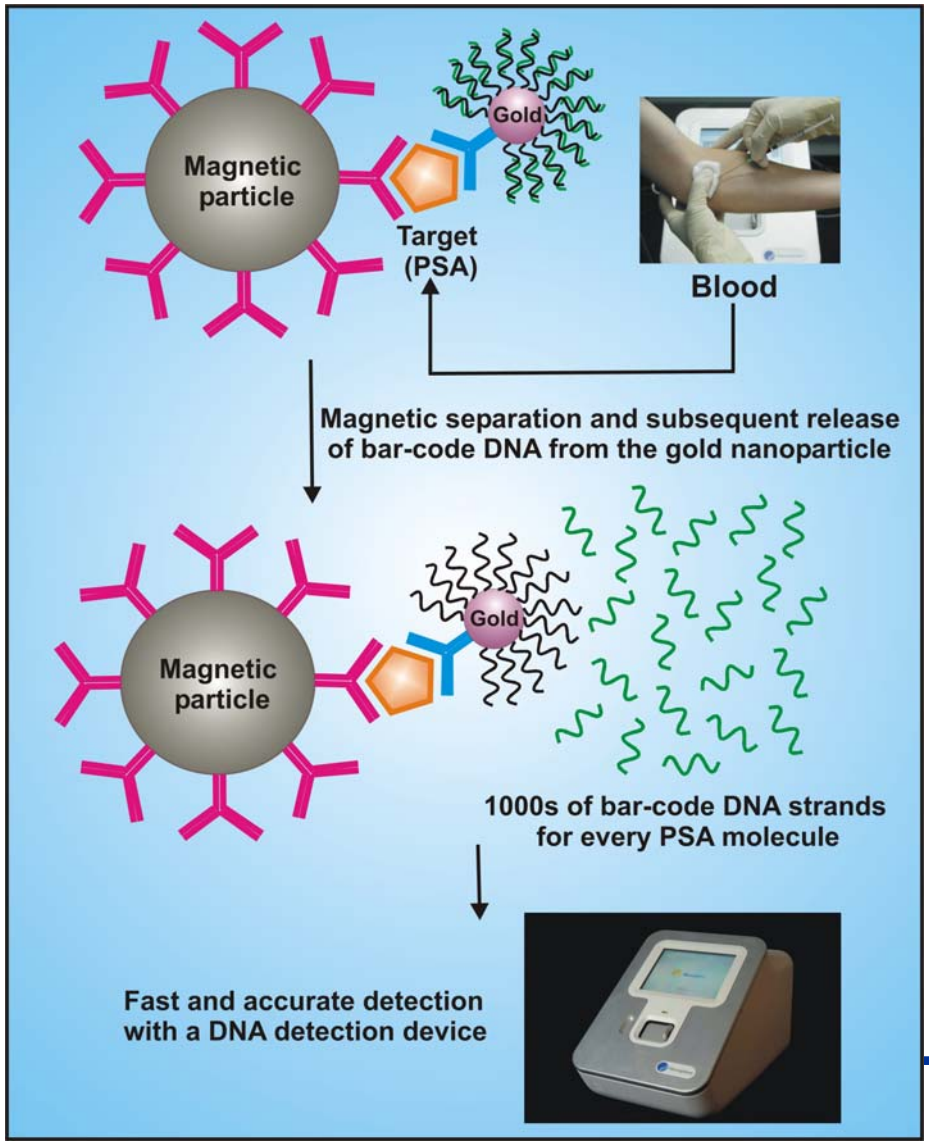
Bone bonding in 2 weeks and osteointegration in 4 weeks because the nanostructure closely match that found in human bone

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

The product received "marketing clearance" from FDA in 2005

Example: NanoBio-Bar-Code Assay,

Chad Mirkin (Northwestern U. and spin-off Nanosphere, Inc.)



1. **One million times more sensitive than previous technology**
2. **Evaluate new biomarkers for diagnosing and following human diseases (e.g. HIV and Alzheimer's Disease).**
3. **Single-cell protein expression experiments.**
4. **In advance clinical testing**

Revolutionary nanotechnology applications, products and services

- Growing area
  - Materials, including bulk, coating, dispersed systems
  - Chemicals, including catalysts
  - Pharmaceuticals
  - Electronics
- Emerging areas in 2004-2005
  - Nanomedicine
  - Energy conversion and storage
  - Agriculture and food systems
  - Molecular architectures
  - Realistic multiphenomena/multiscale simulations
  - Environmental implications
  - Converging new technologies

Tools: Nanoscale Instrumentation and Metrology - research needs -

- Analysis of biomolecules and polymers ('soft')
- Measurements of large domains, as compared to the characteristic nanoscale feature with good L and T accuracy
- The ability to precisely manipulate nanostructures
- Depth-dependent measurements
- The chemical identification at the nanoscale
- Measure multiple features and properties of a nanostructure with a single platform tool
- Metrology: - Standards to ensure reliability and repeatability
  - Standard reference materials
- Priorities: - 3-D measurements with high L and T resolution
  - Simultaneous measurements several properties
  - Instrumentation for properties not yet measured

Nanotechnology holds major implications in nanoelectronics

- Nanotechnology offers the tools
  to understand / transform the silicon technology (< 10 nm gate)

- A platform for new developments
  Molecular electronics, Quantum computing, Few electron devices, DNA computing, Surface computing, 3D architectures, Neural, Flexible electronics, Displays, Nanostructured batteries.

- Integration with biosystems
  Versatile and small sensors; Physical and mental performance; Neural prosthesis; Integration of info-biosystems at nanoscale

- The quest for smallness and speed will be enhanced by the needs for new architectures, three-dimensional integration at the nanoscale, functionality and integration with application driven developments such as those in biomedicine

Nanotechnology holds major implications in energy conversion and storage

Energy conversion

- Fuel cells; Photovoltaics, space harvesting systems
- Photo or electro-catalytic reduction of CO_2 to produce a liquid fuel

Storage

- H_2 storage; Reversible hydrogen chemisorption
- Batteries and supercapacitors

Enabling other technologies

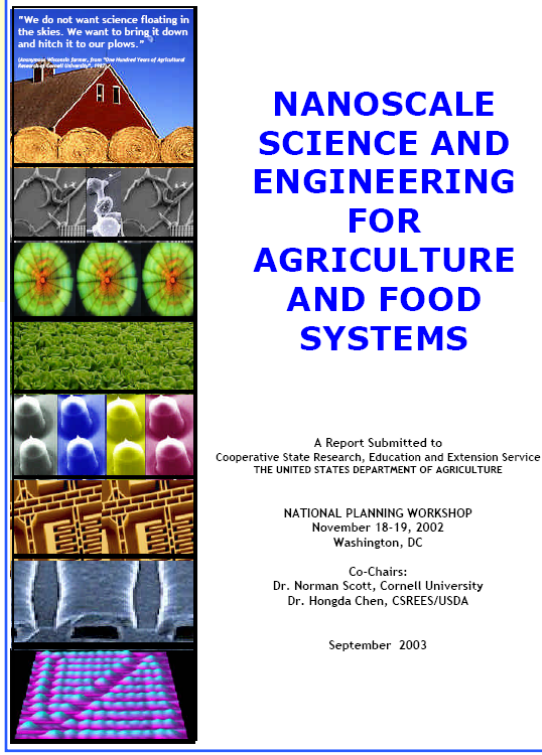
- Separation nanotechnologies both for fission fuel reprocessing, and for mining uranium from sea water
- Superconductors, or quantum conductors
- Photodiodes for lighting
- Materials that will enable deep drilling, geothermal heat mining.

Nanotechnology holds major implications in the environment

- Nanoscale manufacturing will in the long term provide the means for sustainable development. For the same outcomes, one needs less material, less water, less energy and less waste. Also, new methods to generate energy, filter water, etc.
- "Exact manufacturing" - the proportion of waste reduces
- Provides means to address current health and environmental issues, as well as unexpected consequences. Understand geo-nanoscience.
- Novel technologies based on molecular processes can be used to remove existing pollutants that cannot be separated or are too expensive to be separated otherwise.
- By using nanoscale sensors one can monitor the situation better, in more detail and over larger areas.

The risk of not doing R&D in nanotechnology would be high

Nanotechnology holds major implications in agriculture and food systems



- NT offers the tools to understand and transform biosystems

  Strong impact on sub-cellular dynamics; Regeneration mechanisms; Genome description; Food characterization

- Solutions to agriculture and food industry

  Diagnostics and treatment; Synthesis of chemical for agriculture; More effective chemicals and biodegradable; Food preparation and conservation; Sensors and control

- A new platform for new developments

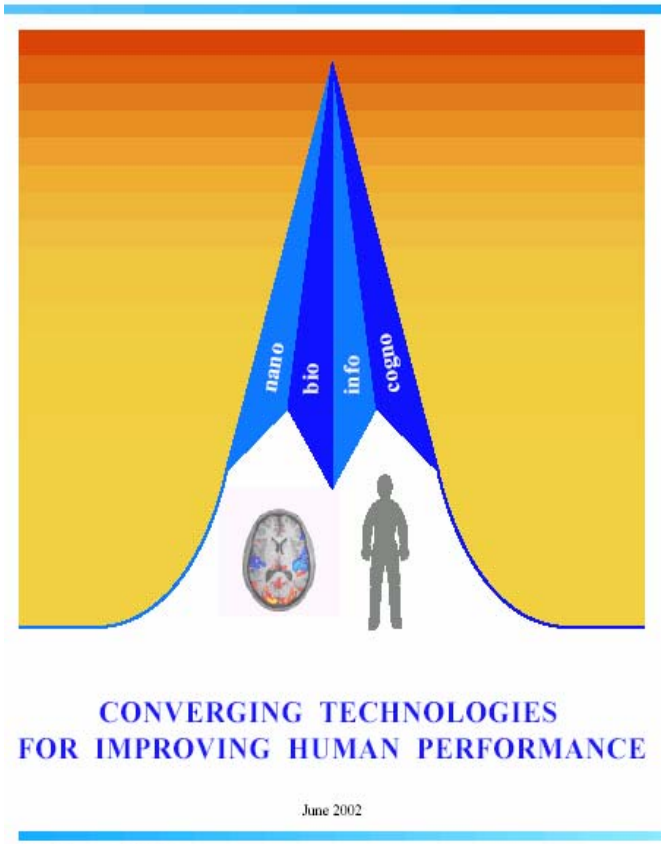
  Nanoscale-based chemical treatment; Bio-engineering and bio-processing, bio-nanomechanical systems, biochips, filtration, fluidics, green manufacturing

- Promise of sustainable development in long term

  Ex. Nano-food market: $2.6B in 2003; $7.0B in 2006; >20B in 2010 (Helmut Kaizer Consultancy, 2006)

Integrating science and technology from the nanoscale

- **Broad and timely opportunity**
  - **Understanding unity in nature beyond renaissance, and technology integration from the nanoscale**
  - **Powerful transforming tools (NBIC: nano-bio-info-cogno) developing at the confluence of disciplines**
  - **Improvement of individual and group human performance becomes possible**
  - **Need for anticipation ('learning before doing') and deliberate choices**
- **NBIC - agents of accelerated, synergistic change**



(December 2001)

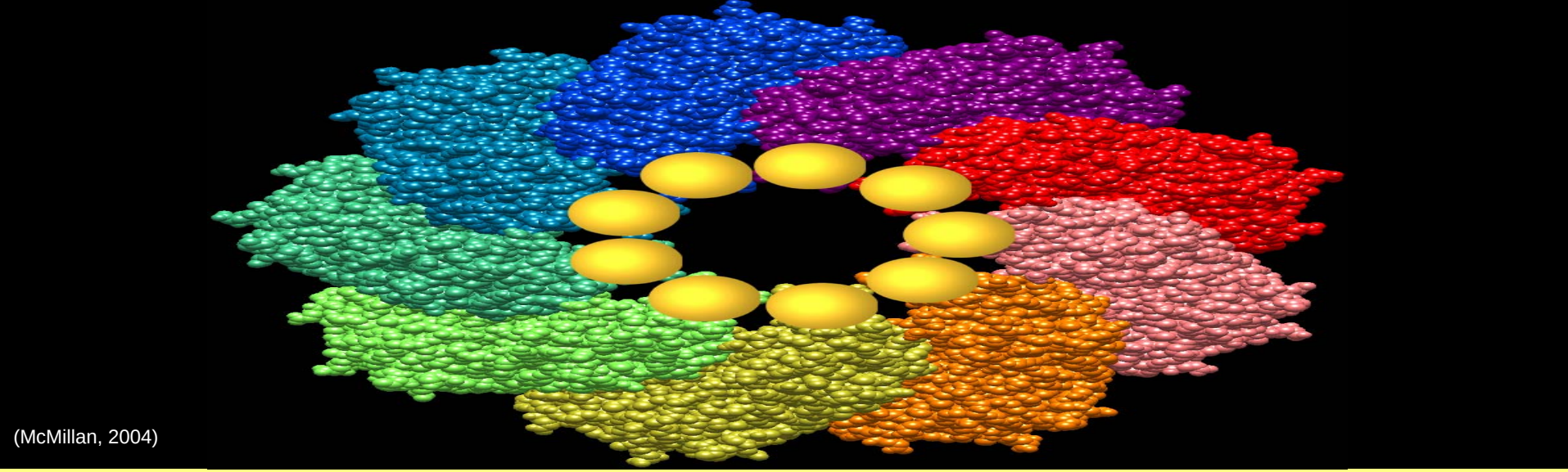
Online www.nsf.gov/nano,
also Kluwer Academic Publ

Nanotechnology is still an art

green in
reflected light

red in
transmitted light

. . . as it was in the 4th century when this masterpiece was manufactured. The dichroism is due to tiny 50 nm particles suspended in glass. In the future - we aim to be able to do such things ‘by design’.



Part B
Four Generations of Nanotechnology Products

- Four generations of nanomanufacturing
- Areas of industrial relevance

New York, November 2006

Manufacturing: Transforming raw materials into products with desired properties and performance – generally in large quantities

Defining Nanomanufacturing (1) :

Aims at building material structures, components, devices/ machines, and systems with nanoscale features in one, two and three dimensions. It includes

- bottom-up directed assembling of nanostructure building blocks (from the atomic, molecular, supramolecular levels),
- top-down high-resolution processing (ultraprecision engineering, fragmentation methods, positioning assembling),
- engineering of molecules and supramolecular systems (molecules as devices "by design", nanoscale machines, etc.),
- hierarchical integration with larger scale systems.

Atoms, molecules ⇨ **nanostructures** (intermediate) ⇨ **materials/ devices/ machines/ systems**

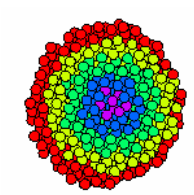
Defining Nanomanufacturing (2)

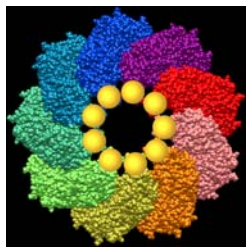
- Fragmentation
- Patterning
- Restructuring of bulk
- Lithography, ..

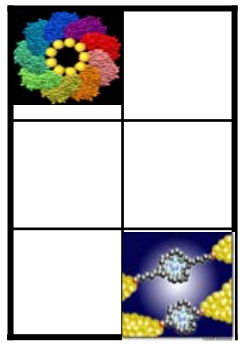
- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

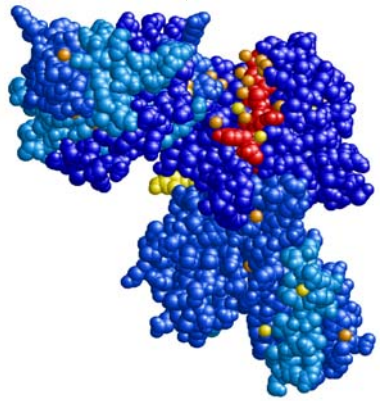
- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration..









Assembling

- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

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

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

NANOPRODUCTS

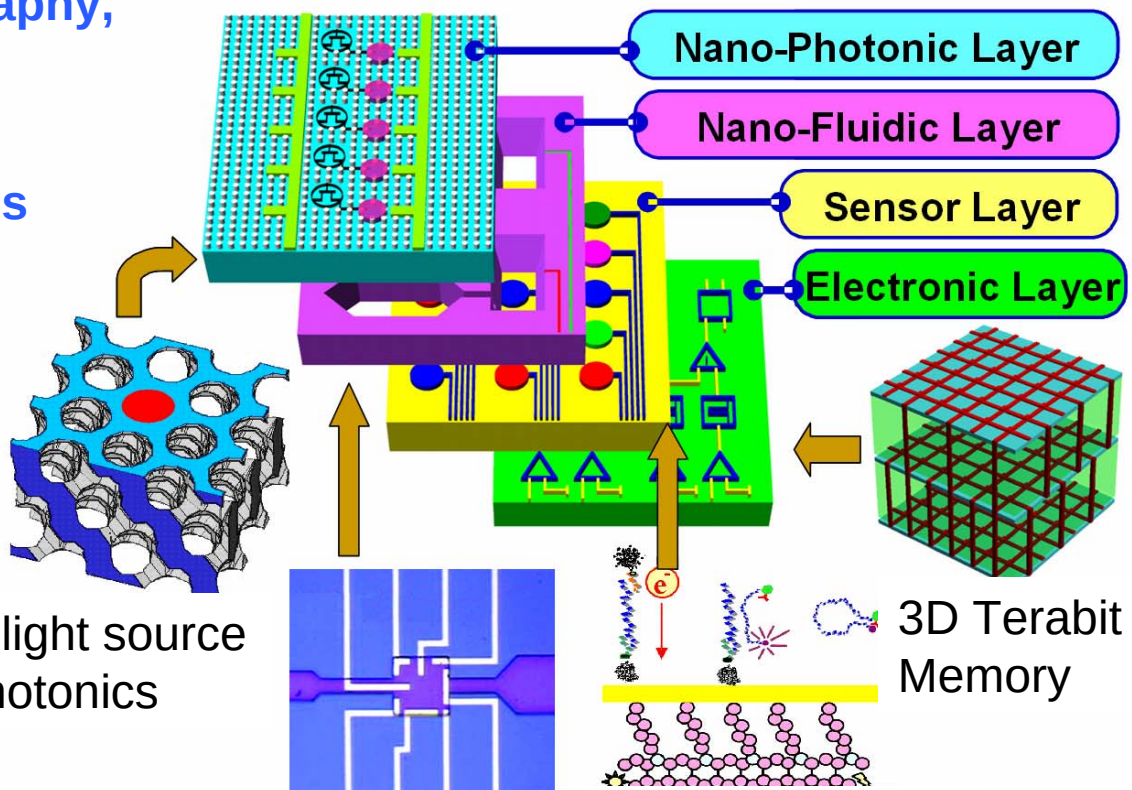
Center of Scalable and Integrated Nanomanufacturing

UCLA, UC Berkeley, Stanford U., UCSD, UNCC, HP Labs

Goals

- 3D nano-manufacturing with 1-20 nm resolution (Plasmonic Imaging Lithography, Ultra Mold Imprinting)
- Massive and parallel integration of heterogeneous nano-LEGOs into devices
- Nano-manufacturing cluster tool

Research Thrusts



Ultra Compact light source & integrated photonics

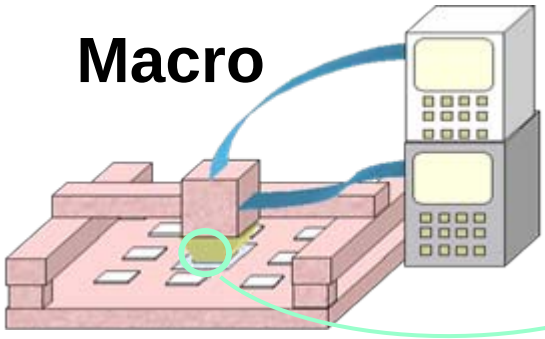
Nano Fluidic Circuits

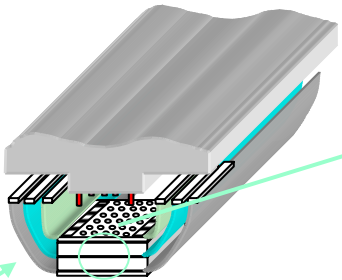
Ultra Sensitive Bio-sensor

3D Terabit Memory

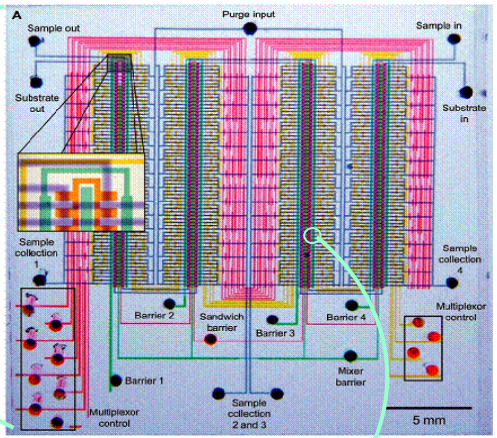
Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, UIUC, NCSU, Caltech

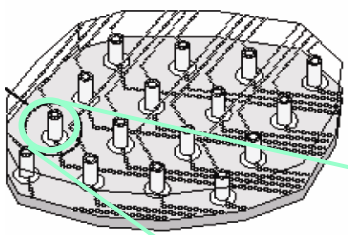
Macro

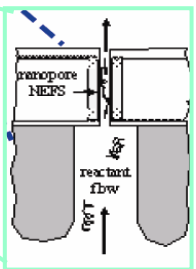




Micro







Nano

Goals - control of composition at nanoscale

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

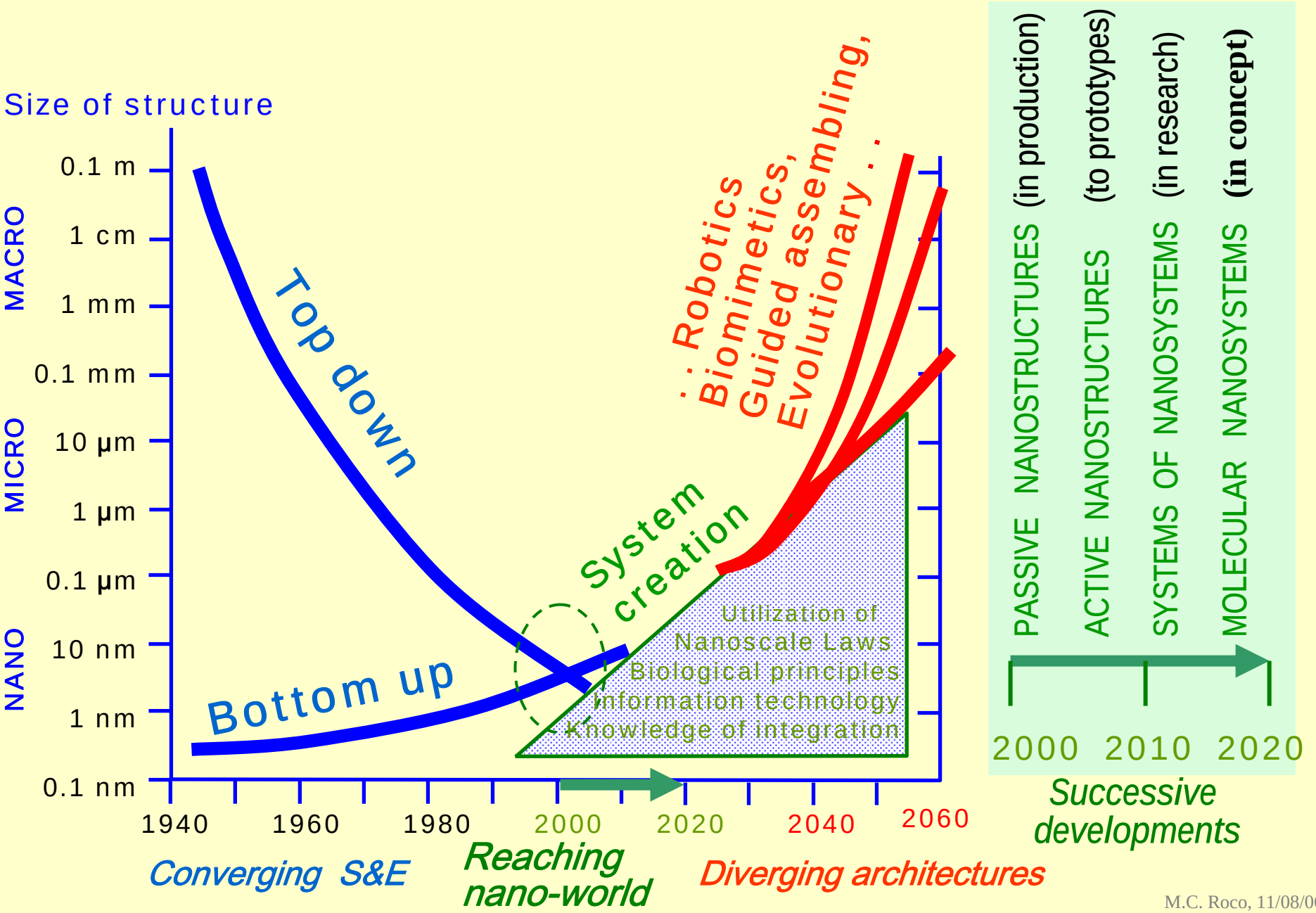
Research Thrusts

Micro-Nano Fluidic Network Toolbit

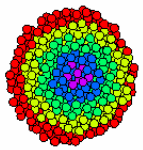
Process Sensing and Control

Manufacturing Systems

Reaching nano-world and system creation



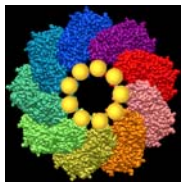
Timeline for beginning of industrial prototyping and nanotechnology commercialization: Four Generations



1st: Passive nanostructures (1st generation products)

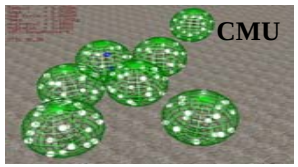
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2000



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

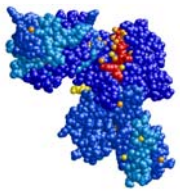
~ 2005



3rd: Systems of nanosystems

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

~ 2010



4th: Molecular nanosystems

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

~ 2015-2020

New R&D challenges

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

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

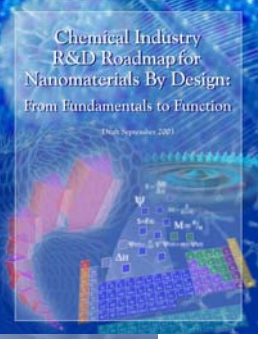
First generation of products: passive nanostructures (~ 2000 –)

- IN PRODUCTION -

- **Goal:** Reaching systematic control in passive nanoscale domains, typically for tailoring macroscale properties and functions

- **Ex. applications:** coatings, nanoparticles, dispersions, nanolayers, sintering, filters, surface nanopatterning, bulk materials - nanostructured metals, polymers, ceramics. Primary areas of relevance are:
  - Materials
  - Chemicals, including catalysts
  - Pharmaceuticals
  - Electronics

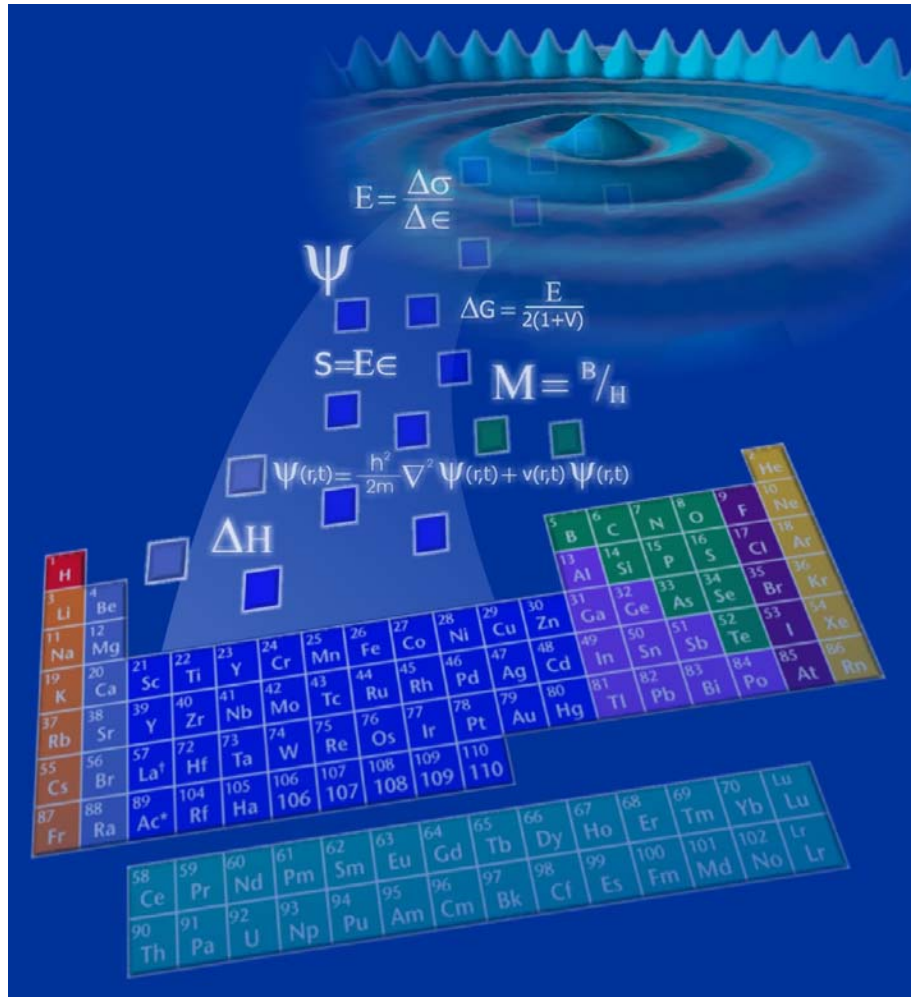
- **R&D focus:** on new properties of materials and new tools
  Ex.: grain boundary simulation, nanomechanics



Nanomaterials By Design

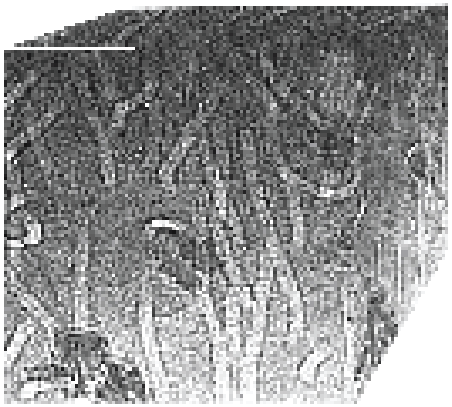
www.ChemicalVision2020.org and NNI

The ability to employ scientific principles in deliberately creating structures with nano-scale features (e.g., size, architecture)
that deliver unique functionality and utility for target applications



Example 1st generation –

Mesoporous Catalyst Materials by liquid crystal templating (Mobil)



Nanostructured porous silica

MCM-41 fabrication and mesoporous structure (courtesy of Mobil)

MCM-41 (1992) - a new class of mesoporous material (MCM-41) molecular sieves: amorphous, hexagonally packed silicates and aluminosilicates with a uniform, honeycomb-like channel structure

The diameter of these channels can be adjusted between ~1.6 to 10 nm during synthesis, yielding surface areas reaching 400-700 m^2/gr

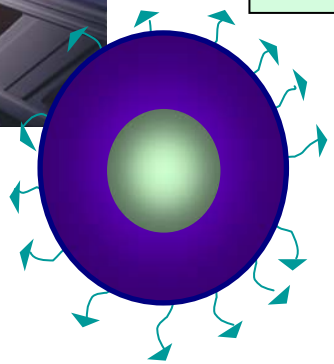
Production - by self assembly of amphiphillic surfactants in micelles in a liquid crystal templating sol-gel process

2006: Research to produce crystalline MCM-41

Example 1st generation –

Aircraft Engines

Healthcare



Nanotechnology Platform

NanoTubes and NanoRods

NanoParticles

NanoCeramics

NanoStructured Metal Systems

Hybrid Materials

Water

Energy

Nanotechnology at General Electric

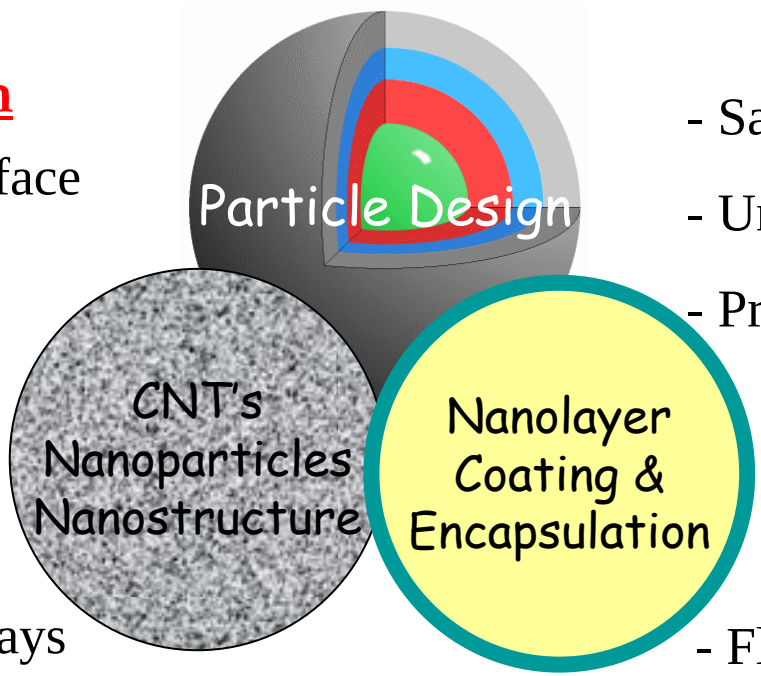
DuPont: Process Engineering & Manufacturing

for synthesis (CVD, Aerosol, Crystallization, precipitation), size reduction, surface treatment, coating, encapsulation, dispersion, incorporation

Nanotechnology platform

Characterization

- PSD, morphology, surface
- Defects
- End-use performance



Manufacturing

- Safety
- Unit operations & Scale up
- Process integration

Applications

Films, Electronics, Displays

EP, Coatings, Personal care, Sensors, N&H

Assembly

- Fluid dynamics
- Field (E&M)
- Molecular template
- Biomolecule assisted

Modeling&Simulation

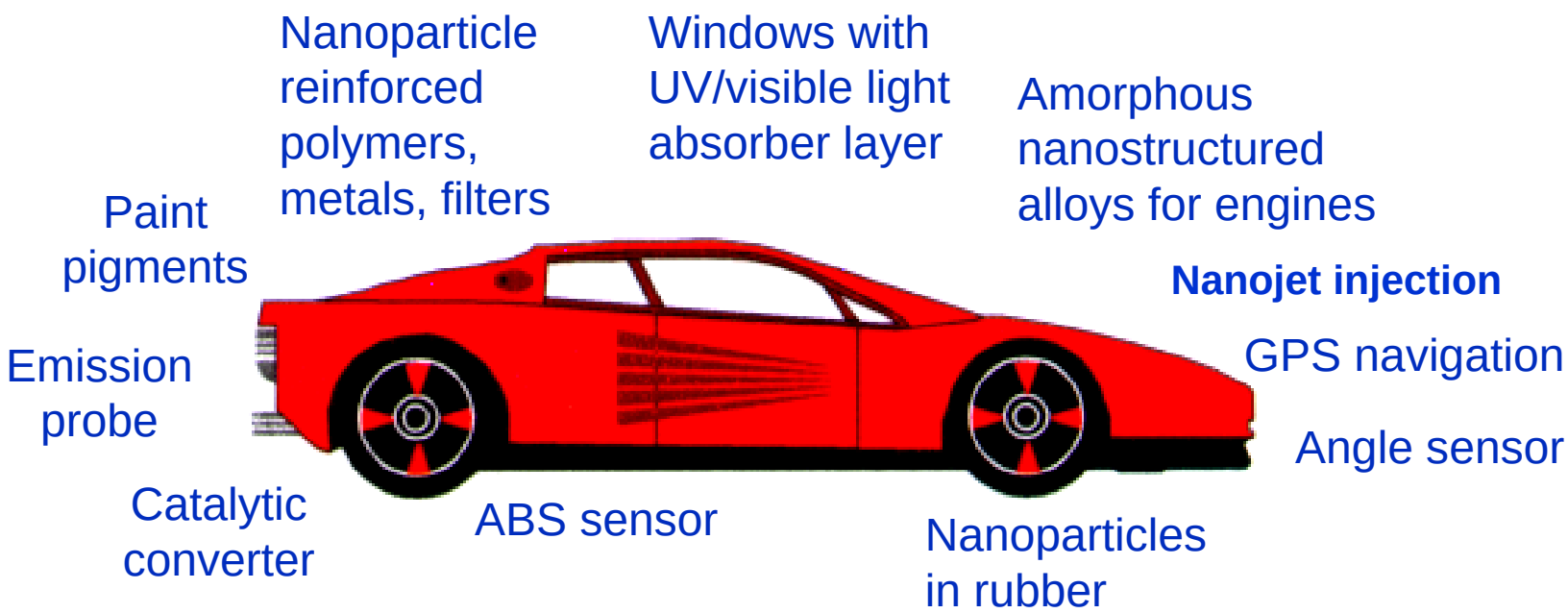
Molecular, Meso, Macro, CFD,

Example 1st generation –

Applications of various nanostructures in a car

Sample of companies involved: GM, Ford, Toyota, Mitsubishi, BMW, all tire companies: there is no major part of car that has not yet been affected by nanotechnology (2003)

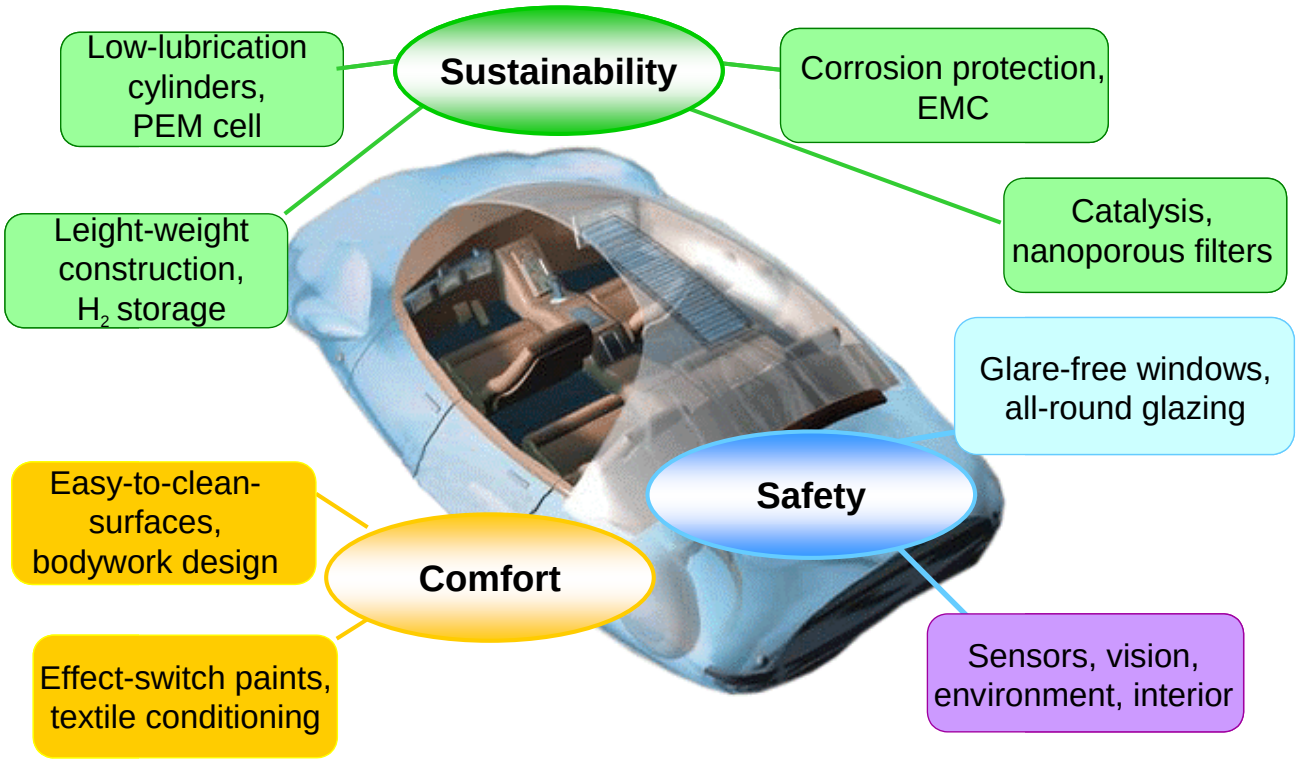
Ex: "Nano in Cars" consortium in Germany - 6 car manufacturers, 10 suppliers, and 26 R&D university and laboratories



Example 1st generation –

Technological targets of NanoMobil (Source: German car manufacturers, BMBF)

Example of system approach, with about 20-25 R&D targets

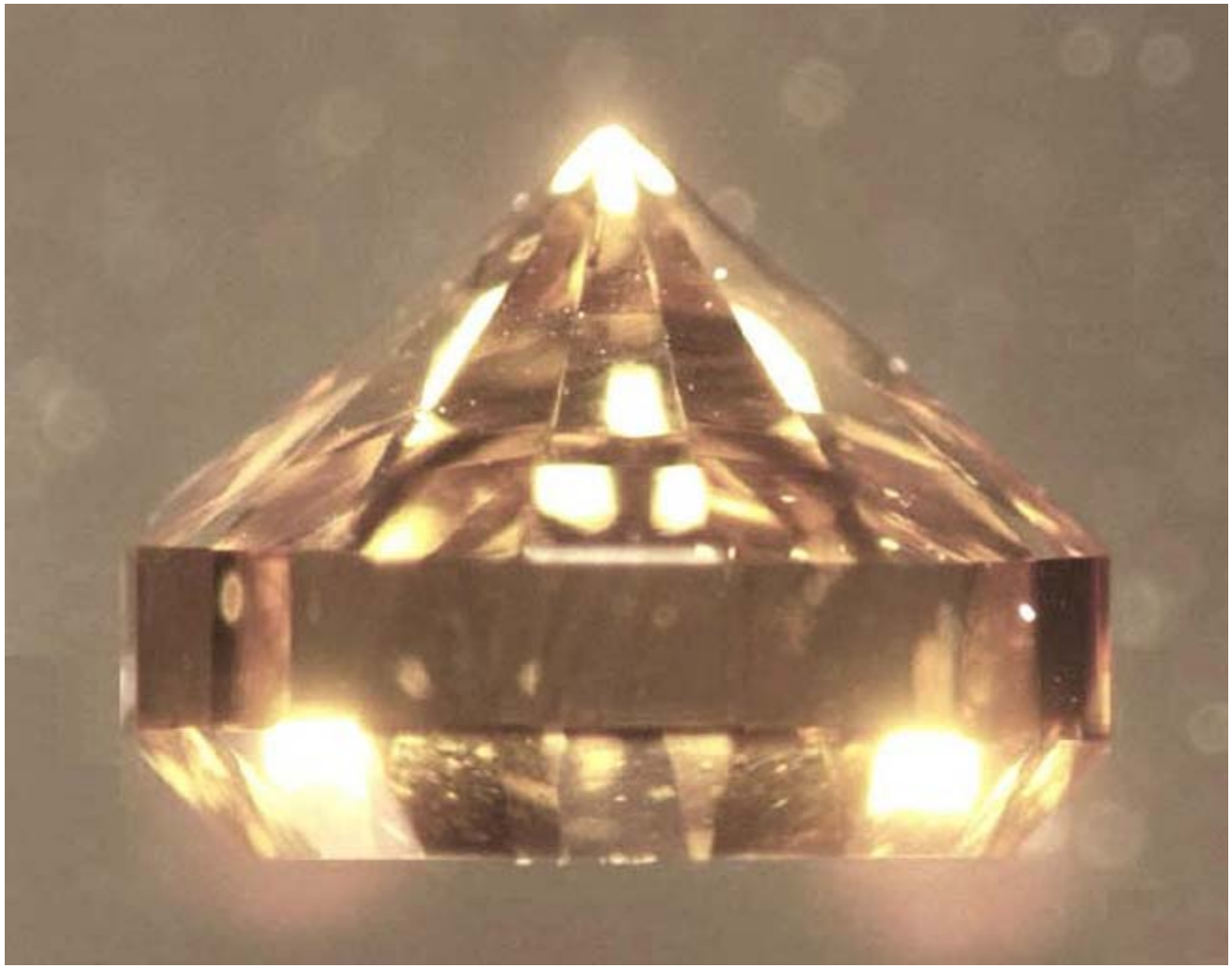


2004: 5 car manufacturers, 11 suppliers, 12 universities, 14 research institutes

http://www.fz-juelich.de/wing/datapool/page/19/Leitinnovation_NanoMobil_09_03_04.pdf

Example 1st generation –

Diamond single crystal 2.5 mm high via molecular control of chemical vapor deposition



Courtesy: R.J. Hemley, Geophysical Lab, Carnegie Institution of WA

Second generation of products: active nanostructures (~ 2005 –)

- IN DESIGN -

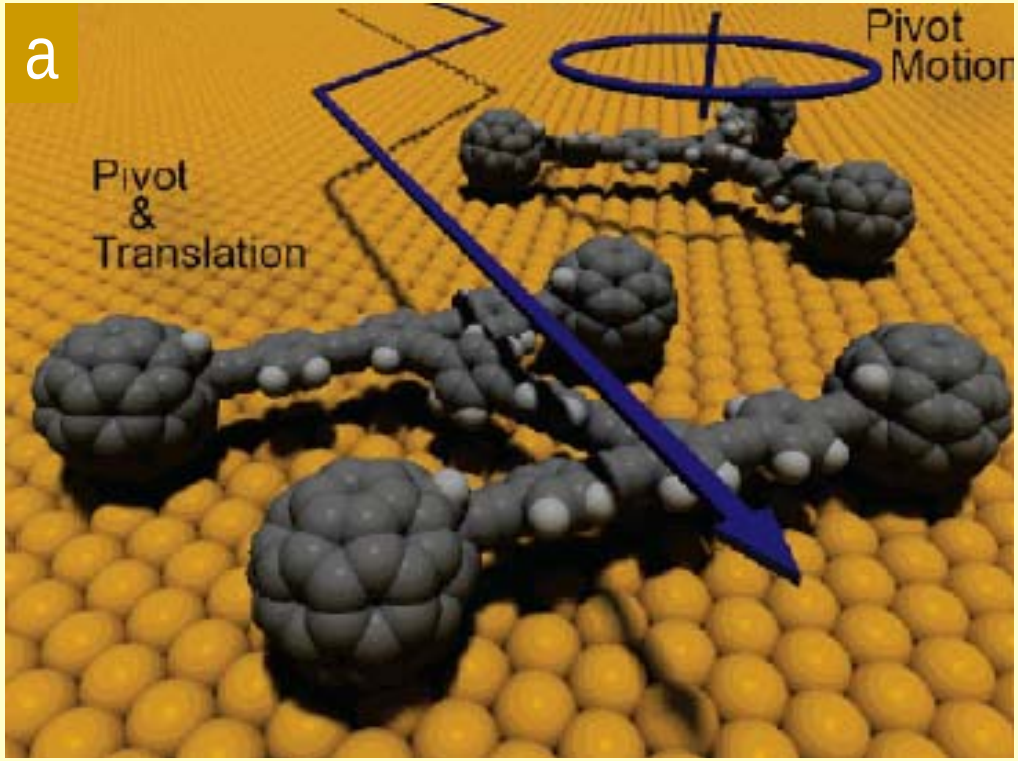
- **Goal:** active nanostructures for mechanical, electronic, magnetic, photonic, biological and other effects; typically for microscale devices and systems

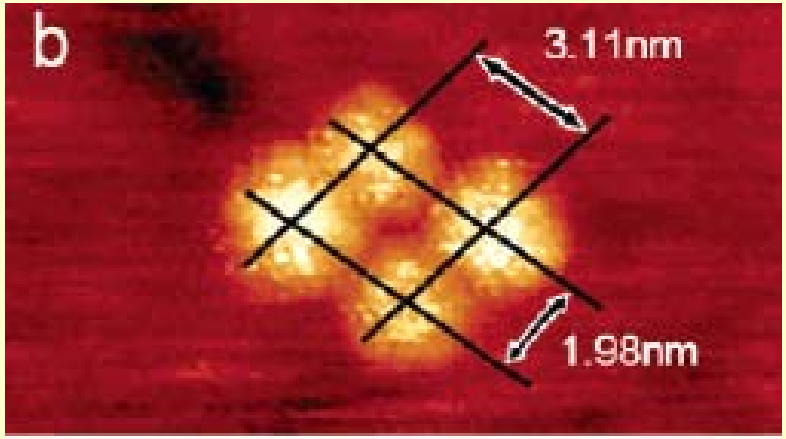
- **Ex. applications:** Targeted drugs, actuators, transistors, sensors, molecular machines, light-driven molecular motors, plasmonics, nanoscale fluidics, various devices. Emerging areas are:
  - Nanomedicine
  - Energy conversion and storage
  - Agriculture and food systems
  - Realistic multiphenomena/multiscale simulations
  - Environmental applications

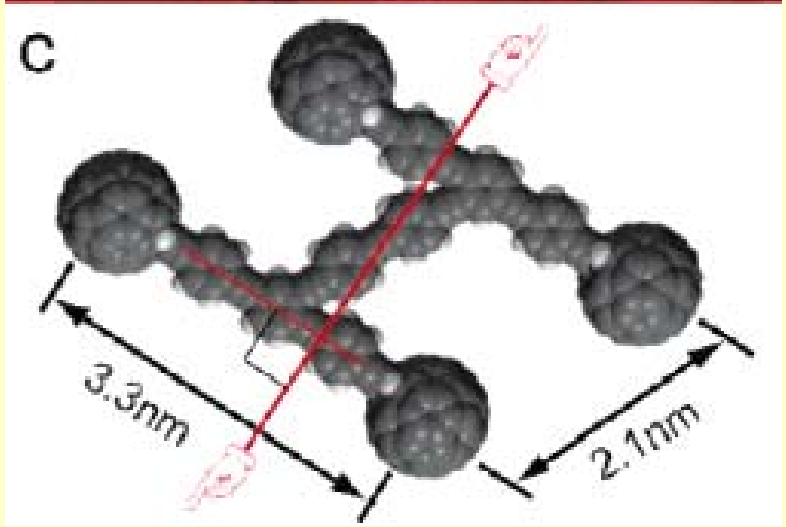
- **R&D focus:** novel devices/machines & device system architectures

Example 2nd generation - active nanostructure:

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



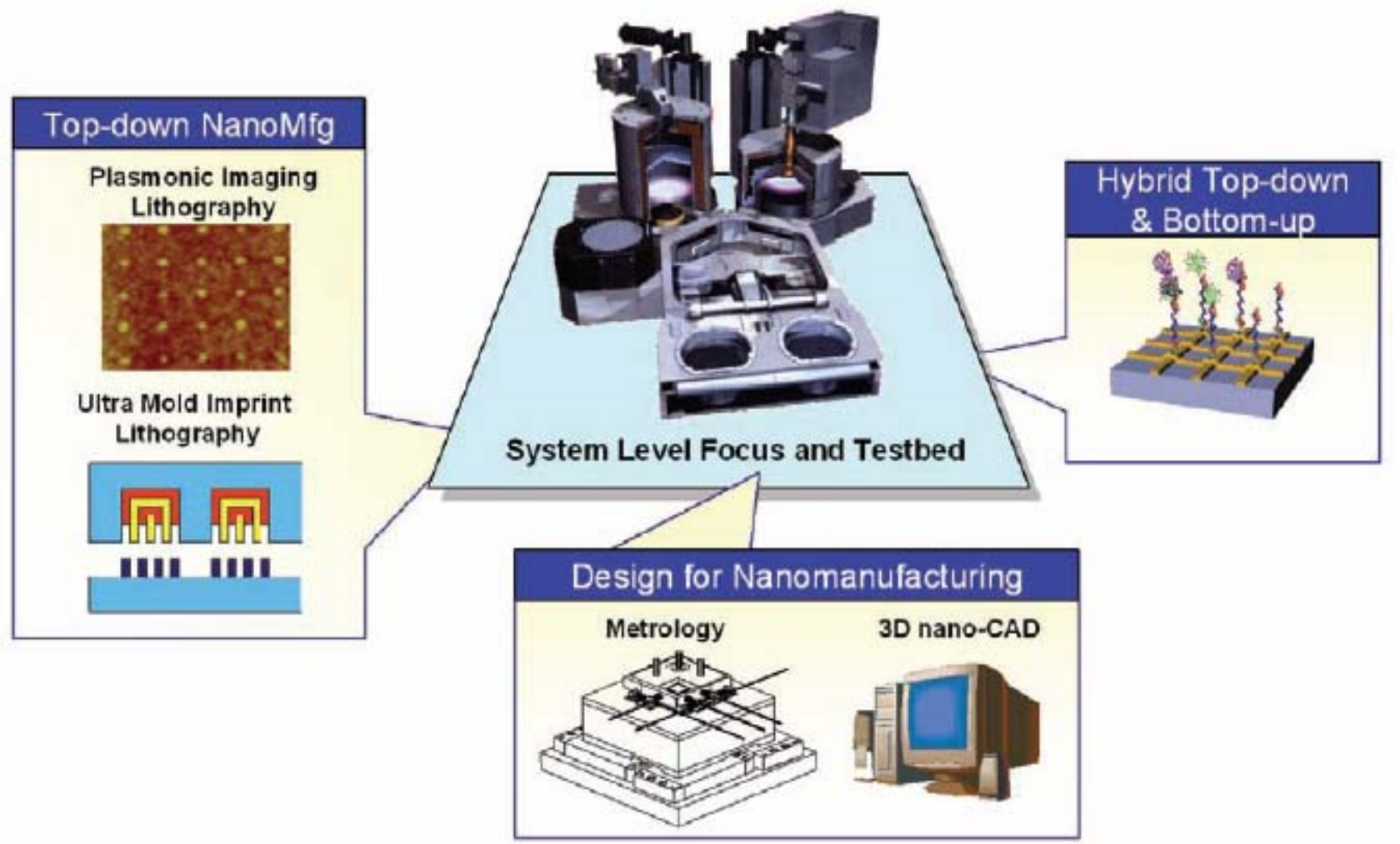




Nano Letters, Vol. 5, 2005; JACS, Vol. 128, 2006

Example 2nd generation –

Nanocluster tools with multiple processes conducted on the same substrate



(courtesy of X. Zhang, SINAM NSEC, University of California, Los Angeles)

Example 2nd generation –

Photocatalytic and hydrophilic processes in self-cleaning of glass

- Transparent coating consists of nanostructured titanium dioxide (TiO2) - integrated with the hot glass during its manufacturing process. The photocatalytic properties of the coating are energized by UV illumination and disintegrate and loosen organic dirt deposited on the glass

- The hydrophilic properties reduce surface tension and lead to sheeting rather than beading of water on the glass, which helps flushing the surface clean and accelerating drying. Self-cleaning glass is manufactured in standard and energy-saving panels

(courtesy of PPG)

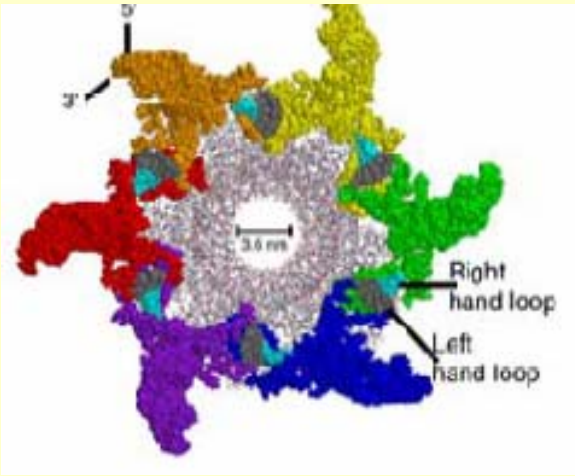
Example 2nd generation –
self cleaning glass coated with a photocatalytic nanoparticles

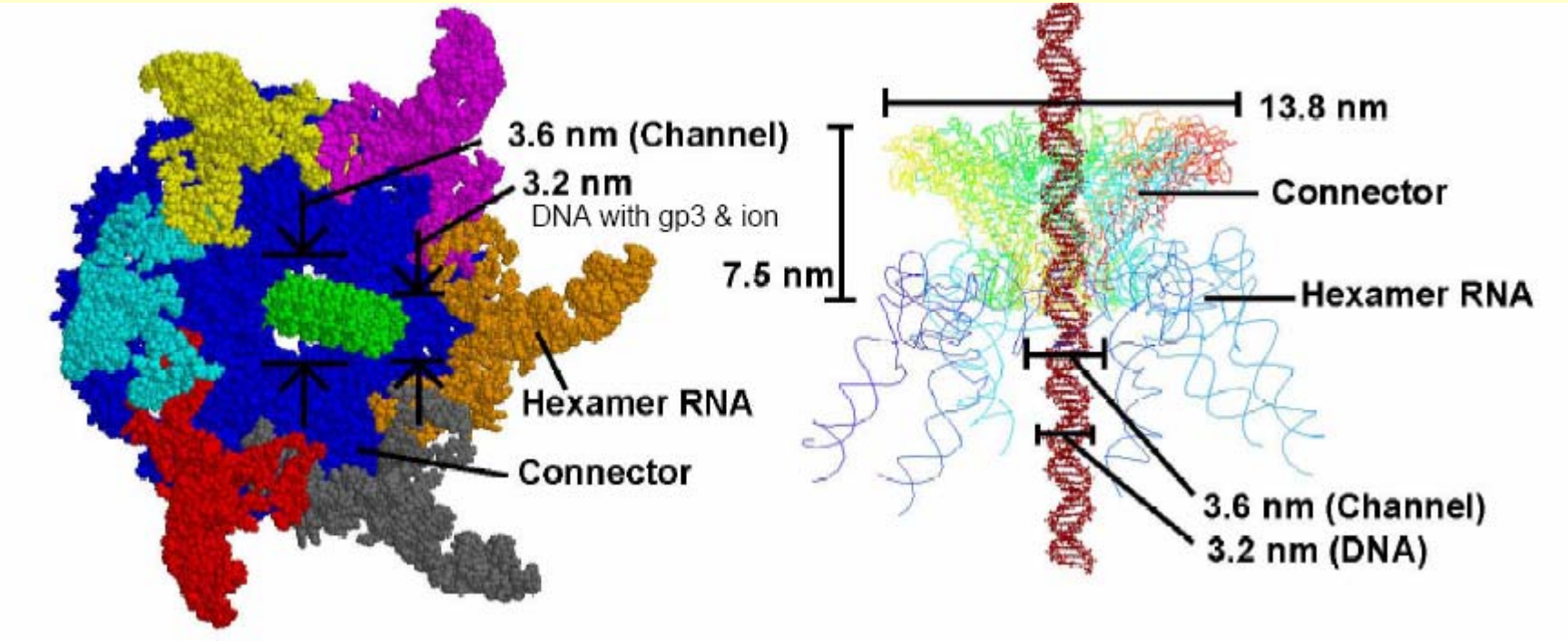
Courtesy: C. Bai, SCIENCE VOL 309 1 JULY 2005

Example 2nd generation - active nanostructure:

Construction of a viral nanomotor driven by a synthetic RNA

P. Guo, Molecular Virology, Purdue University, 2004

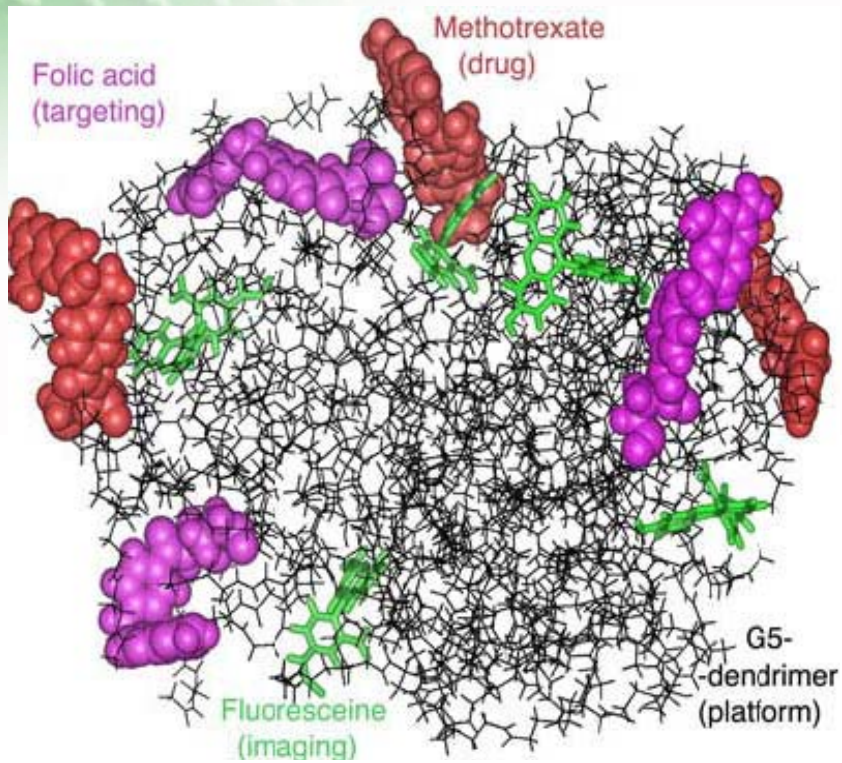




Example 2nd generation - active nanostructure

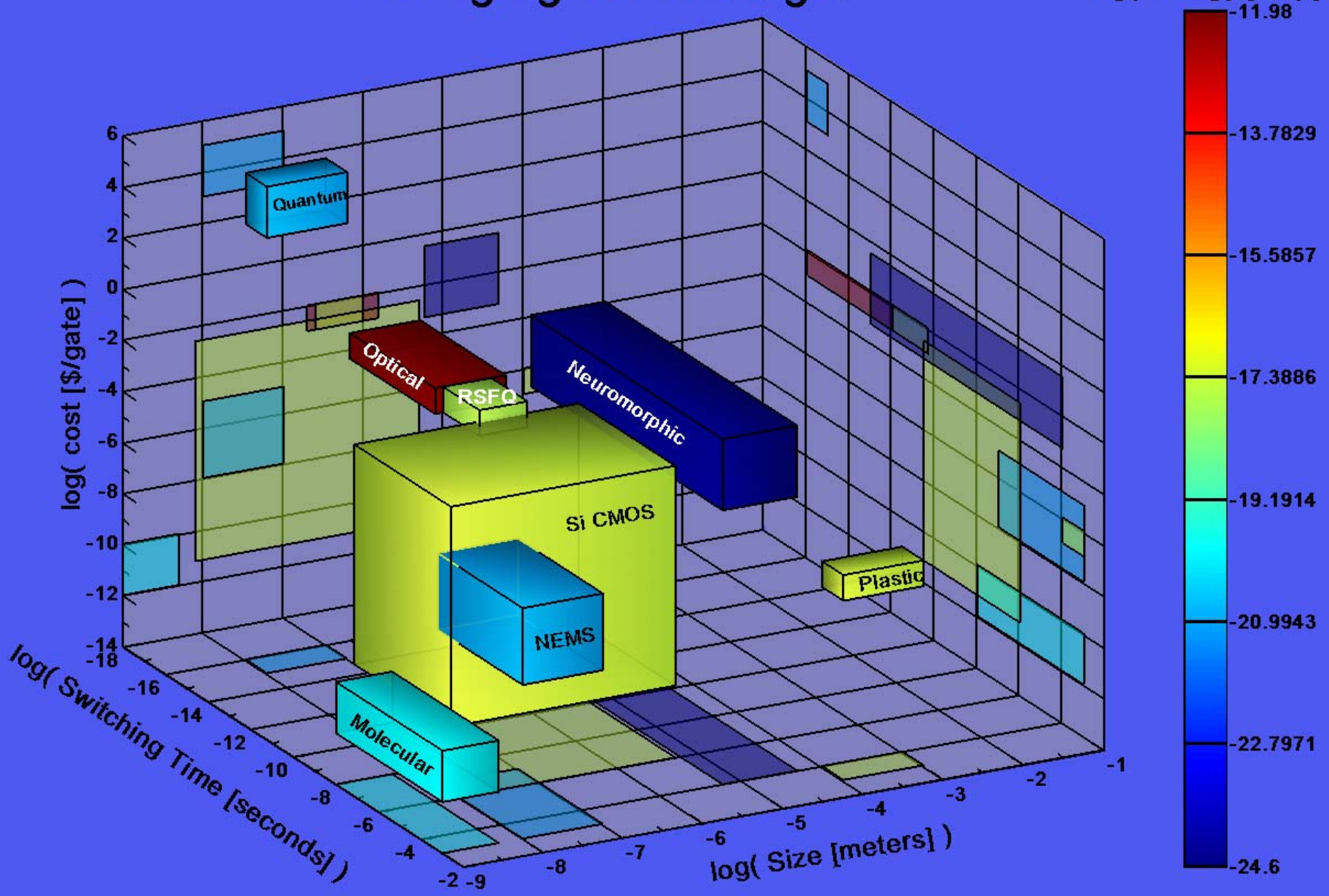
Multi-functional Nano-platforms: 'Find – Detect – Treat'

NCI Alliance for Nanotechnology in Cancer



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

Emerging Technologies



Motivation for hybridizing other devices with CMOS

Third generation of products:
3D systems of nanosystems (~ 2010 –)

- IN RESEARCH -

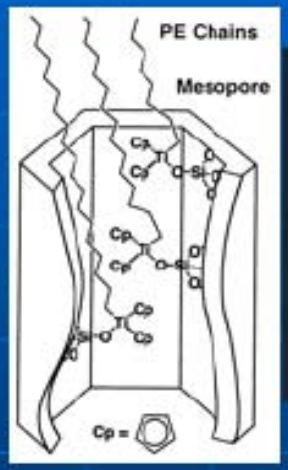
- **Goal:** engineer and manufacture 3D nanosystems with heterogeneous components, systems of nanosystems; typically for nanoscale assemblies and systems

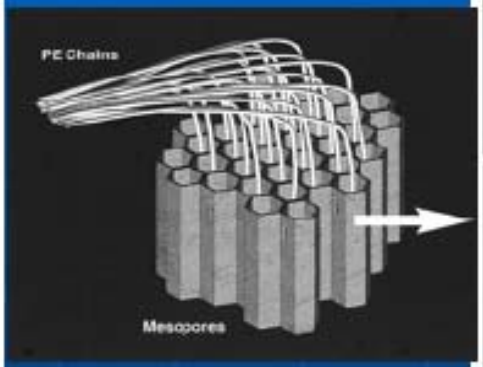
- **Ex. applications:** multiscale selfassembling, networking of structures and devices at the nanoscale with hierarchical architectures, chemical manufacturing, robotics, nanosystems with long scale order, biomedical. Emerging areas are:
  - Nanosystem biology for medicine
  - Nanosystem architectures
  - Realistic multiphenomena/multiscale simulations
  - Environmental bio implications
  - Converging new technologies from the nanoscale

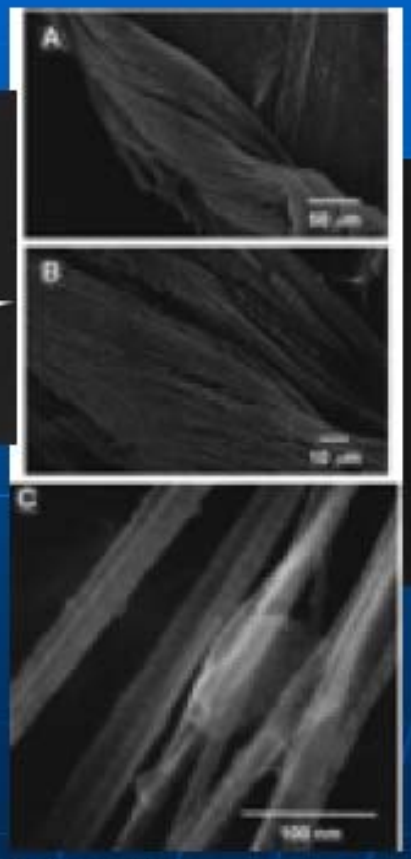
- **R&D focus:** Design and interaction of supramolecular systems and heterogeneous nanostructures; system architecture of nanosystems, modular integration

Example 3rd generation - nanosystems

Nanotechnology







Catalytic polymerization in mesoporous silica

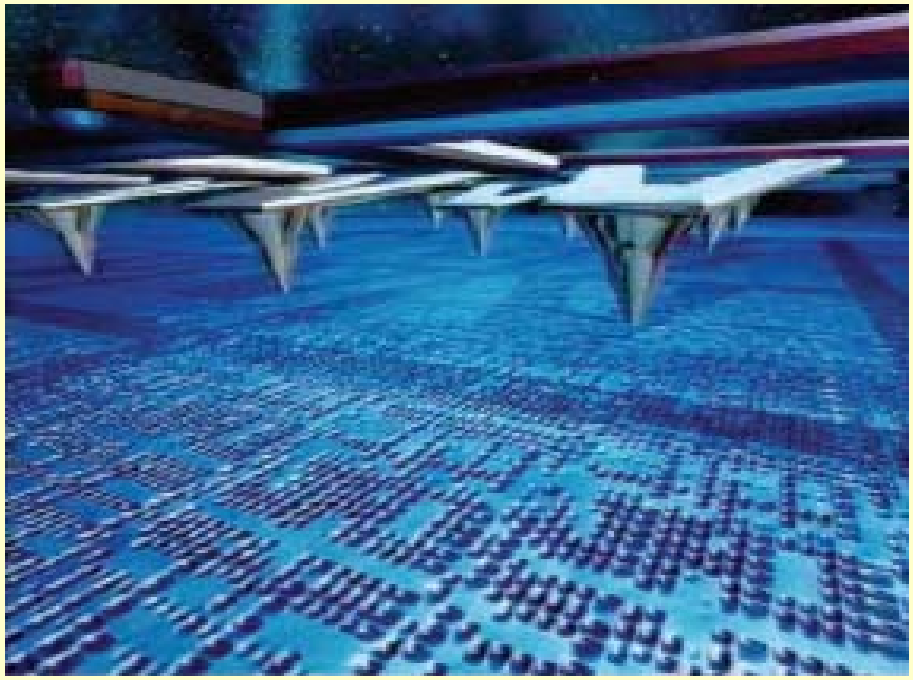
Cotton-like Fibrous Mass

Kageyma, Tamazawa, and Aida, *Science* 285, 2113

PSU

Example 3rd generation - nanosystems

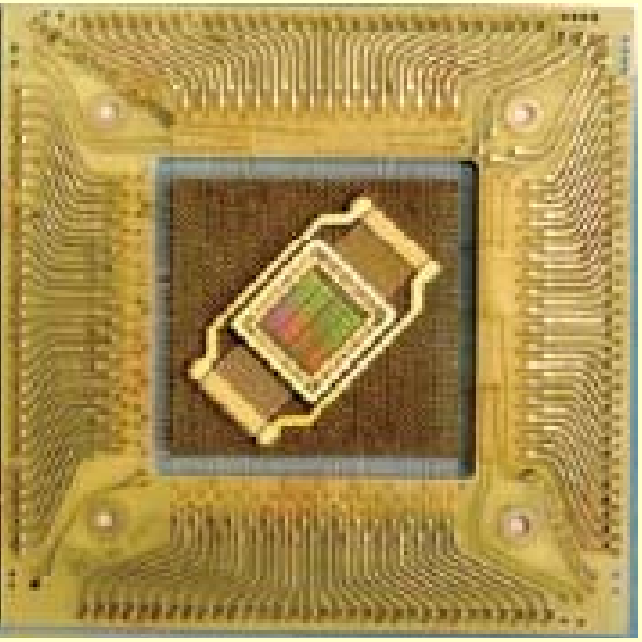
Probe Array Nanofabrication (IBM / Millipede)



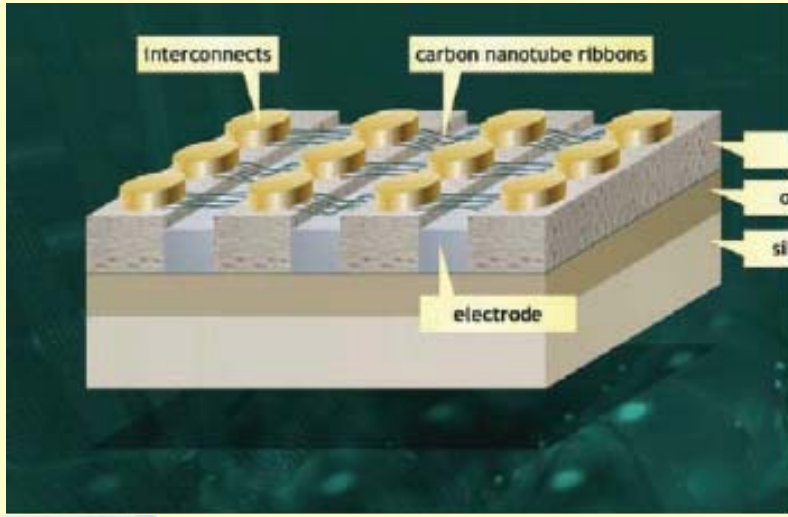
Millipede nanopatterning (courtesy of IBM Zurich Research Laboratory)

- 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

Other examples combining 2nd and 3rd generations

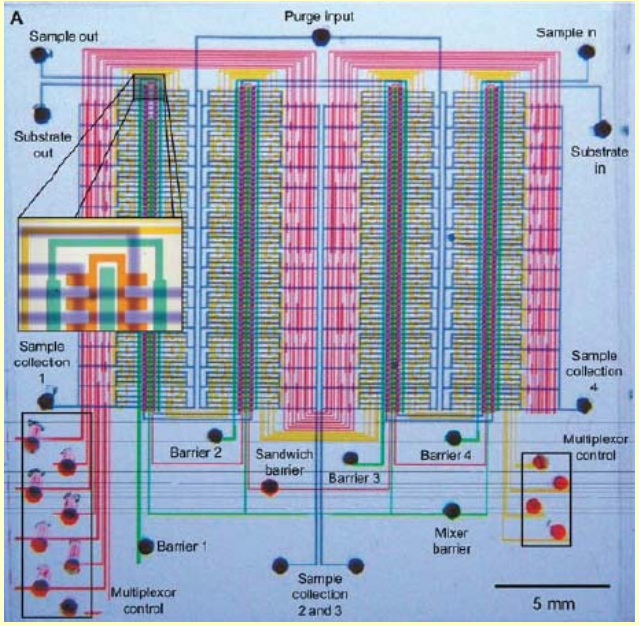


GMR/MRAM memory - 4 Mbits with 10 ns access time (courtesy of Motorola)



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

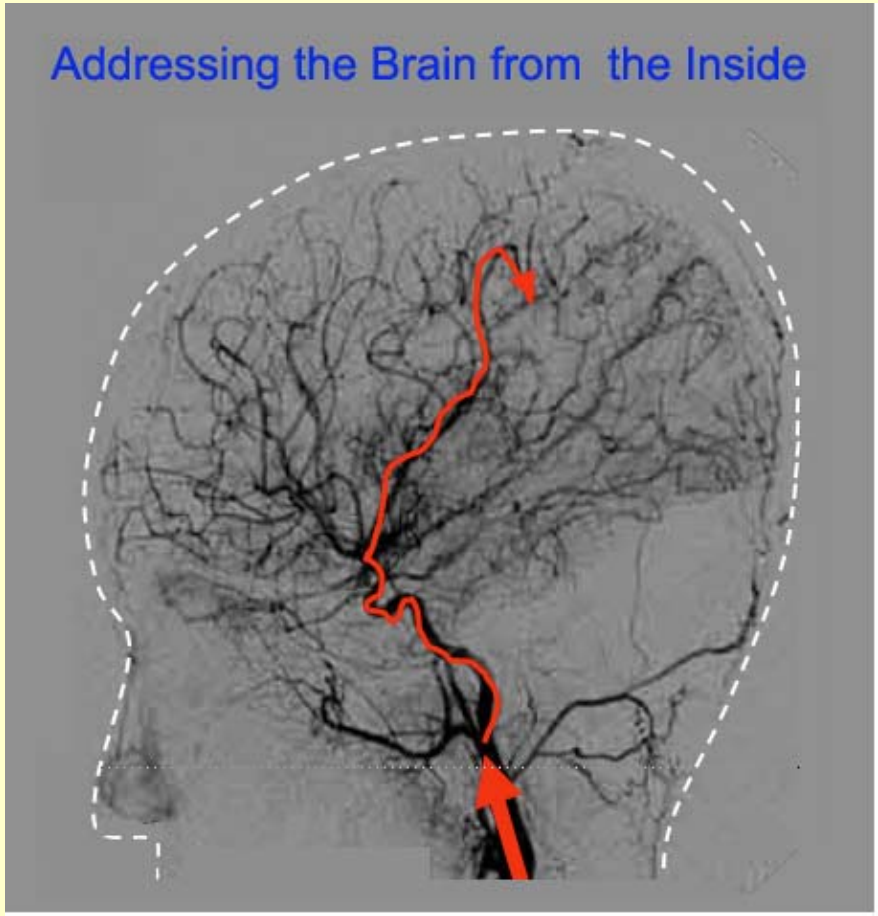
(courtesy of Nantero)



Microfluidics systems with nanocomponents (courtesy Thorsen et al.)

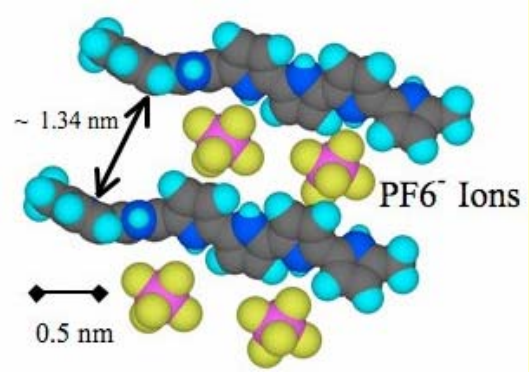
Example 3rd generation: Neuro-vascular Central Nervous Recording/ Stimulating System: Using Nanotechnology Probes

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

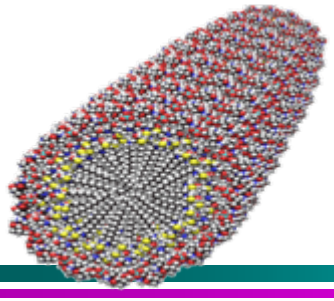
Fourth generation of products: molecular nanosystems (~2020?)

- IN RESEARCH -

- **Goal:** heterogeneous molecular nanosystems; typically for nanoscale systems and hybrid bio-assemblies

- **Ex. applications:** molecules as devices, monitor and condition cells as nanobiosystems, multiscale selfassembled systems with molecular components, nanoscale-based regenerative medicine and artificial organs, high added value 'smart' or/and adaptive components in larger systems; gene therapy based on NT

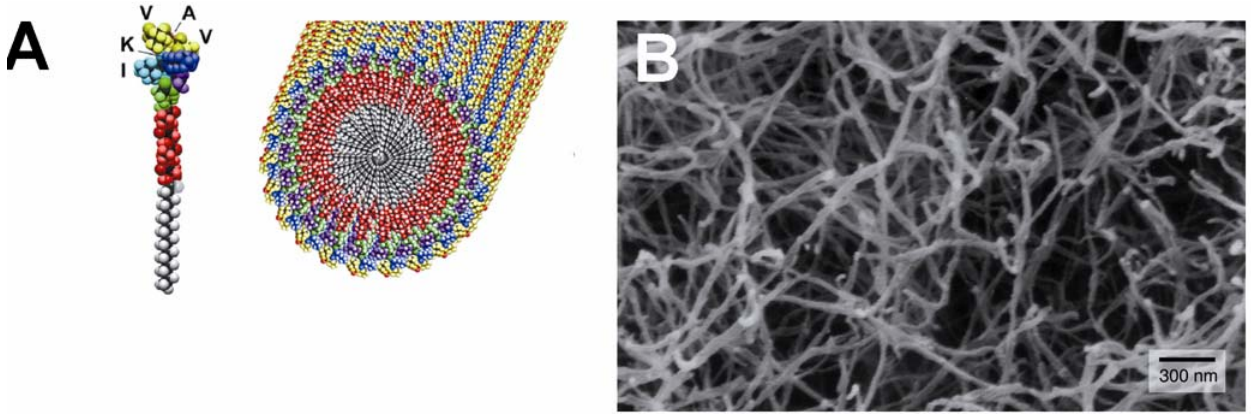
- **R&D focus:** atomic/molecular design, collective behavior and chemical-mechanical interaction of molecules, tissue nanoengineering, nano-bio-info-cognitive convergence, neuromorphic engineering

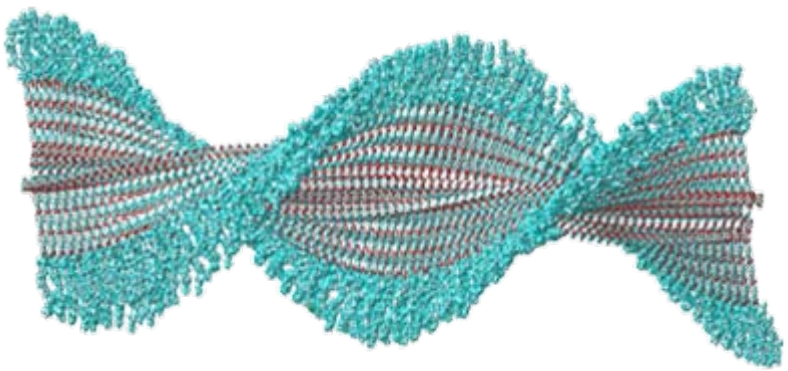


Designing molecules for hierarchical selfassembling

EX: SAMUEL I. STUPP, *Northwestern University*

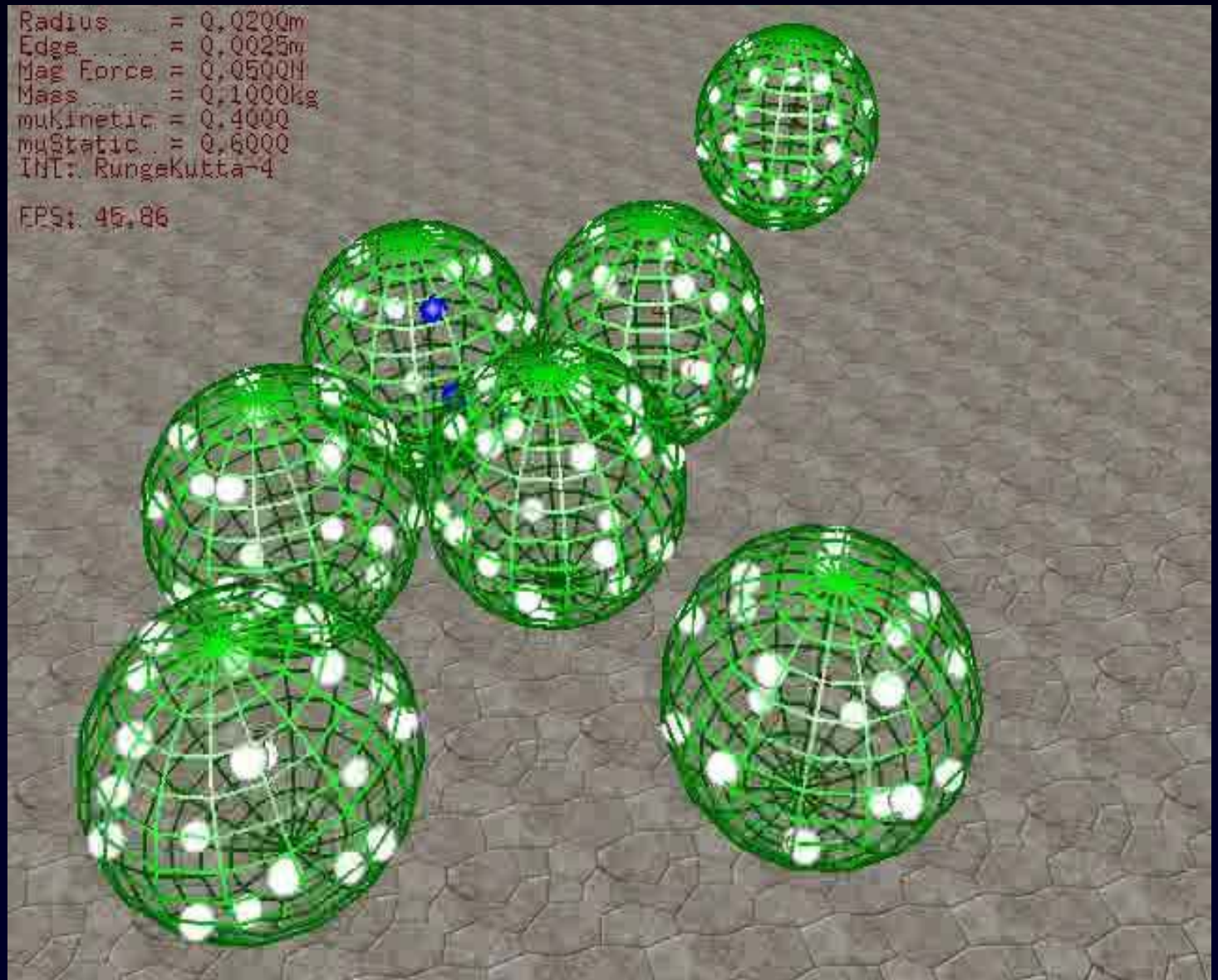
Application: biomaterials for human repair (nerves, tissues, wounds), reactive filters, others





Miniature Micro/Nano-Robots-II: “Claytronics”

(Seth Goldstein, CMU)



Four generations of nanoproducts for nanoelectronics

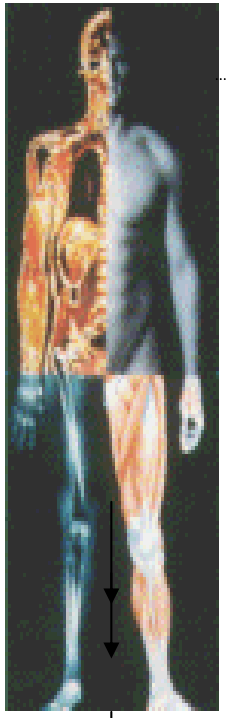
- First generation. Scaling down "masked-lithography of thin-films" - Nanoscale components (ex: passive nanoscale layers) with new physics
- Second generation (with state change of devices during operation)
  - Improving manufacturing: "directed self-assembly" leading to CMOS scaled to its ultimate limits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

Reference: International Technology Roadmap for Semiconductors

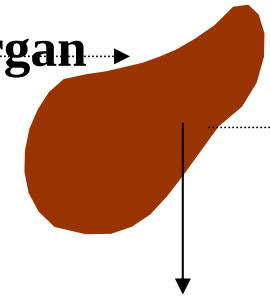
Examples of levels for intervention of nanobiotechnology

4 generations of nanotechnology products for human life extension

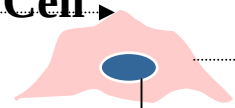
Human



Organ



Cell



Molecule

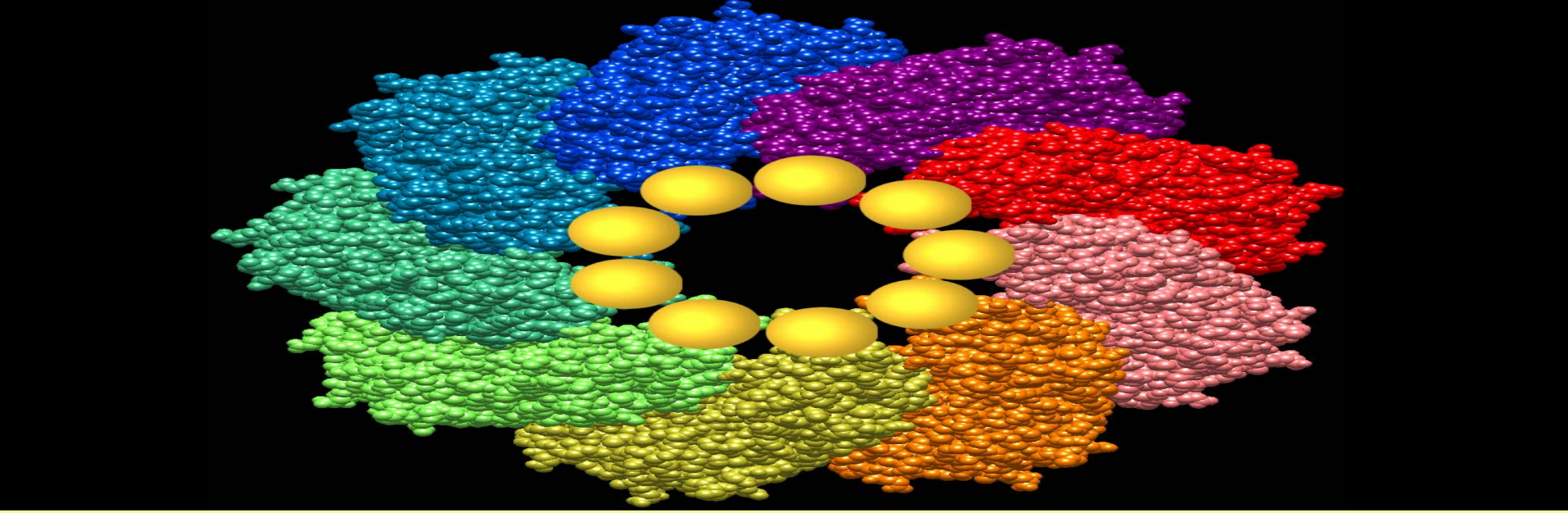
- (1st) Joint replacement
- Non-invasive and invasive diagnostics for rapid patient monitoring
- Cognitive-assist devices
- Targeted cancer therapies

- (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 changes
- Cell ageing
- Stem cell therapies

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

(modified after NBIC Report, 2003)



Part C
National Nanotechnology Initiative: The Long-term View

- **Motivation and timeline**
- **Outcomes in the first five years of NNI**
- **New frontiers in 2005 and long-term planning**

New York, November 2006

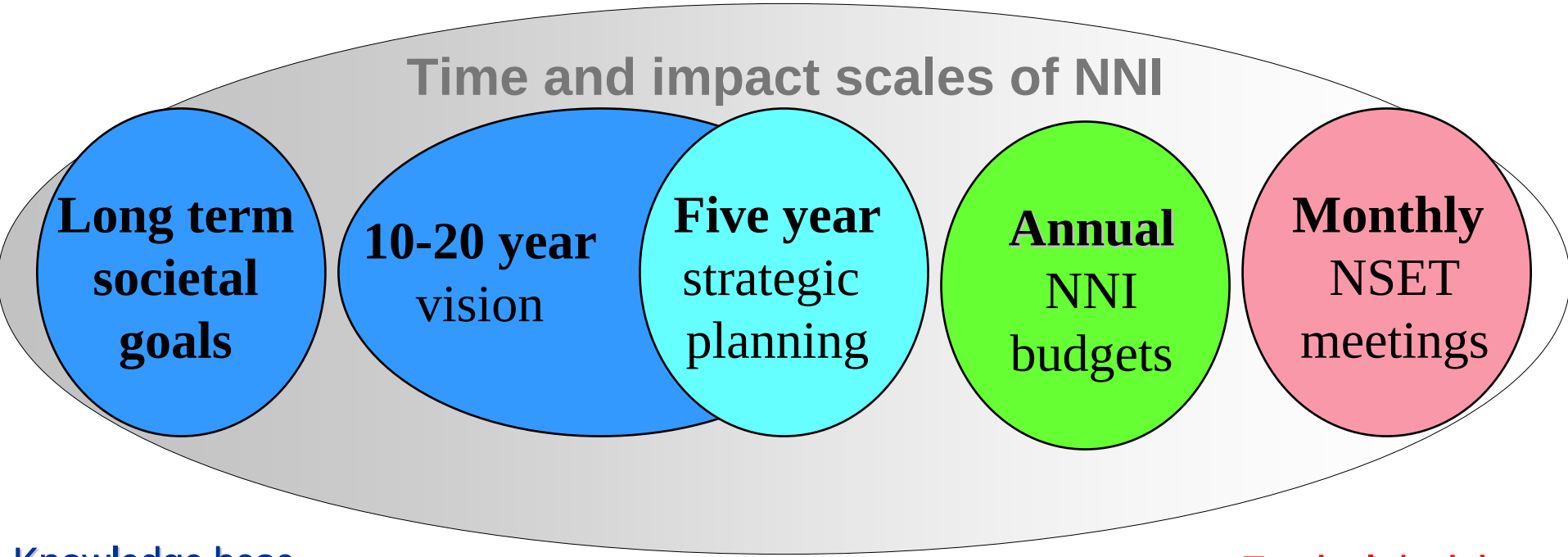
R&D towards the Next Industrial Revolution

1999 metrics, 2004 check the progress, 2015 to satisfy first criteria

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 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)**

The long-term vision drives NNI



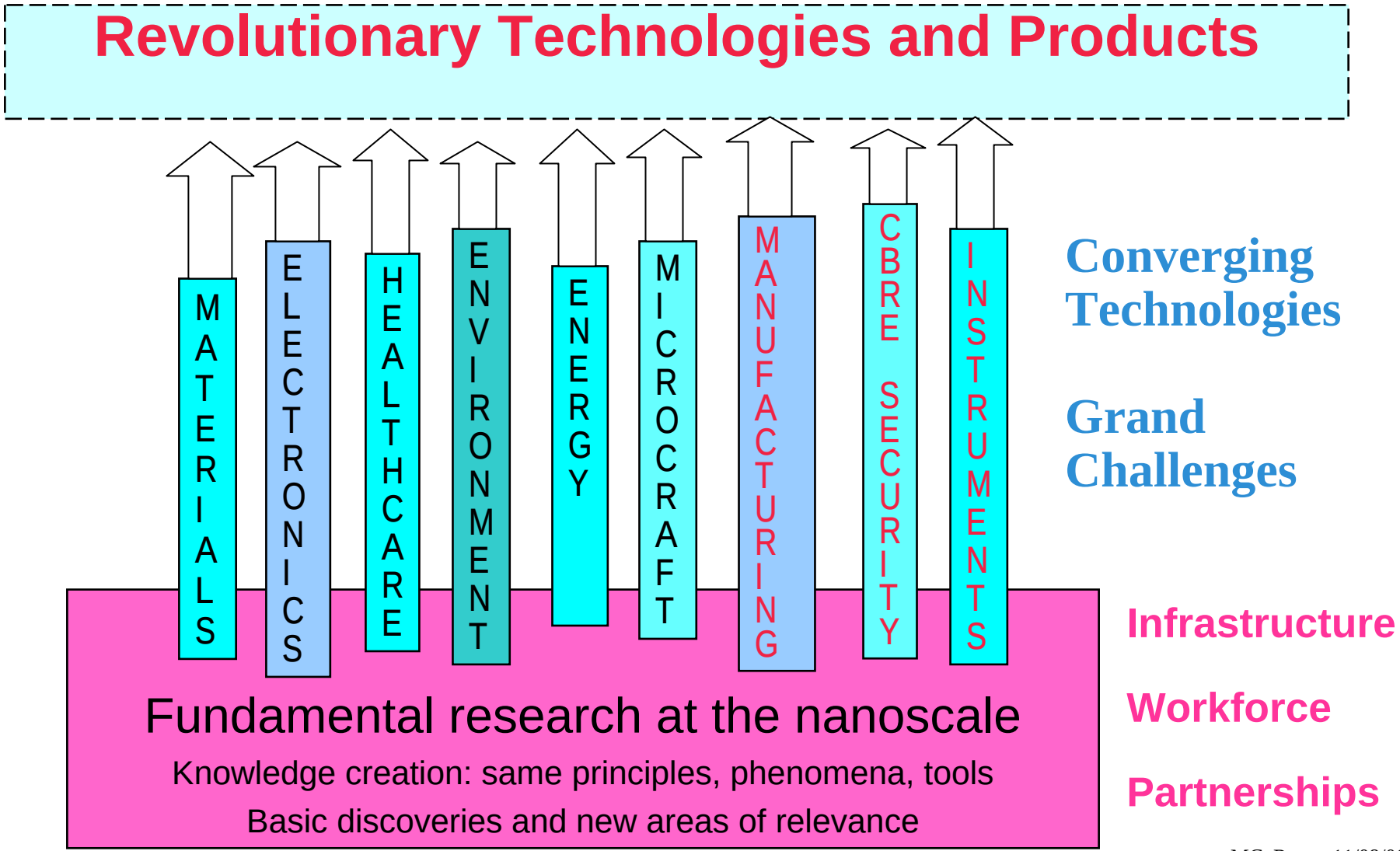
Knowledge base
Economy
Quality of life
Responsible NT
World context

1999 Research Directions I
2004 Research Directions II
10 topical reports in 03-04
Evaluation PCAST, NRC

Annual budgets
FY 2001, .. , 2005
EOP evaluation, OMB, GPRA, COV

Tactical decisions
Programs
Partnerships
Safety issues

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



NATIONAL NANOTECHNOLOGY INITIATIVE

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

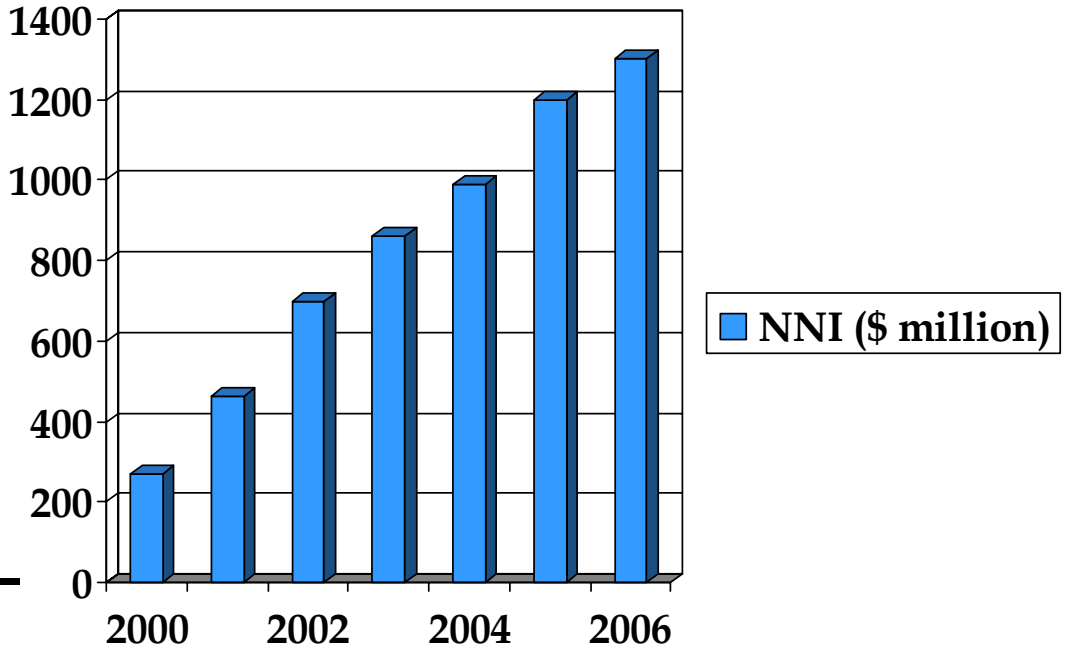
Fiscal year (all in million $)	*2000* Actual	*2001* En./Actual	*2002* En./Actual	*2003* En./Actual	2004 En../Actual	2005 En./Actual	2006 En/Est	2007 Req
NSF	97	150 /150	199 /204	221 /221	249 /256	305/335	344/344	373/
DOD	70	110 /125	180 /224	243 /322	222 /291	276/352*	230/436*	345/
DOE/BES+FS	58	93 /88	91.1 /89	133 /134	197 /202	211/208	207/207	258/
HHS/NIH+NIOSH	32	39 /39.6	40.8 /59	65 /78	70 /106	89/168	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	53/79	75/78	86/
EPA	-	/5.0	5.0 /6	5 /5	5 /5	5/7	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	11/3	3/
DOJustice	-	/1.4	1.4 /1	1.4 /1	1.4 /2	1/2	2/1	1/
Congressionally-directed		/464	/ 697	/ 862	/ 989			
add to DOD and NASA		/25	/40	/80	/103			
TOTAL	270	422 /489	600 /737	770 /942	849 /1092	982/1200	1054/1303	1278/
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)

NNI FY 2006 Budget
Total = $1,303 million

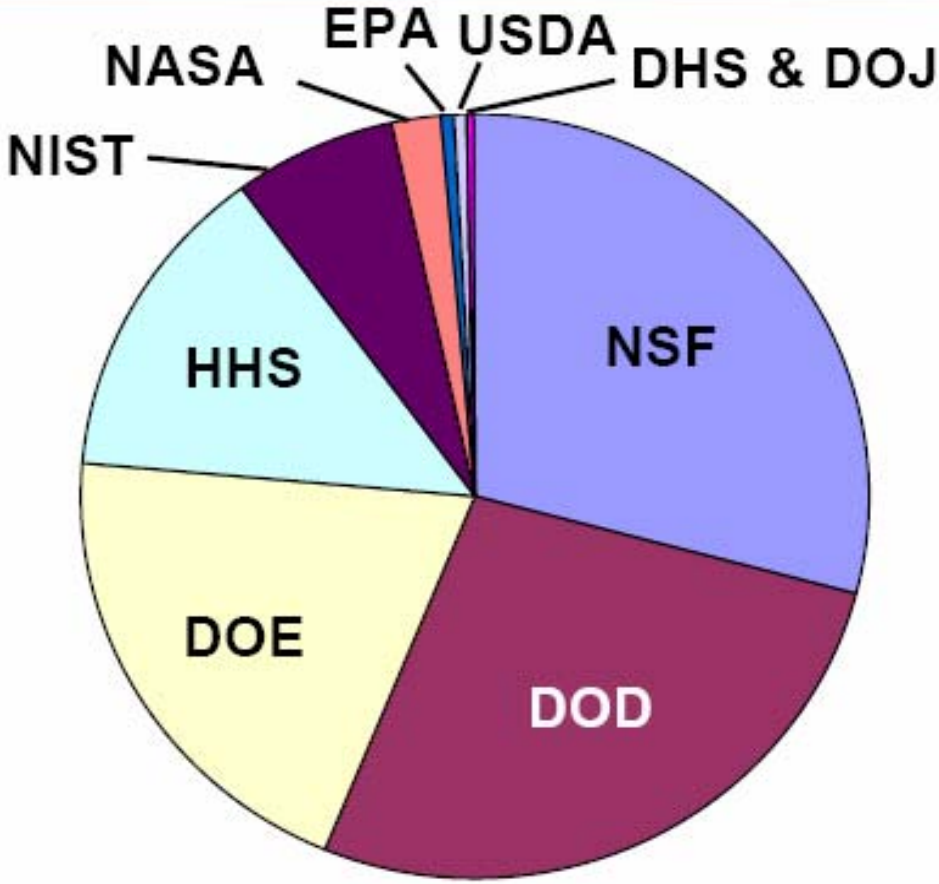
Fiscal Year	NNI
2000	$270M
2001	$464M
2002	$697M
2003	$862M
2004	$989M
*2005	$1200M
*2006	$1303M
*2007	>$1278M

* Includes Congressionally directed additional funding



NNI FY 2007 Budget Request

Total = $1,277 million



How is the Government Investing NNI Funding?

$1.3 Billion is FY2006 Estimated NNI Funding

NSF - 344

DOD - 257+

Congr. Adds

DOE - 207

HHS - 175

NIST - 78

NASA - 50

EPA - 5

USDA - 3

DOJ - 2

DHS - 1

Academia ~65 % → Single and Multiple Investigators; Centers and User Facilities

Government Intramural ~25% → Centers and User Facilities; NRL, AFRL, ARL NIH, NASA, NIST, EPA, FDA, DOE Nat Labs

Industry ~10% → SBIR, STTR, ATP, DOD Contracts

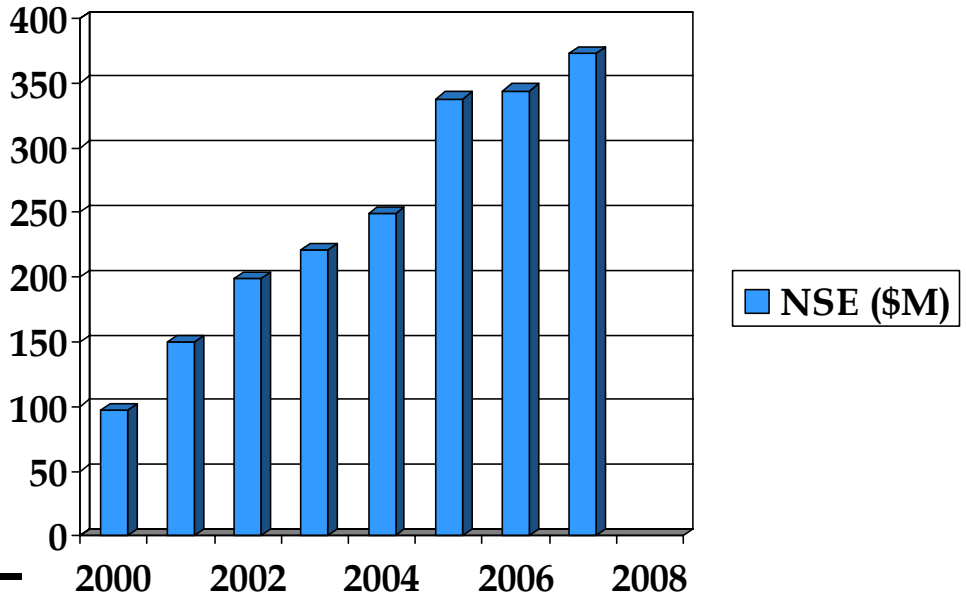
NSF - a pioneer at the international level in Nanoscale Science and Engineering (NSE)

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

FY 2008 Request: $389M ~1/4 of Federal and ~1/12 of World Investment

- Fundamental research - seven PCAs with new priorities
- Establishing the infrastructure - over 3,000 active projects; 24 large centers, 2 user facilities (NNIN, NCN), multidisciplinary teams
- Training and education - 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



Accomplishments 2001-2005(1)

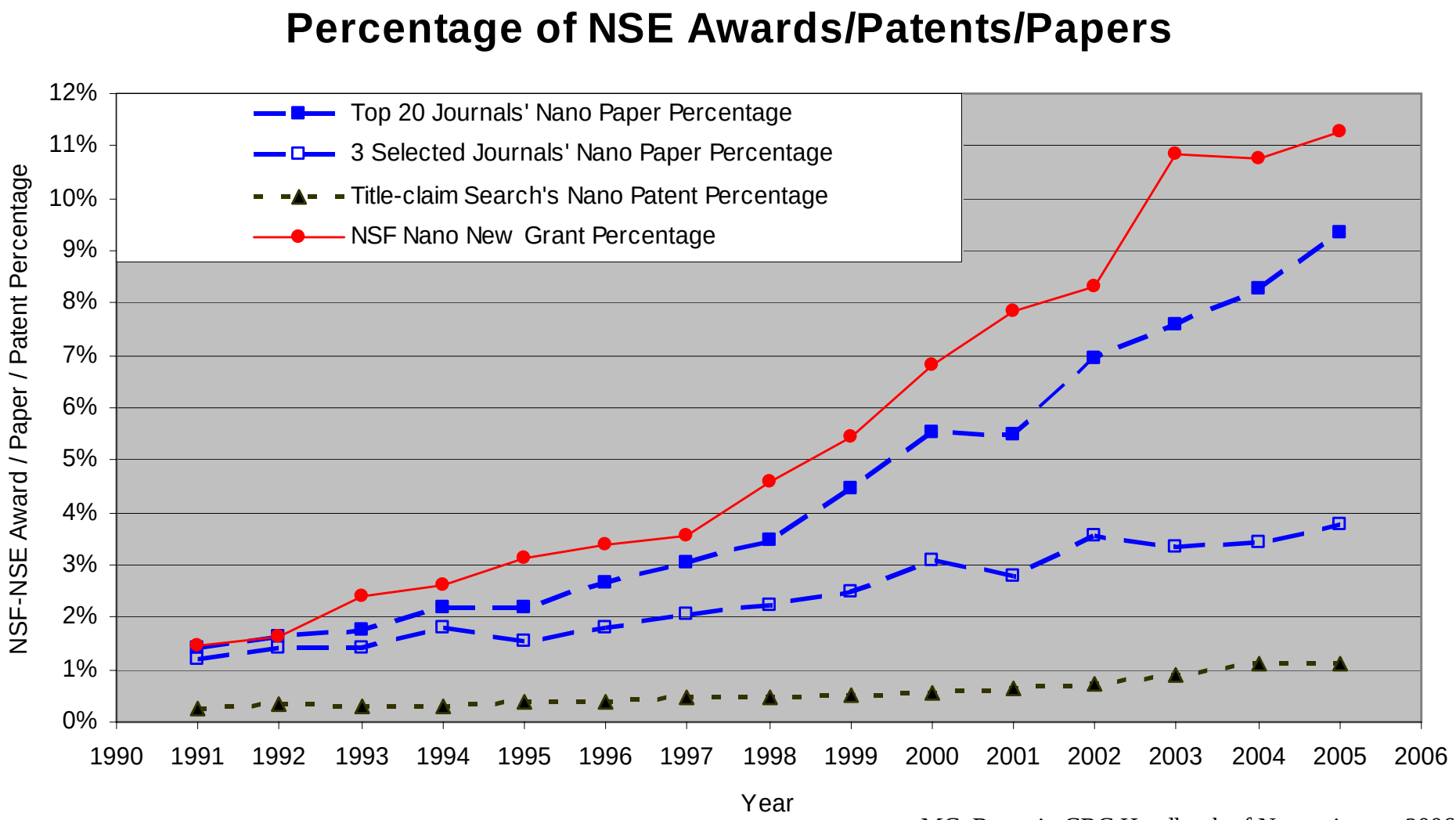
- Developed foundational knowledge for control of matter at the nanoscale:
  over 4,000 active projects in > 500 universities, private sector institutions and gov. labs in all 50 states
- "Created an interdisciplinary nanotechnology community" [1]
- R&D / Innovation Results: With ~25% of global gov. investments, the U.S. accounts for ~ 50% of highly cited papers, ~ 60% of USPTO patents[2], and ~70% of startups[3] in nanotechnology worldwide.
  More than 2,000 US nanotech companies in 2006;
  Roughly half of companies were small businesses,
  and NNI SBIR/STTR investment was ~$70 million
- Infrastructure:
  over 59 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

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 - 2005; 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.

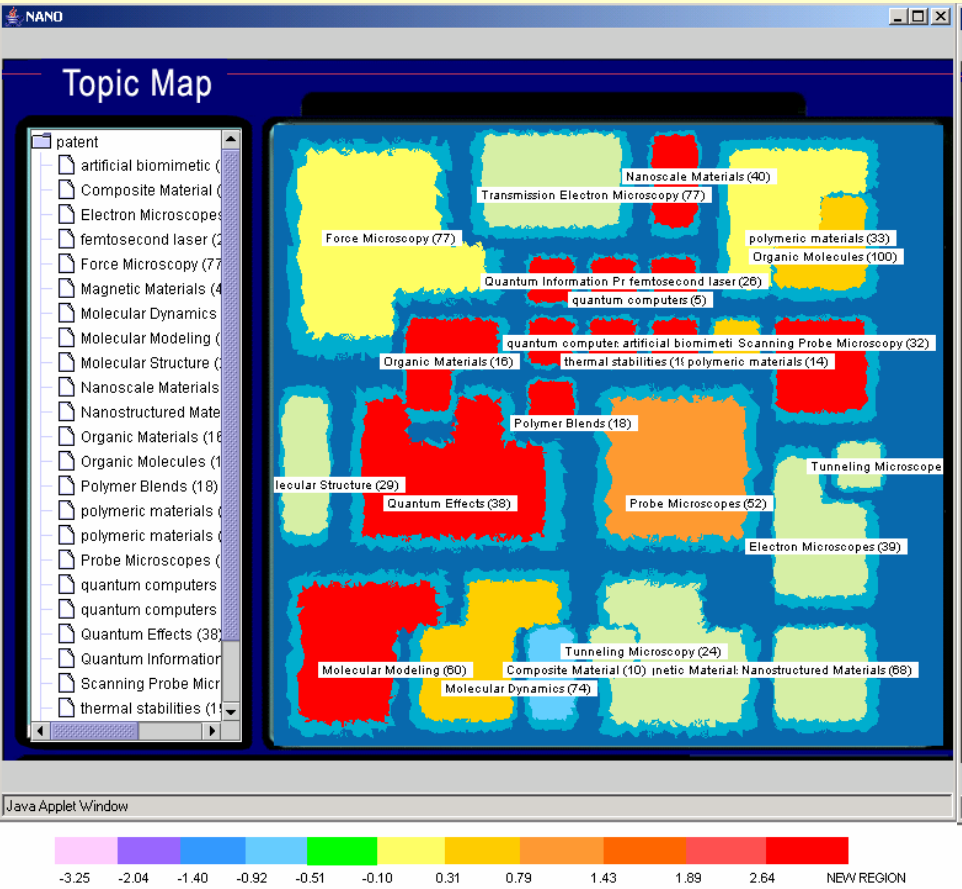
Keyword search for nanotechnology contents: NSF awards, USPTO patents and ISO papers



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

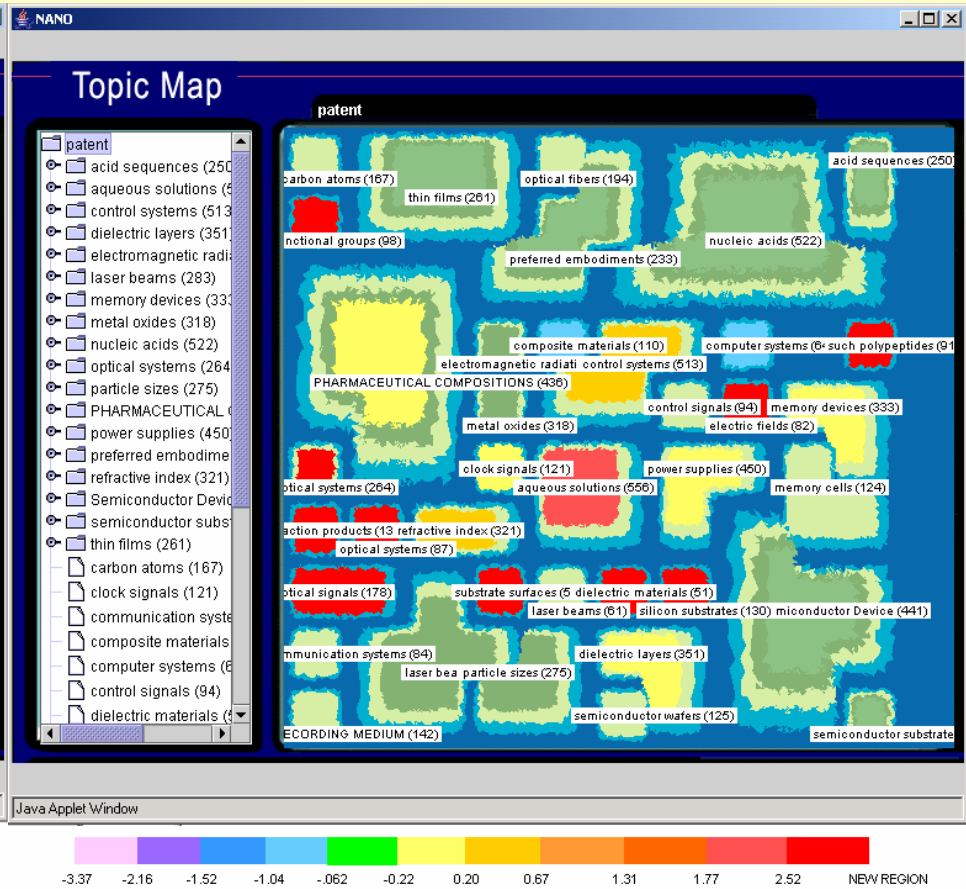
NSE content map analysis
grant – patent topic association

NSE Grant Content Map (2001-2002)



-3.25 -2.04 -1.40 -0.92 -0.51 -0.10 0.31 0.79 1.43 1.89 2.64 NEW REGION

NSE Patent Content Map (2001-2002)



-3.37 -2.16 -1.52 -1.04 -.062 -0.22 0.20 0.67 1.31 1.77 2.52 NEW REGION

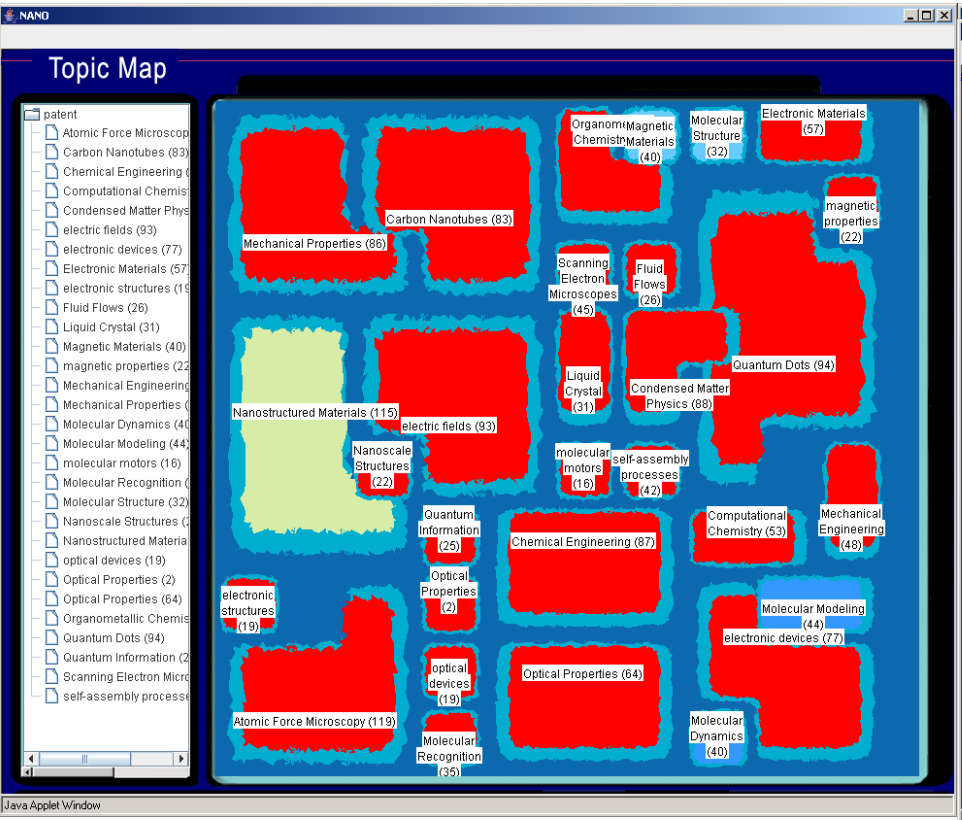
***Region color indicates the relative growth rate (red – highest rate)**

(source: NSF sponsored research; J. Nanoparticle Research, 2005, Issue 3)

MC. Roco, 11/08/06

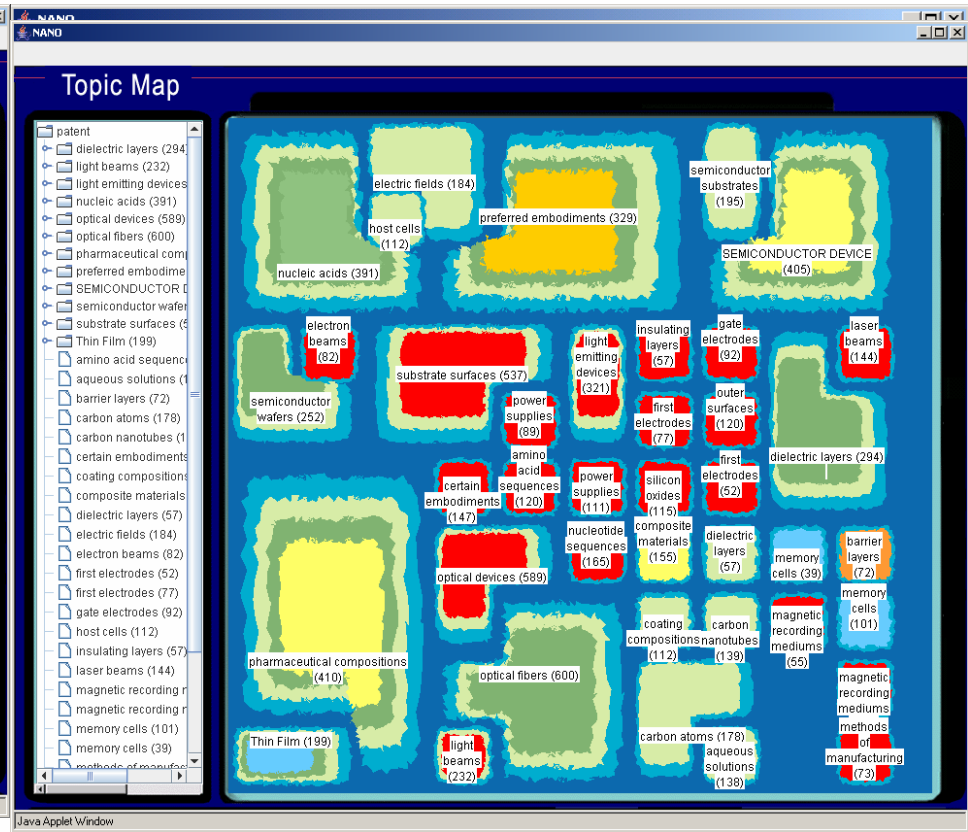
NSE content map analysis
grant – patent topic association

NSE Grant Content Map (2003-2004)



-2.31 -1.10 -0.46 0.01 0.43 0.83 1.25 1.73 2.36 2.82 3.57 NEW REGION

NSE Patent Content Map (2003-2004)



-2.88 -1.67 -1.03 -0.55 -0.13 0.26 0.68 1.16 1.79 2.25 3.00 NEW REGION

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

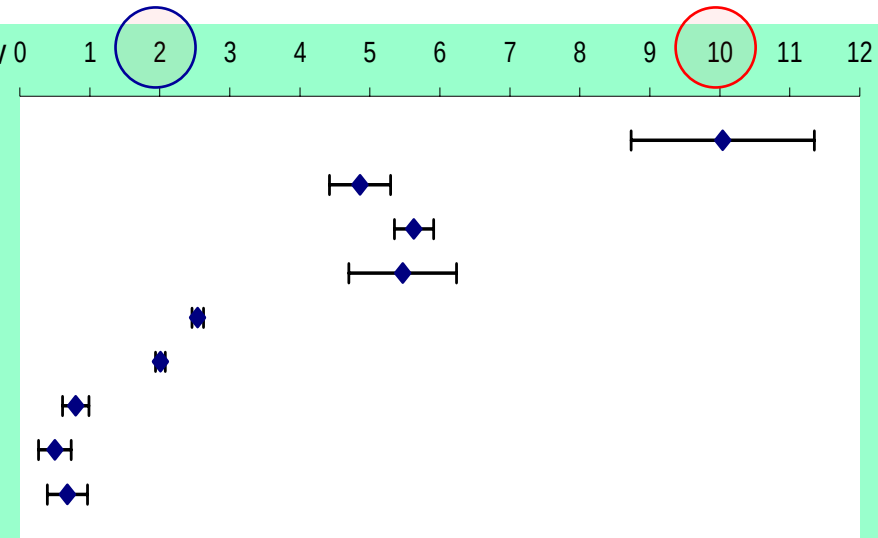
(source: NSF sponsored research)

Number of citations of Nanoscale Science and Engineering patents

(analysis NSF sponsored research and USPTO patents)

95% CIs based on pooled StDev

Group	N	Mean	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

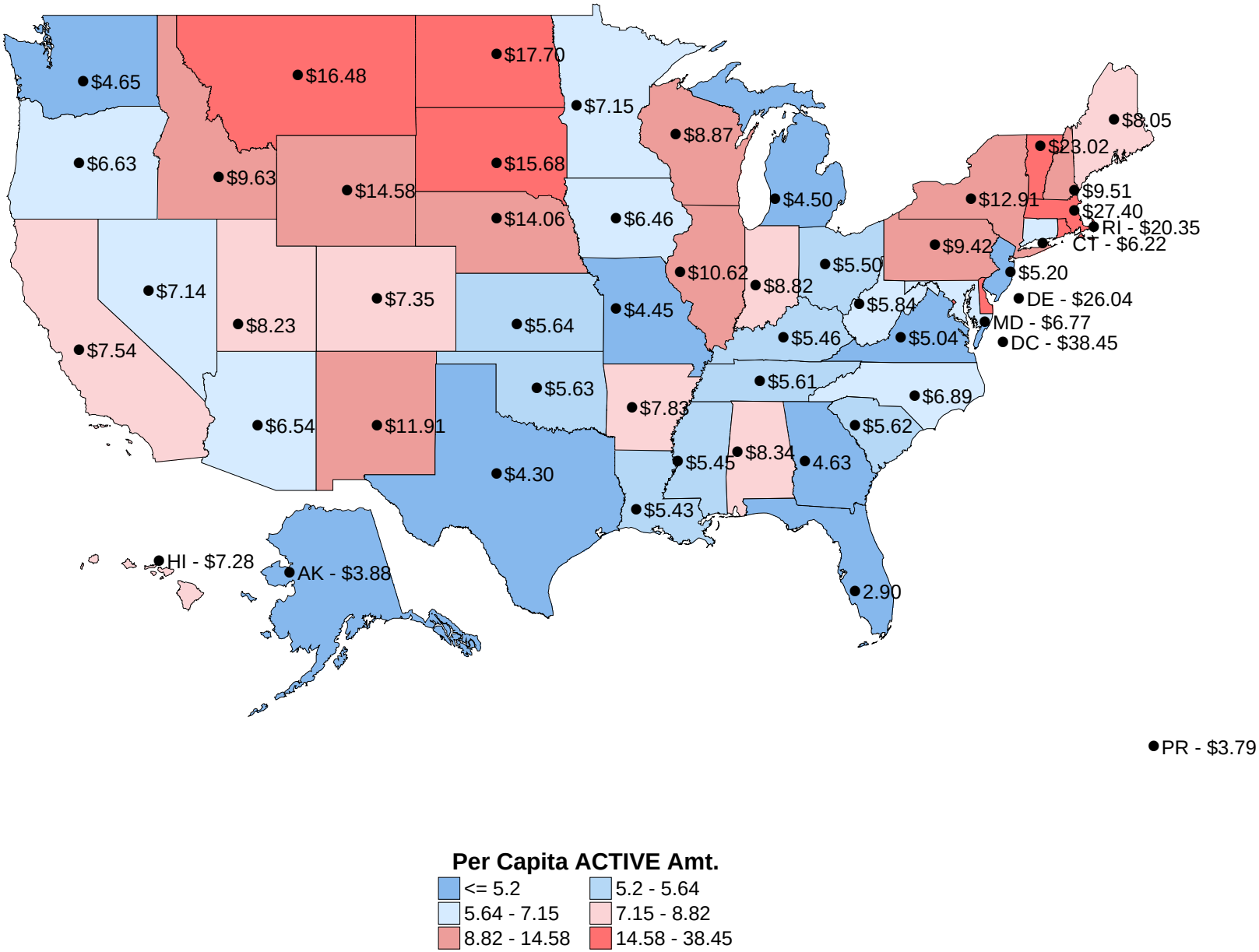


Pooled StDev = 11.70

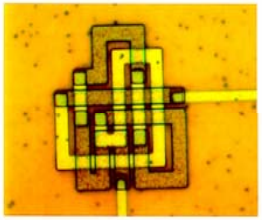
NSF Principal Investigator's patents had significantly higher number of cites measure than most other comparison groups. It shows the relevance of fundamental research for nanotechnology development.

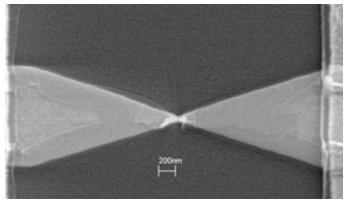
(from J. Nanoparticle Research, 2005, Vol. 7, Issue 3, 343-376; Fig. 14a)

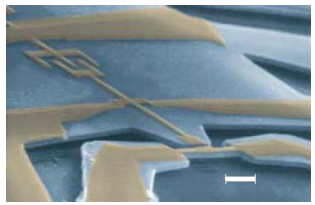
Per capita & year ACTIVE NSF/NNI Award Amt. by State for FY 2001- 2005

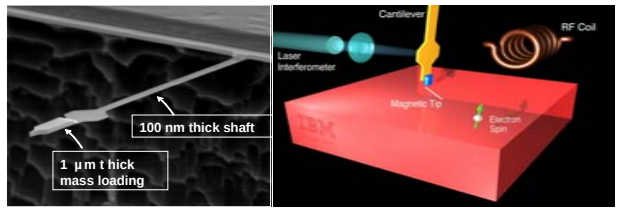


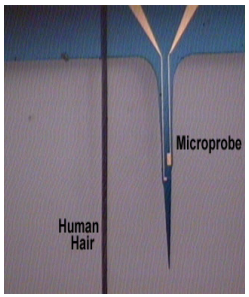
National Nanotechnology Infrastructure Network (NNIN)

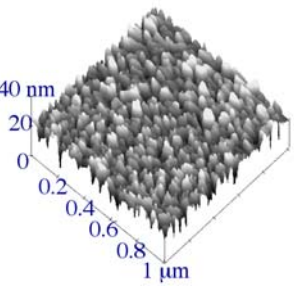


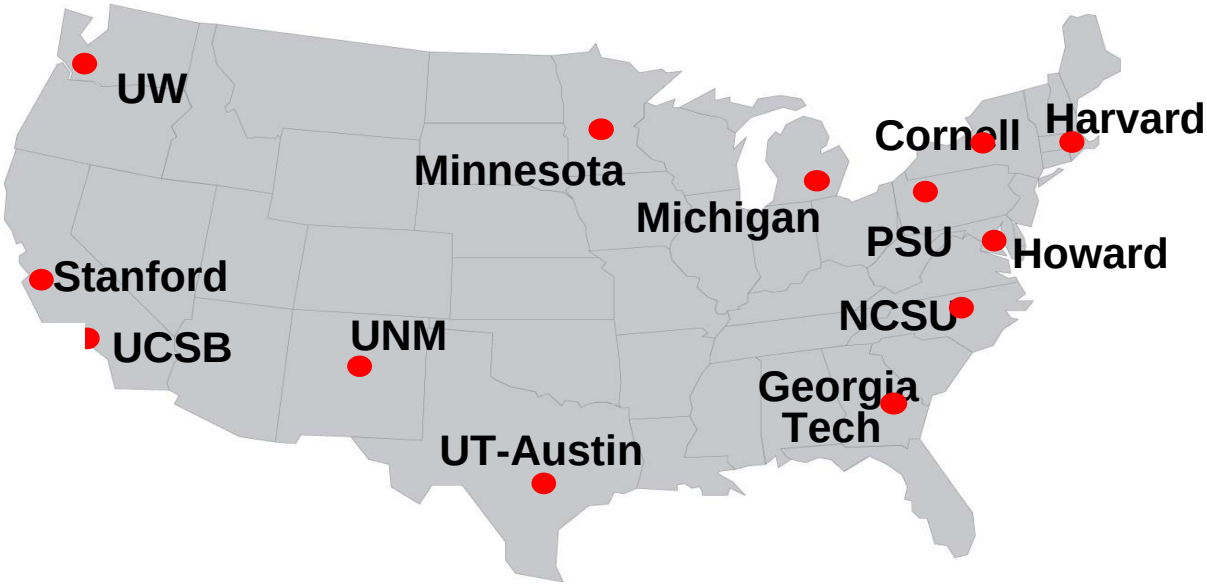












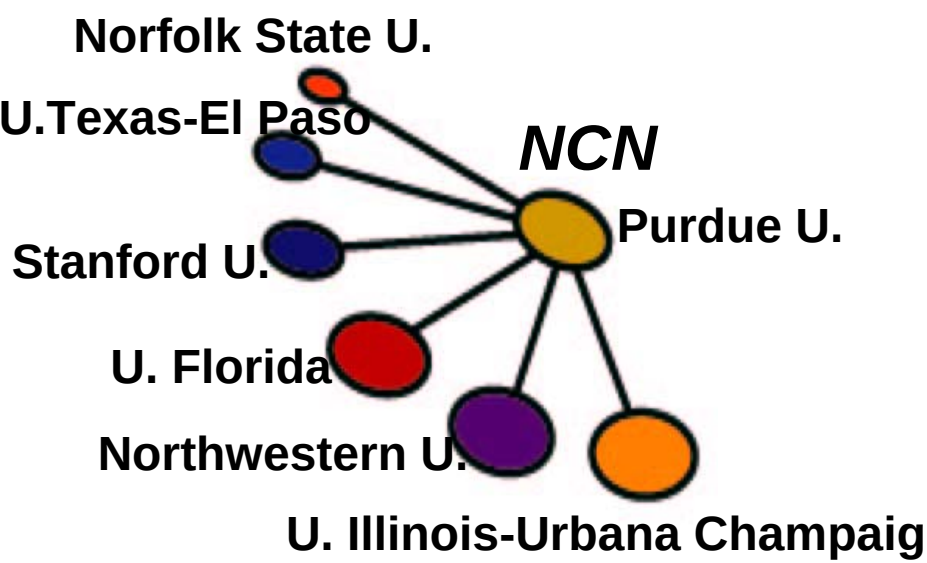
Cornell U (Lead)
Stanford U
U Michigan
Georgia Tech
U Washington
Penn State U
UC Santa Barbara
U Minnesota
U New Mexico
U Texas –Austin
Harvard U
Howard U
No. Carolina State U

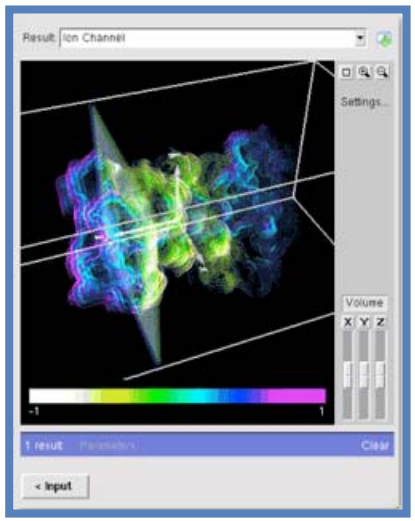
An integrated national network of user facilities providing researchers open access to resources, instrumentation and expertise in all domains of nanoscale science, engineering and technology

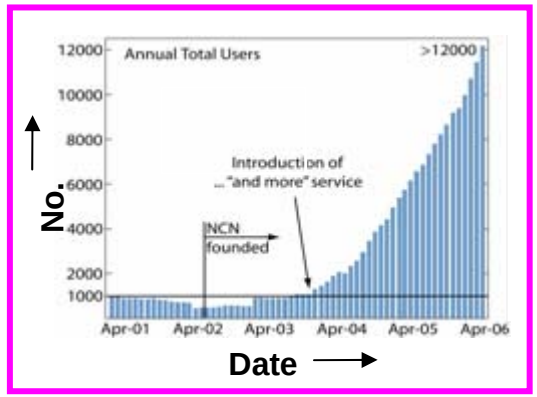
http://www.NNIN.org ***(over 4000 users/2005)***

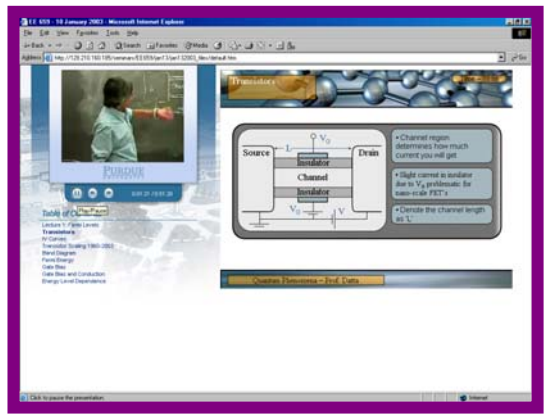
Network for Computational Nanotechnology (NCN)

A National resource to accelerate the transformation of nanoscience to nanotechnology through theory, modeling, and simulation and collaboration enabled by cyberinfrastructure









NSF Infrastructure and Research Network

http://www.nanoHUB.org (over 8,000 users in 2005)

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

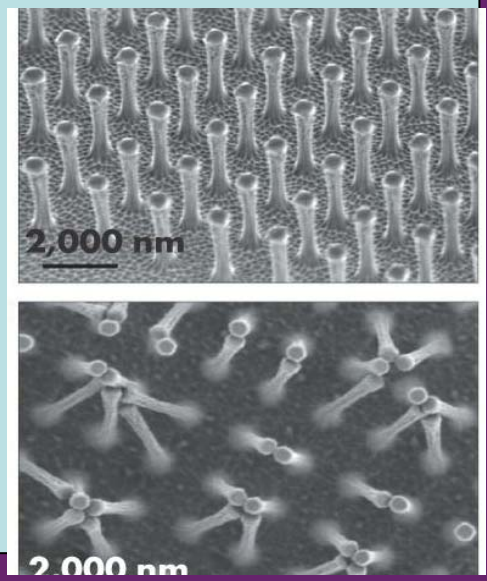
Center for Nanoscale Materials at Argonne

Spring '04

Center for Integrated Nanotechnologies

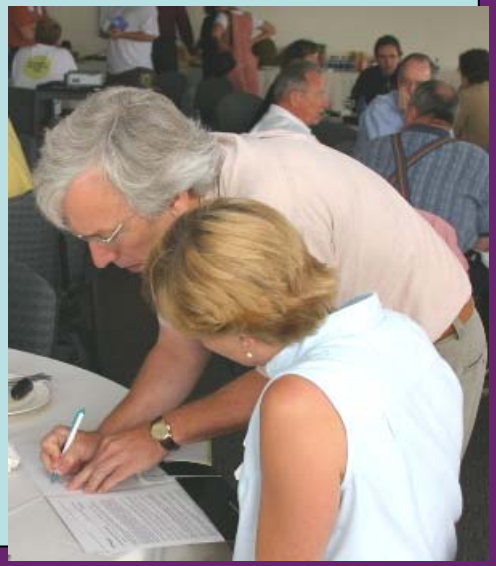
Nanotechnology Informal Science Education Network

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**

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

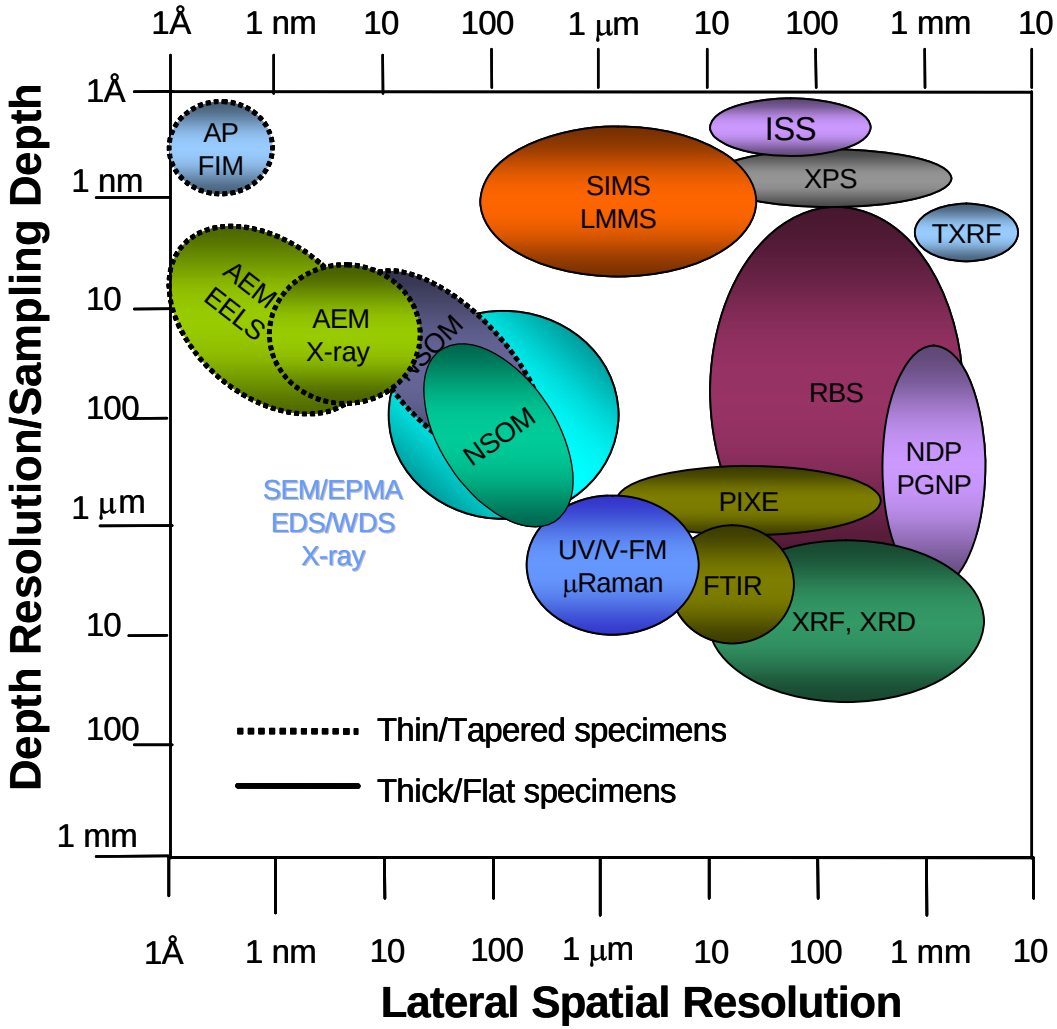
New catalysts for chemical manufacturing

Knowledge for no suffering from cancer when treated

Control of nanoparticles in air, soils and waters

Current status: Trade-off of depth resolution versus lateral resolution at the nanoscale at one location, time-averaged

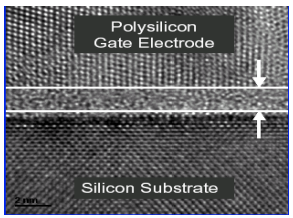
(NNI workshop, 2005)



Example Challenge 2015:
Transistor beyond/integrated CMOS under 10 nm

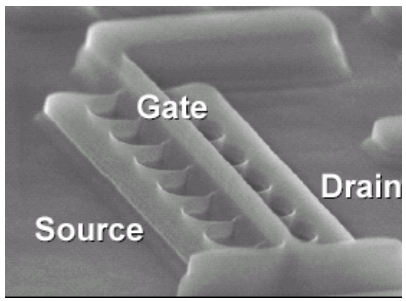
- In the 70s, 80s and 90s
  Geometrical scaling was the major driver

- 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

Challenge 2015: To simulate engineering problems from basic principles at the nanoscale

Using nanotechnology to build the highest speed processors

2004 (Cray X1):
50+ TFLOPS (fastest computer in the world)

~ 2010 (Cray Cascade):
DARPA – NSF – DOE acad. support
1,000 + TFLOPS

~ 2015 (Cray target):
10-100,000 TFLOPS

Challenge 2015: To Eliminate Suffering and Death Due to Cancer

"A Vision Not a Dream!" by using nanotechnology, A v. *Eschenbach, NCI*

Where We Want To Be ← Where We Are

Detection and Diagnosis

Detection and Diagnosis

Malignant Tumors With Metastases

Year 0 | Year X | Year Y | Year Z

Prevention

Prevention

Cancer results from accumulation of multiple genetic changes in a cells.

Nanotechnology will allow earlier detection and prevention (Year 0)

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

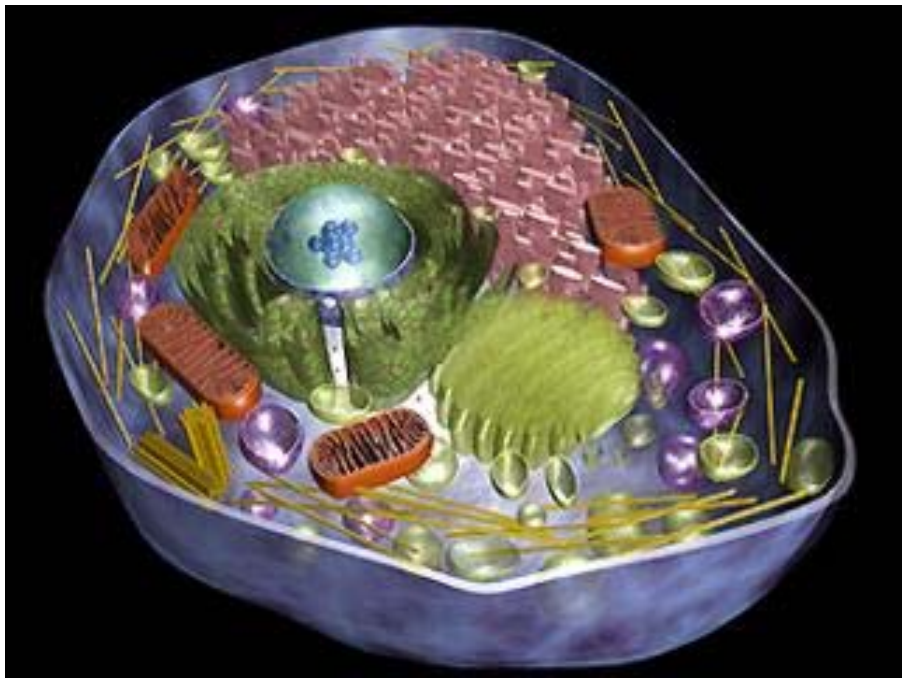
Converging technologies from the nanoscale

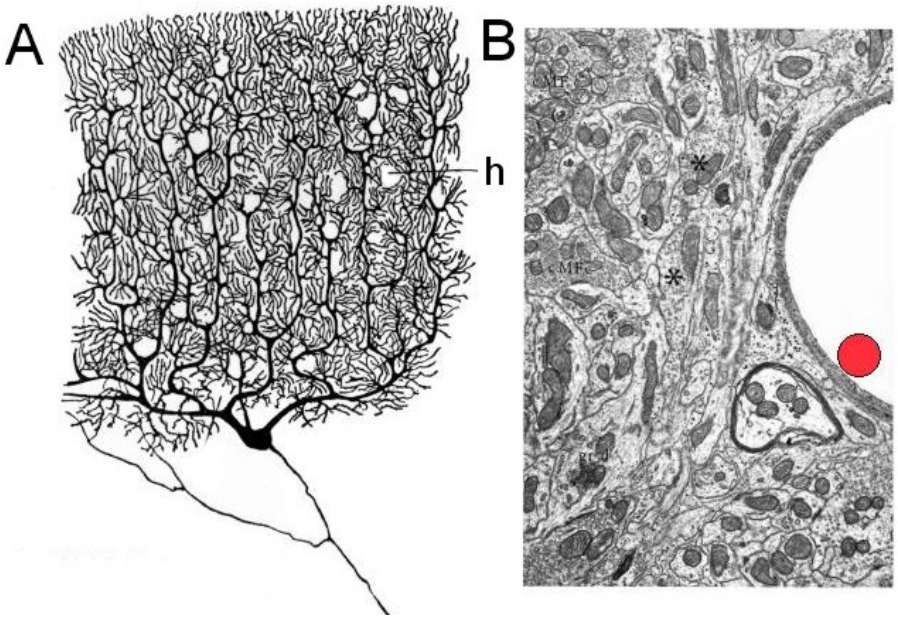
Including: artificial organs, manufacturing multidisciplinary platforms, etc.

Life-cycle biocompatible/sustainable development

Education: nanoscale instead of microscale-based

Challenge 2015: Specify the state of a cell and of nervous system from the nanoscale





R. Llinas, 2003

The Cell

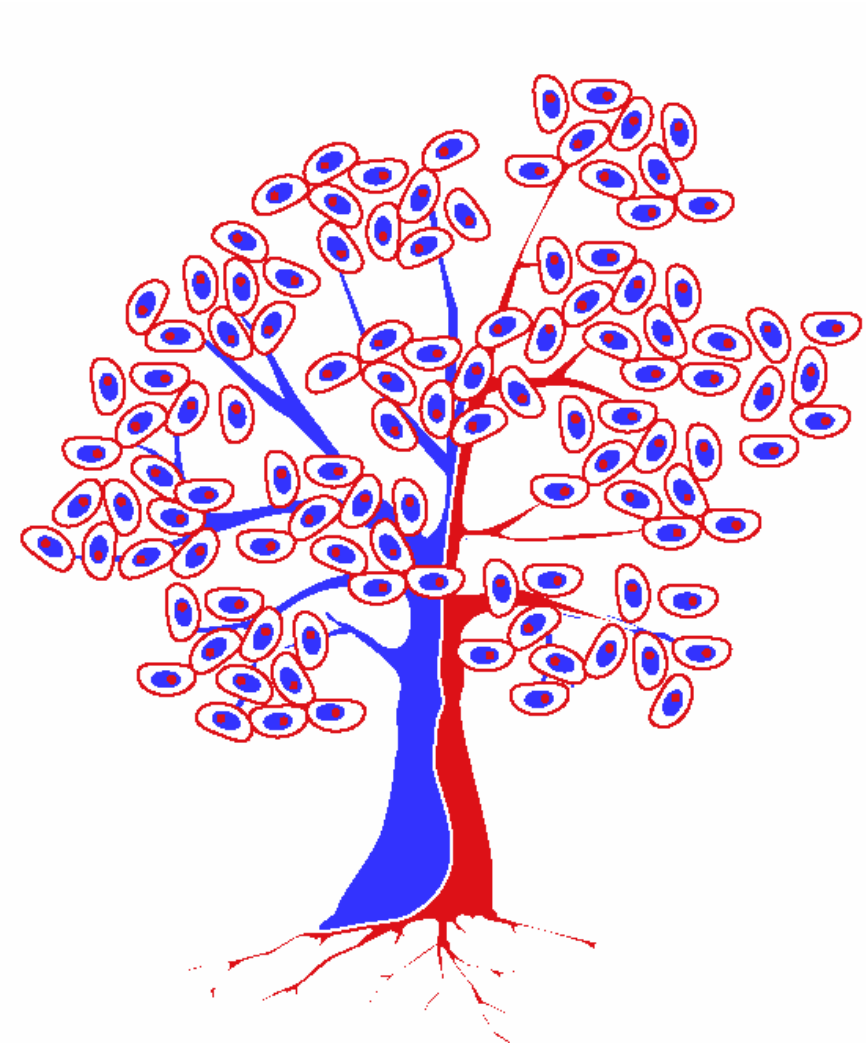
– basic nanosystem of life

The brain

– complex system based on nanoscale processes

Measure and simulate, 3 dimensional, highly parallel, . . .

Example program:
Vision for 2020: Regenerative medicine (2004-)



Combine precision assembly of matter (nanotechnology), building blocks of living systems biotechnology), spatio-temporal flow of information (IT), and cognitive sciences. Working group of 6 Federal agencies (NIH, FDA, DOD, NASA, DOC, NSF, Jan. 2004)

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: in vivo control of biology for med.**
- **Nano-informatics: libraries for integrating databases**

Nanomedicine Initiative Vision (NIH)

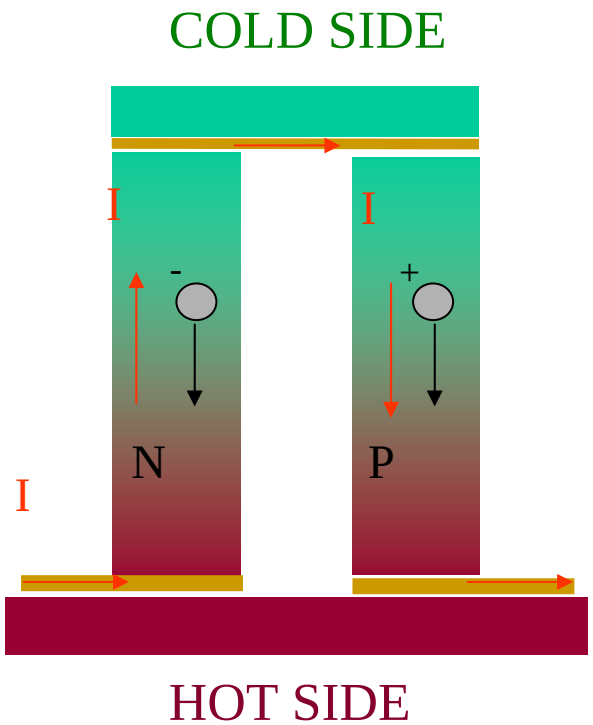
The overarching goal is to create the *conceptual and literal interface* between biology and medical devices at the scale of biomolecular processes.

Steps to achieve the goal:

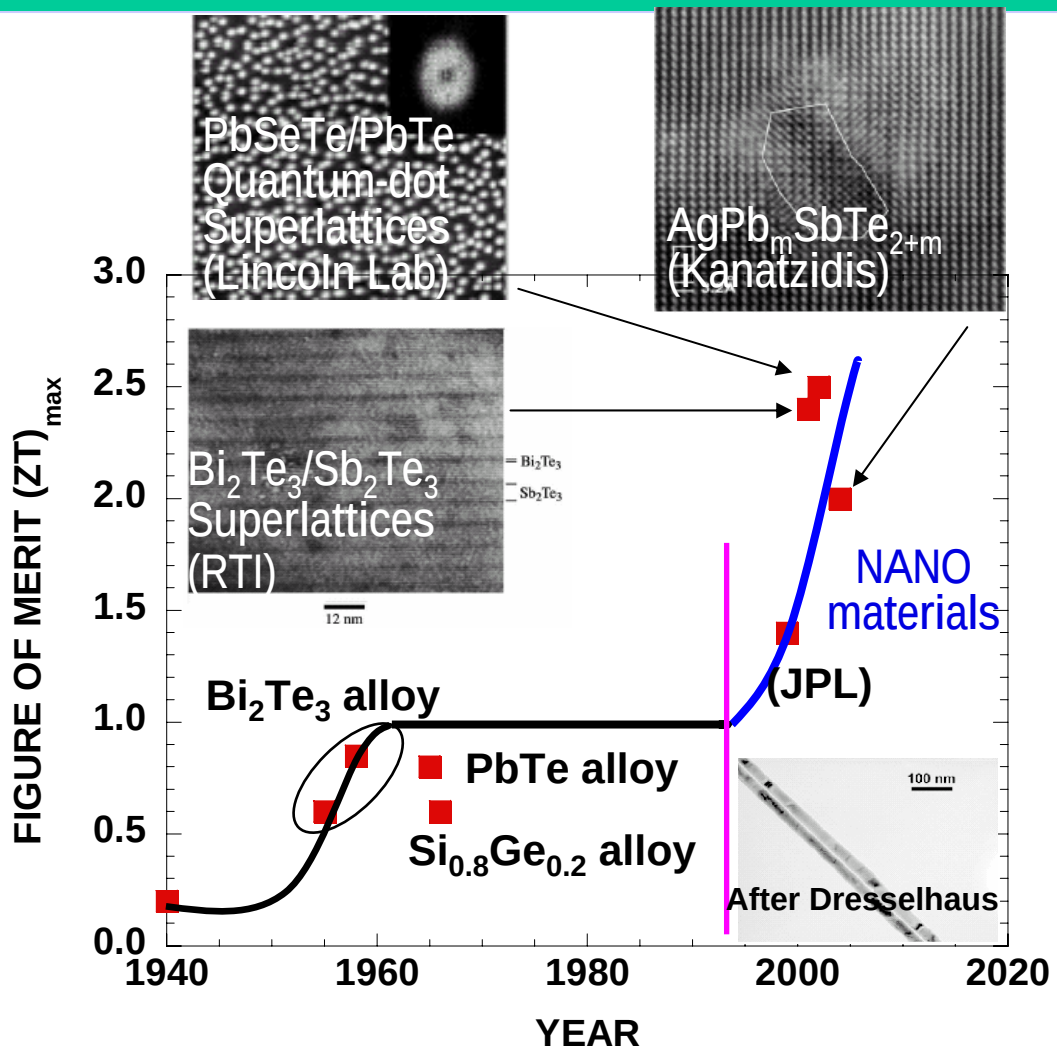
- Characterize quantitatively the physical and chemical properties of molecules and nanomachinery in cells;
- Gain an understanding of the engineering principles used in living cells to "build" macromolecules, molecular complexes, organelles, cells, and tissues; and
- Use this knowledge of properties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

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

Direct Thermo-electric Energy Conversion



Electron flux vs. phonon flux



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

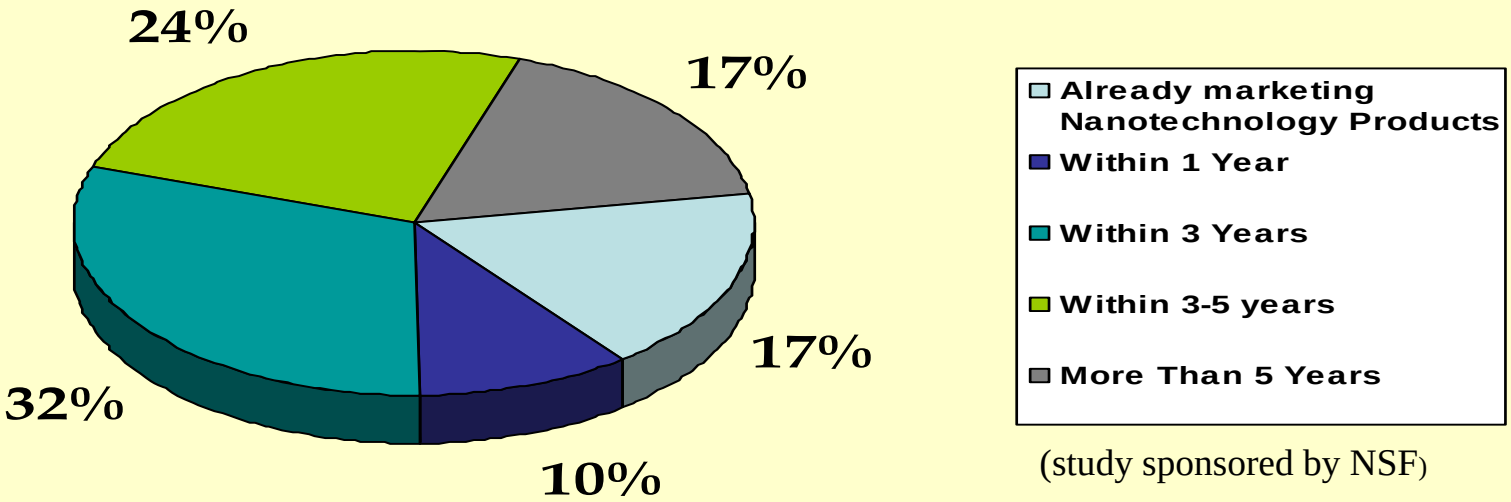
Industry surveys

- 19 of the 30 Dow Jones companies have launched nano initiatives
- All Fortune 500 companies in emerging materials / electronics / pharmaceuticals

- Timeline for commercialization (http://nano.nccms.org)

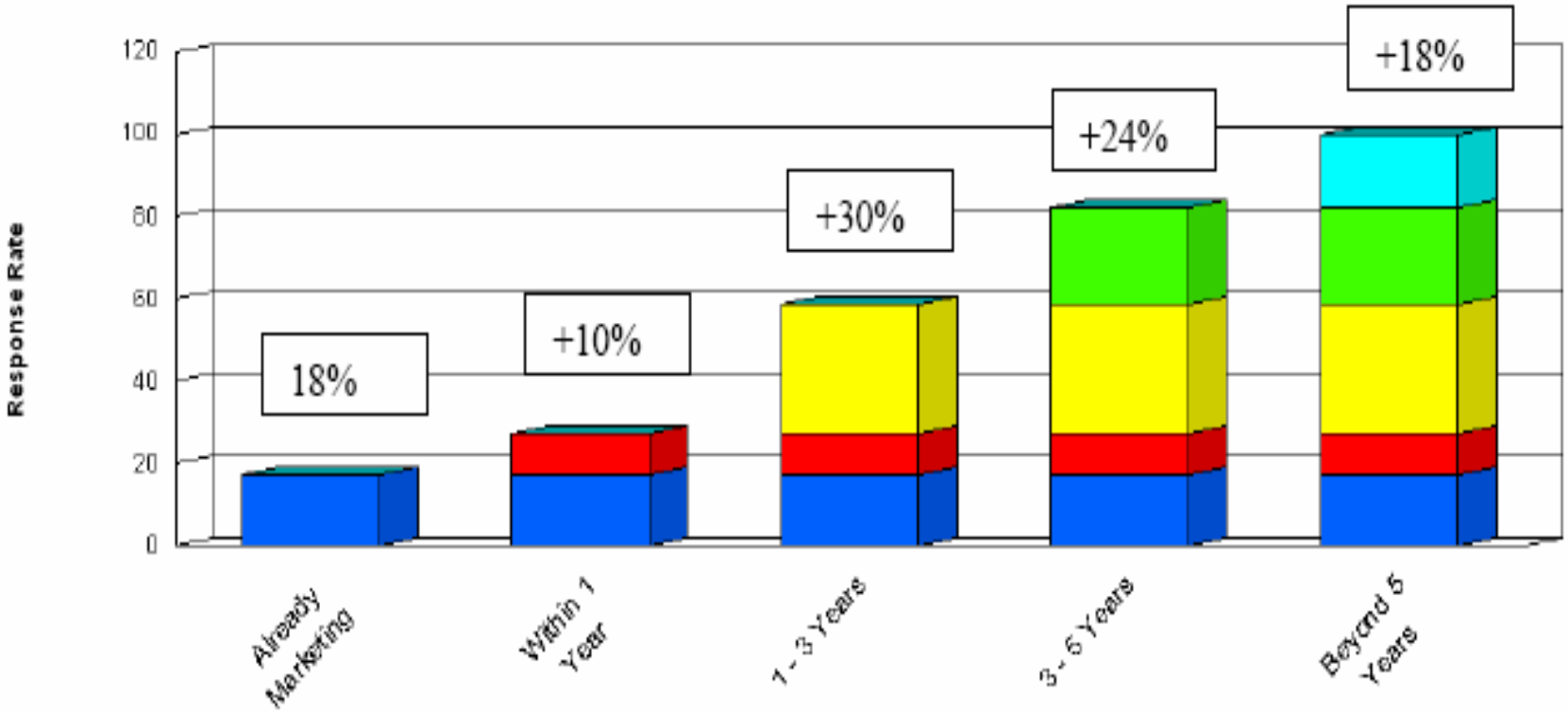
Survey by National Center for Manufacturing Sciences (2005):

600 manufacturing companies: 83% expect products in < 5 years



(study sponsored by NSF)

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

(National Center for Manufacturing Systems, Jan 2006)

NNI-Industry Consultative Boards for Advancing Nanotech (1)

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-Biotechnology (BIO lead), 10/2004-**
  - Collaborative activities in key R&D areas
  - 2 working groups, R&D collaboration and EHS; joint funding

NNI-Industry Consultative Boards for Advancing Nanotech (2)

Key for development of nanotechnology, Reciprocal gains

In development

- **NNI - Pharmaceuticals (Phrma lead), 4/2004-**
  - **Joint road map for nanomaterials R&D**
  - **2 working groups, including on EHS**
  - **Use of NNI R&D results, and identify R&D opportunities**
- **NNI – Forestry and paper products (FS lead), 10/2004-**
  - **Workshop / roadmap for R&D**
  - **2 working groups (nanotech in industry, EHS)**
  - **Exchange information, use NNI results, support new topics**
- **NNI - Automotive Industry, 3/2005-**

Other contacts: industry sectors such as aeronautics, plastics, food products, energy-related

Nanosys Inc.

Nanocomposite Solar Cells

Goal:

• Develop high performance, low cost lightweight flexible solar cells

Approach:

• Innovative solar cell design that combines precisely engineered inorganic semiconductor nanocrystals with a light-weight, flexible host-matrix

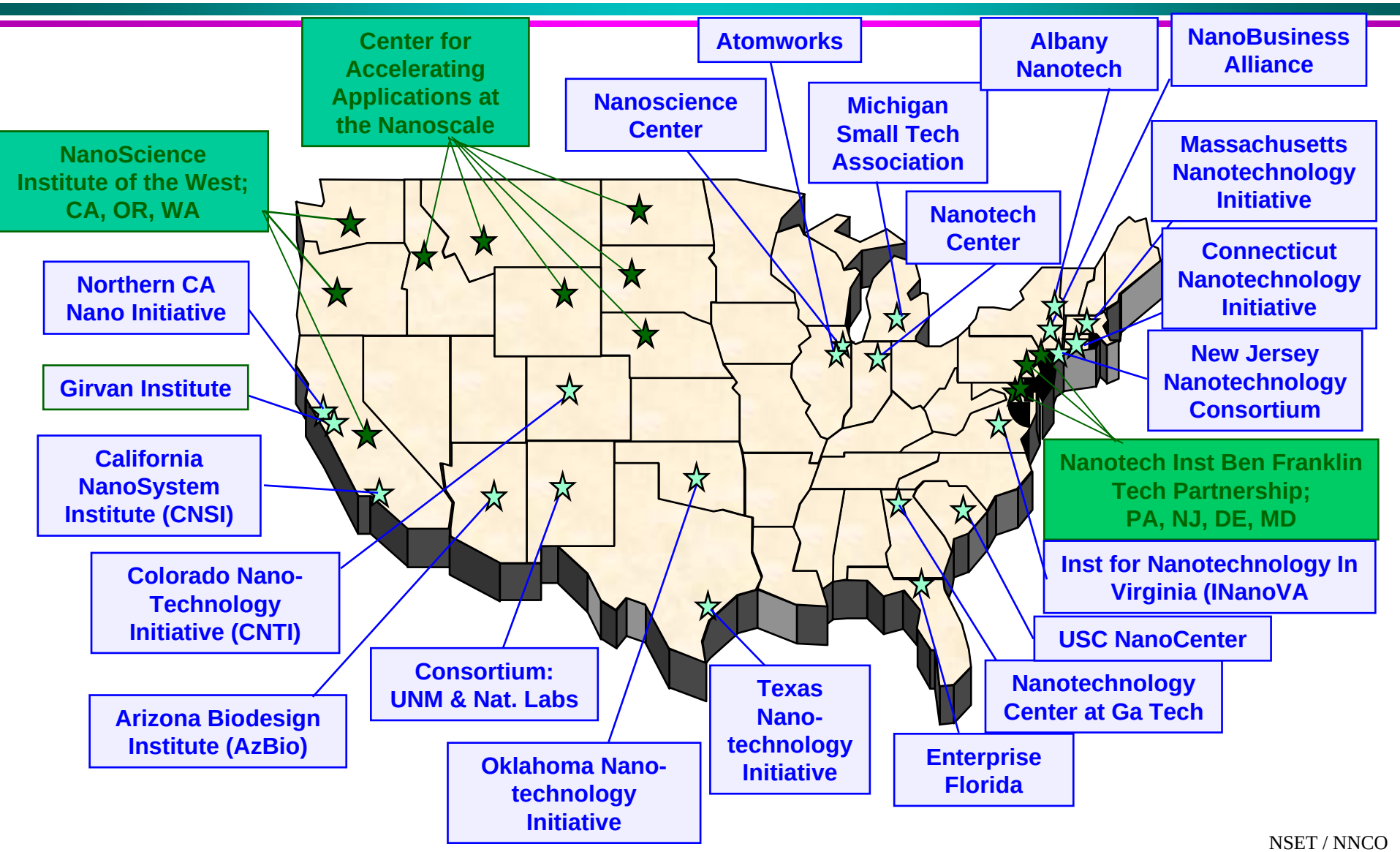
Technical Objectives:

• Develop optically and electronicly enhanced nanocrystals
• Develop new Device Components
• Develop Advanced Device Architectures

Commercialization Strategy:

• Nanosys focuses on nanotechnology element in the end product
• Partner with industry leaders to jointly develop and manufacture nano-enabled component into end product.
• Our partner provides marketing resources and access to end customers

Sampling of Current Regional, State, & Local Initiatives in Nanotechnology



NNI challenges

- Coherent long-term (5-10 year) programs: new priorities – how to handle budget constrains; support interdisciplinary research and education, flexible infrastructure, and broad societal implications; Nano-bio - in infancy

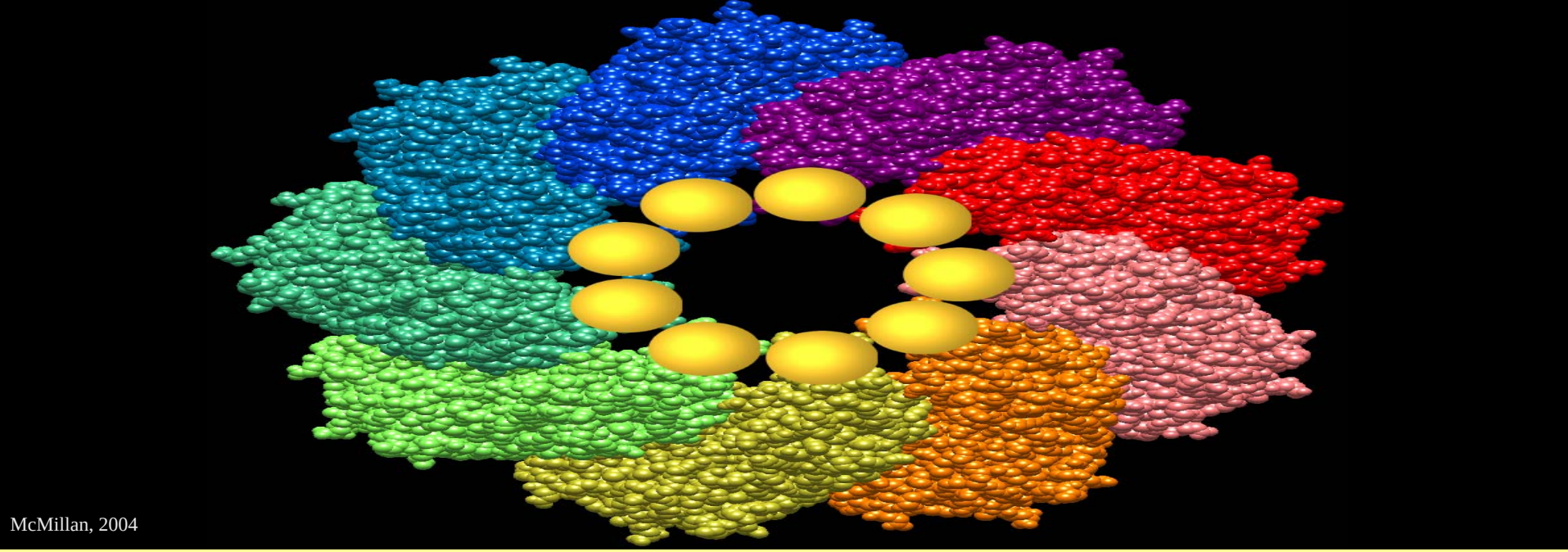
- Horizontal versus vertical S&T development

- More responsible and effective
  in including public, industry and states perspectives

- Collaboration and synergism among agencies

- Need for system-oriented programs, focused on topics such as:
  the new catalyst, new transistor, conditioning the cell

- International collaboration and competition



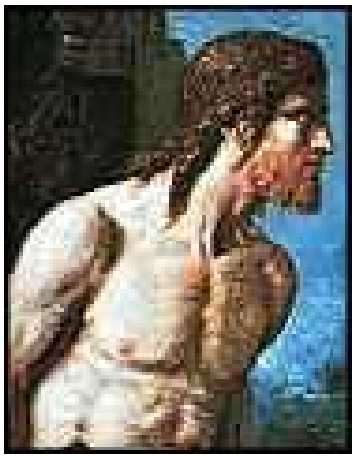
Part D
Aspects of Societal Dimension

- Governance and risk governance of nanotechnology development

New York, November 2006

Chances and risks of technology

- **<u>Human potential and technological development are coevolving</u>, and quality of life has increased tremendously with technological advancements**



S&T at the core of human endeavor; However, there is a perceived tension between the society and technology (maybe because significant changes, accelerated path, larger benefits & risks). Prometheus giving the fire: "An eternity of torture"

<u>Technology implications are global issues</u> (human development, EHS, E-W & N-S balance) that need to be addressed together through international collaboration

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 risk governance

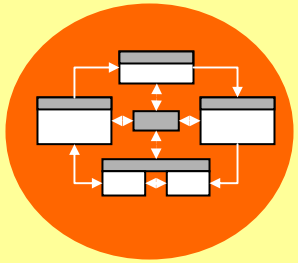
Governance of nanotechnology development: four roles

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

Nanotechnology Governance and Risk Governance

NANOTECHNOLOGY GOVERNANCE

- Investment policy
- Science policy
- Education policy
- Risk governance
- Building capacity
- . . . .



NANOTECHNOLOGY RISK GOVERNANCE

SCOPE
- Conceptual framework for integrated approach for decision-makers
- Neutral, constructive platform for all actors

GOALS
- Deficits & recommend.
- Cross stakeholders
- Multiple authorities
- Cross-boundary, global
- Short & Long-term view

WHAT IS DIFFERENT
- Structure NT development: 4 generations; 2 frames
- Include social context in assessment (ELSI +)
- Governance approach: corrective and adaptive

RISK GOVERNANCE APPROACH
- Begin with the IRGC framework
- Methodologies for 2 risk frames
- Focus: EHS, ELSI, EGI, PSI, HDI
- Stakeholder engagement
- Risk communication
- Risk governance methods

Need for a specific framework for risk governance of nanotechnology

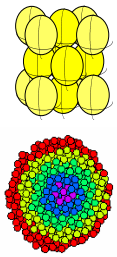
Focus on risk analysis for the higher-risk, high production applications:

- Open and complex system
  - fundamental (high risk)
  - developments are not known (role organizations)
  - accelerated (upstream measures needed)
  - cross S,E&T (complex interactions)

- With broad implications (general platform)
  - affects most areas of economic activity, effect of the "food chain" of the nanotech products (need for comprehensive evaluation of societal implications)
  - global technological implications, cross-borders (connect models for governance at the national and the international levels, E-W, N-S)

TIMELINE FOR BEGINNING OF INDUSTRIAL PROTOTYPING AND NANOTECHNOLOGY COMMERCIALISATION:

FOUR GENERATIONS OF PRODUCTS AND PRODUCTION PROCESSES

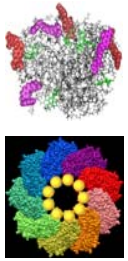


1st: Passive nanostructures (1st generation products)

a. *Dispersed and contact nanostructures*. Ex: aerosols, colloids

b. *Products incorporating nanostructures*. Ex: coatings; nanoparticle reinforced composites; nanostructured metals, polymers, ceramics

~ 2000

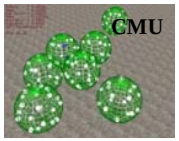


2nd: Active nanostructures

a. *Bio-active, health effects*. Ex: targeted drugs, biodevices

b. *Physico-chemical active*. Ex: 3D transistors, amplifiers, 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

Frame 1

Risk Governance Frame 2

Categorization of nanotechnology into two risk perception frames of reference

- Criteria for structuring
  - Level of complexity of the nanotechnology products/ processes and dynamic changes in structure, state, functions when used
  - Evolution of knowledge
  - Potential social implications; the measures to address them.
- Two risk perception frames are proposed
  - Frame 1 Passive Nanostructures
    Typical risk: Component complexity
    (Passive nanostructures, with steady structure / state / functions)
  - Frame 2 Nanodevices and Nanosystems
    Typical risk: System uncertainty
    (Active nanostructures and nanosystems)

Strategies as a function of the generation of NT: 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

NT application areas

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)

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

Passive and Active Nanostructures, Nanosystems and Molecular Nanosystems

FRAME 1

1. Passive (steady function) Nanostructures: with new properties and functions for same chemical composition; inert or reactive nanostructures that have stable behavior and quasi-constant properties during their use.

FRAME 2

2a. Active (evolving function) Nanostructures:
the structure, state and/or properties change during their use; successive changes may occur either intended or unforeseen reactions in the external environment.

2b. Nanosystems: passive and/or active nanostructures are integrated into systems. Large and complex systems of nanosystems are expected to have multiple applications.

2c. Molecular Nanosystems: engineered nanosystems where the main components are molecular or supramolecular devices, connectors, etc. each playing a particular function. Emerging behavior is expected, particularly for applications based on biological systems.

Examples of potential products of nanotechnology

FRAME 1

First Generation (2000 -)

- Cosmetics / sunscreens
- Higher efficiency chemicals
- Enhanced textiles
- Food and drink additives
- Increased data storage in computer chips
- Harder ceramics and metals
- Wound dressings that release intensive antimicrobials

FRAME 2

Second Generation (2005 -)

- Catalysts to clear up waste streams
- Localised drug delivery which target specific cells
- Agricultural sensors to release pre-programmed and self-regulated delivery of nutrients or pesticides
- Sensors which detect and control chemical or biological releases
- Nano-bio devices e.g. medical implants such as artificial heart valves; activated heart implants; remote activation of nanostructured implants in the brain; drugs for cognitive functions
- Nanodevices with active photonic, electronic, biological, mechanic components

Examples of potential products of nanotechnology

FRAME 2

Third Generation (2010 -)

- Industrial products based on complex nanosystems, nanorobotics
- Creation of completely new plants and food products
- Brain-machine interface
- Brain-to-brain interaction
- Regenerative medicine
- Hybrid systems; e.g. modified viruses and bacteria

Fourth Generation (2015/2020 -)

- Novel designs of molecules for selfasseembling in products
- Cell ageing therapies
- Nanoscale genetic therapies
- Neuromorphic engineering
- Human-machine interface
- Complex, large nanosystems integrated with applications in industry, agriculture, energy conversion and other areas

Nanotechnology Risk Governance
- *Types of deficits* -

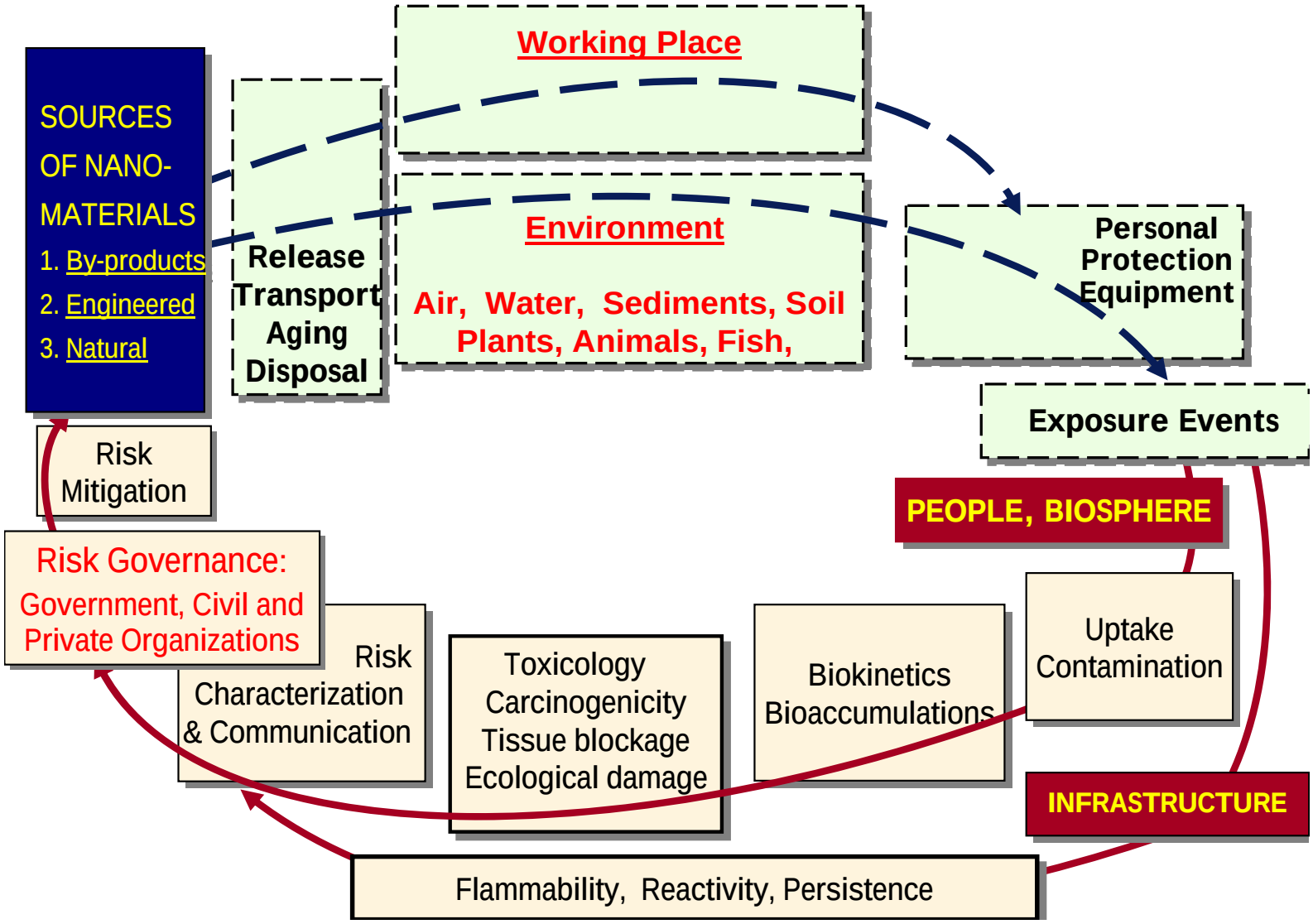
(1) First generation of products of passive nanostructures

- Limited understanding of the new properties and functions on toxicity and bioaccumulation
- Limited knowledge on nanomaterials exposure rates
- Gaps in the regulatory systems at national and global levels

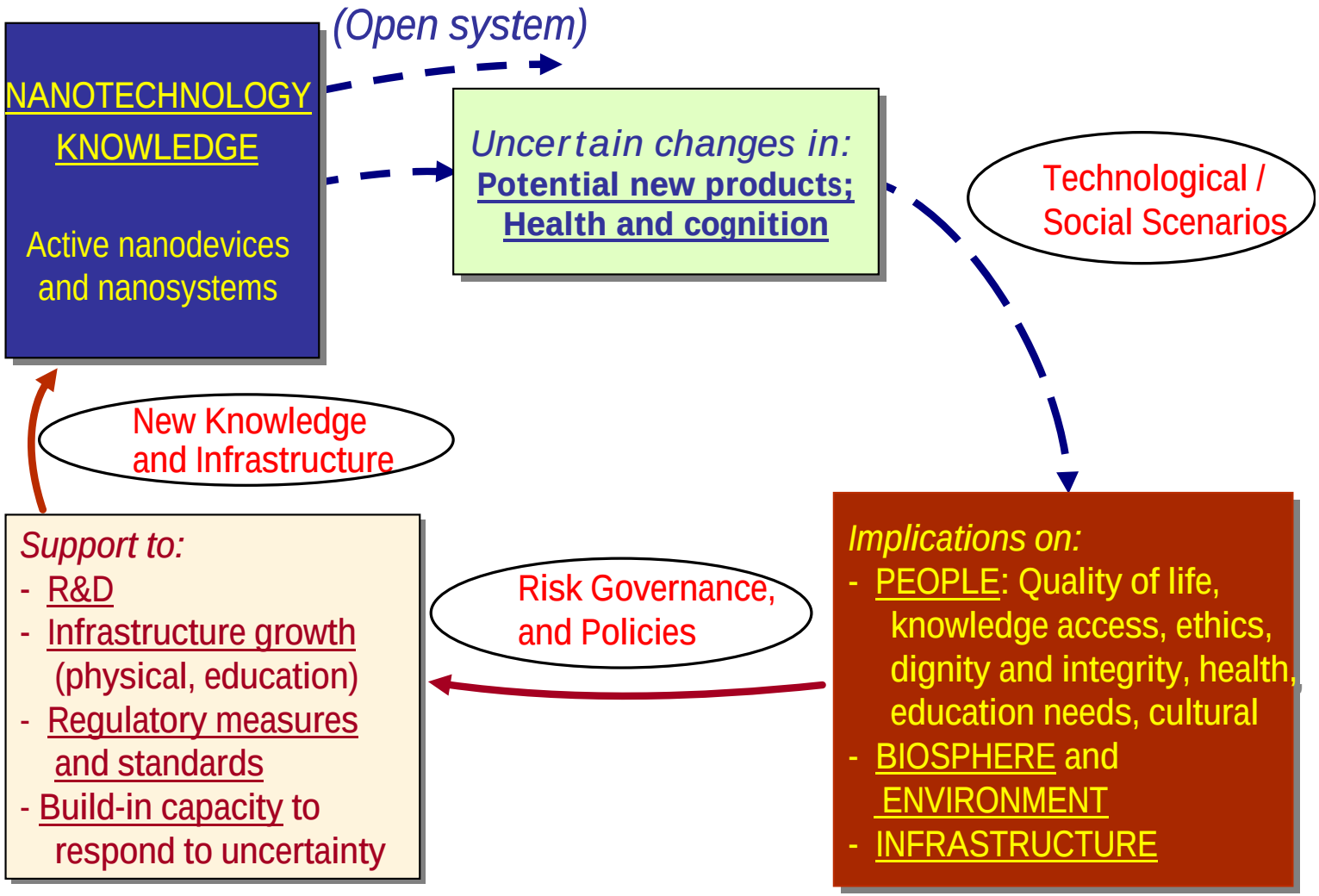
(2) Second to fourth generation of nanoproducts

- Uncertain and/or unknown implications of the active nanodevices, nano-bio applications, and nanosystems on evolution of nanotechnology
- Potential human effects (e.g. health, changes at birth, brain understanding and cognitive issues, and human evolution)
- Lack of a framework through which organization and policies can address such uncertainty

EHS RESEARCH AND REGULATION FOR NANOMATERIALS (FRAME 1): KEY PHYSICO-BIOLOGICAL PROCESSES AND DECISION STEPS DURING THE LIFE-CYCLE OF NANOMATERIALS RELEASED EITHER IN THE ENVIRONMENT OR AT THE WORK PLACE



RISK GOVERNANCE FOR ACTIVE NANOSTRUCTURES AND NANOSYSTEMS (FRAME 2): KEY DECISION PROCESSES IN THE OPEN LOOP APPROACH



Key Research Needs for the Two Nanotechnology Risk Frames

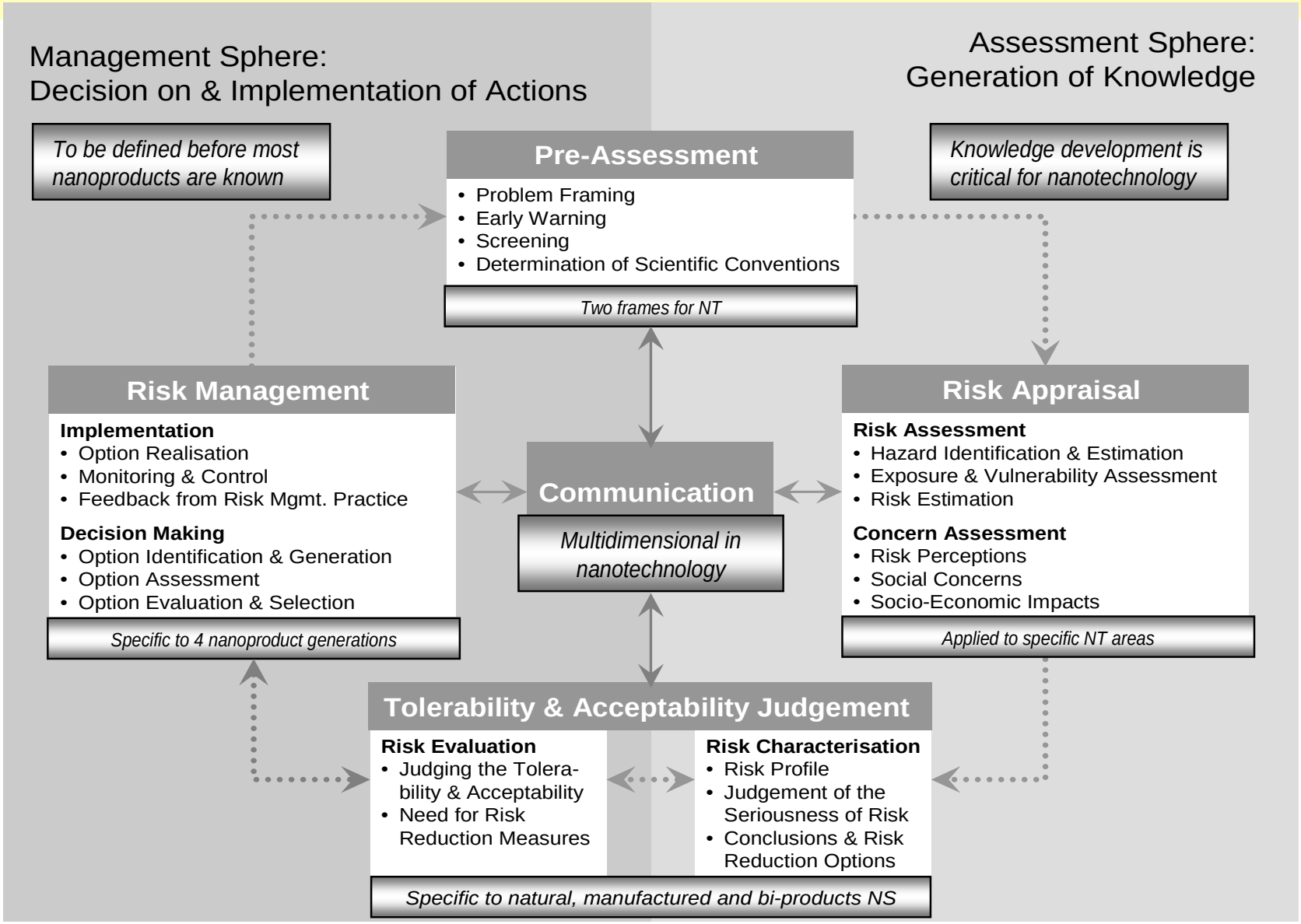
Nanotechnology Risk Debate	Hazard	Exposure	Risk
Frame 1	Testing strategies for assessing toxicity; Best metrics for assessing particle toxicity	Exposure monitoring methodologies; Methods for reducing exposure and protective equipment	Risk assessment methodologies; Communication and education concerning EHS and ELSI.
Frame 2	Identifying the hazards using scenarios; Matrix for assessing the identified hazards	Estimation of exposure for events with great uncertainties using methods such as casual chain	Communication and education concerning EHS and ELSI; Developing capacity to address uncertain/ unknown and ambiguous developments.

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 information 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

IRGC RISK GOVERNANCE FRAMEWORK FOR NANOTECHNOLOGY



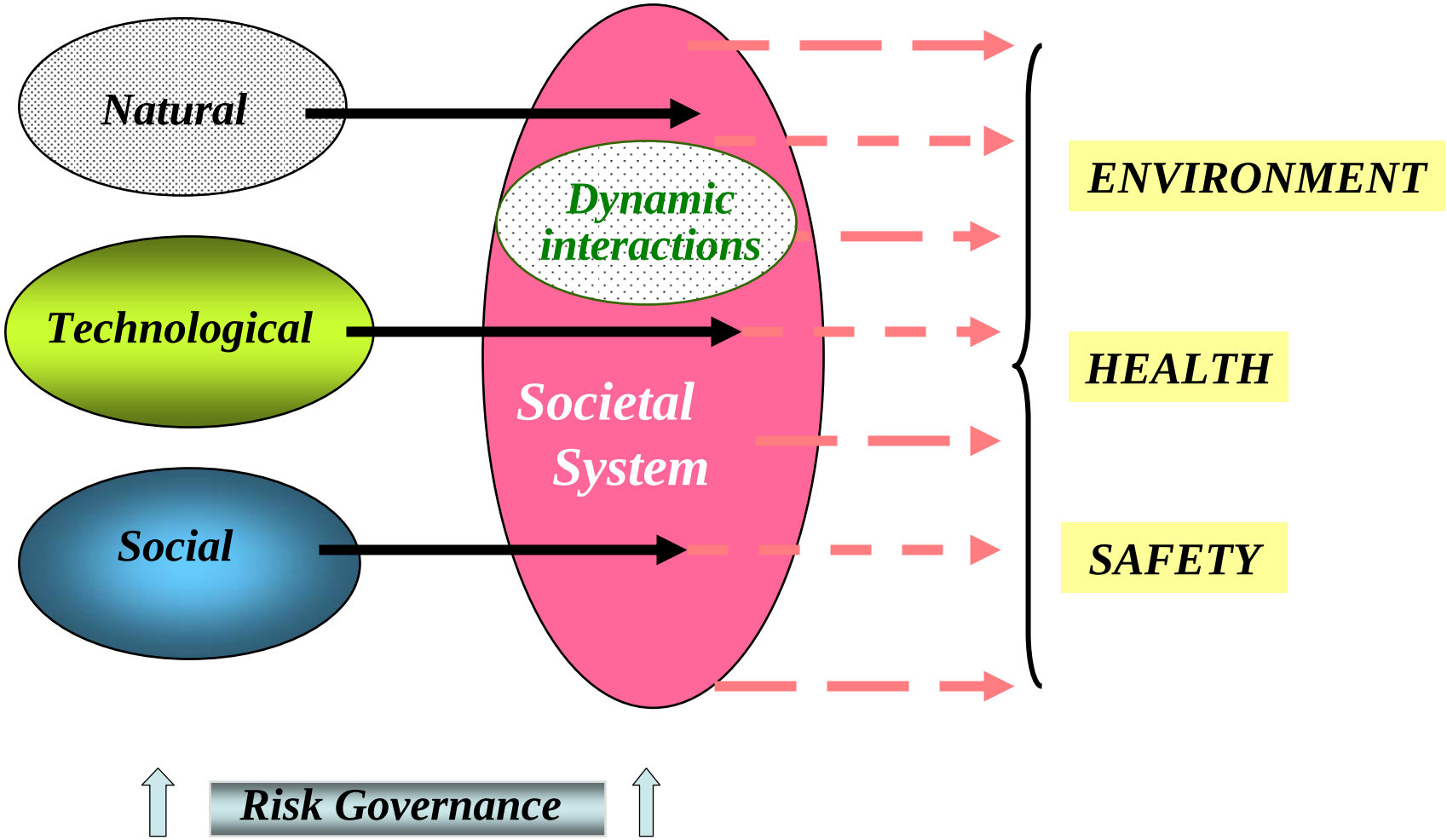
The Risk Management Escalator and Stakeholder Involvement

(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**	

Sources of risks and the governance approach

Various dimensions: EHS, ELSI, Education Gap, Human Development Issues, Political and Security Issues



J. Nanoparticle Research, 2005, 7(2-3)
MC. Roco, 06/06/06

SURVEY ON NANOTECHNOLOGY GOVERNANCE

www.irgc.org (M.C. Roco and E. Litten)

- Part A: The Role of Government

  Responders: 11 countries on nanotechnology governance; and 26 countries and EU on their nanotechnology R&D programs; December 2005 (146 pages, on the web)

- Part B. The Role of Industry

  Responders: Industrial Technology Research Institute (Chinese Taipei), Allianz and NanoBioNet (Germany), Ayanda Biosystems and Swiss Re (Switzerland), Chair of the International Organization for Standardization Technical Committee 229 on Nanotechnologies (UK), Canon, Environ, Intel, NanoDynamics Inc. and Pfizer (US)

- Part C. The Role of Risk Research Organizations

  Responders: Ochanomizu University (Japan), Institute for Occupational Health Sciences (IST) (Switzerland), Centre for Nanotechnology in Society (University of California, US); Center for Science Technology and Public Policy (University of Minnesota, US); Woodrow Wilson International Center for Scholars (US)

- Part D. The Role of NGOs

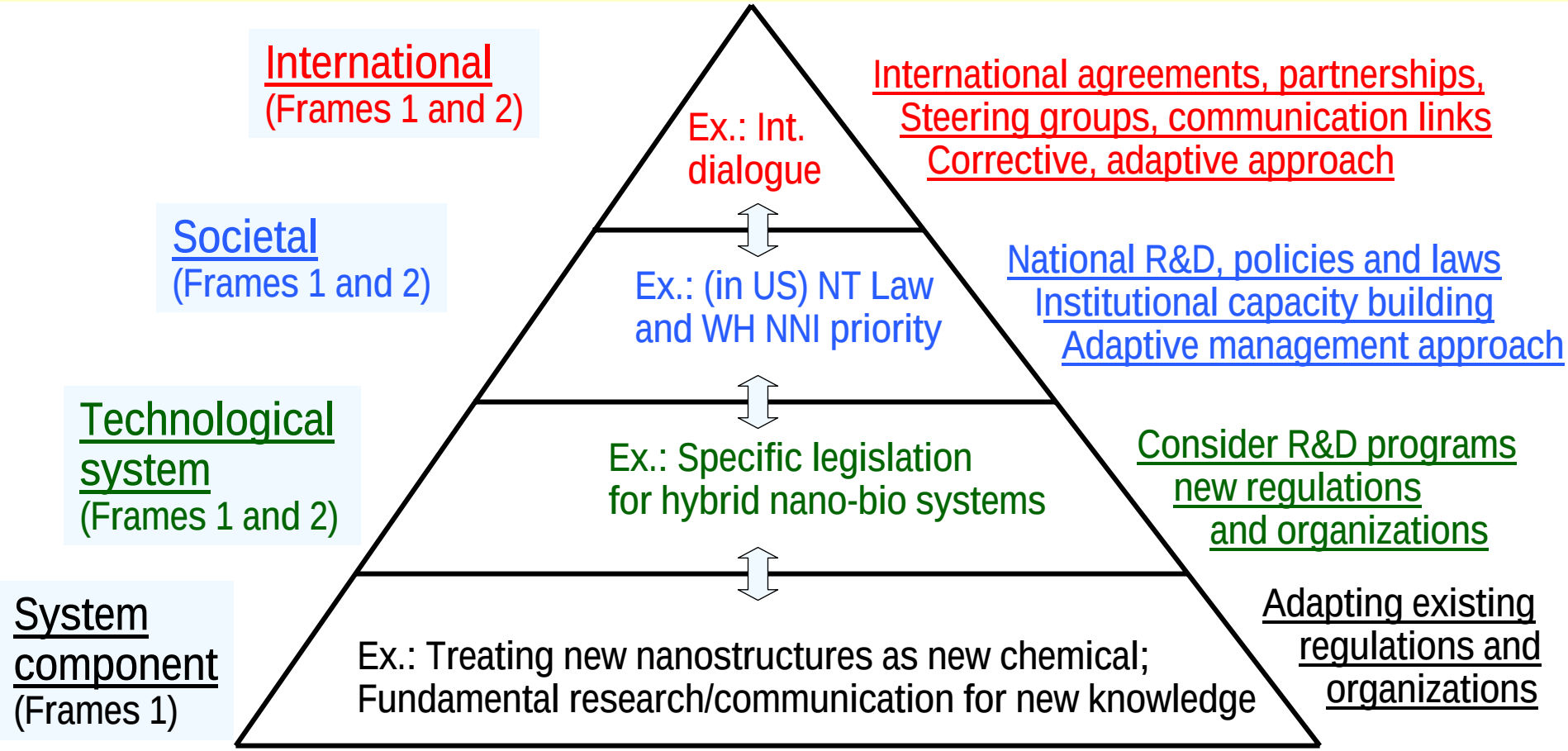
  Responders: ETC Group (Canada), Demos, The Forum for the Future, Greenpeace (UK), the Center for Responsible Nanotechnology, Environmental Defence, Foresight Nanotech Institute, the National Resources Defence Council and Sciencecorps (US).

IRGC Survey on Nanotechnology Governance
Areas of relevance in governance (December 2005)

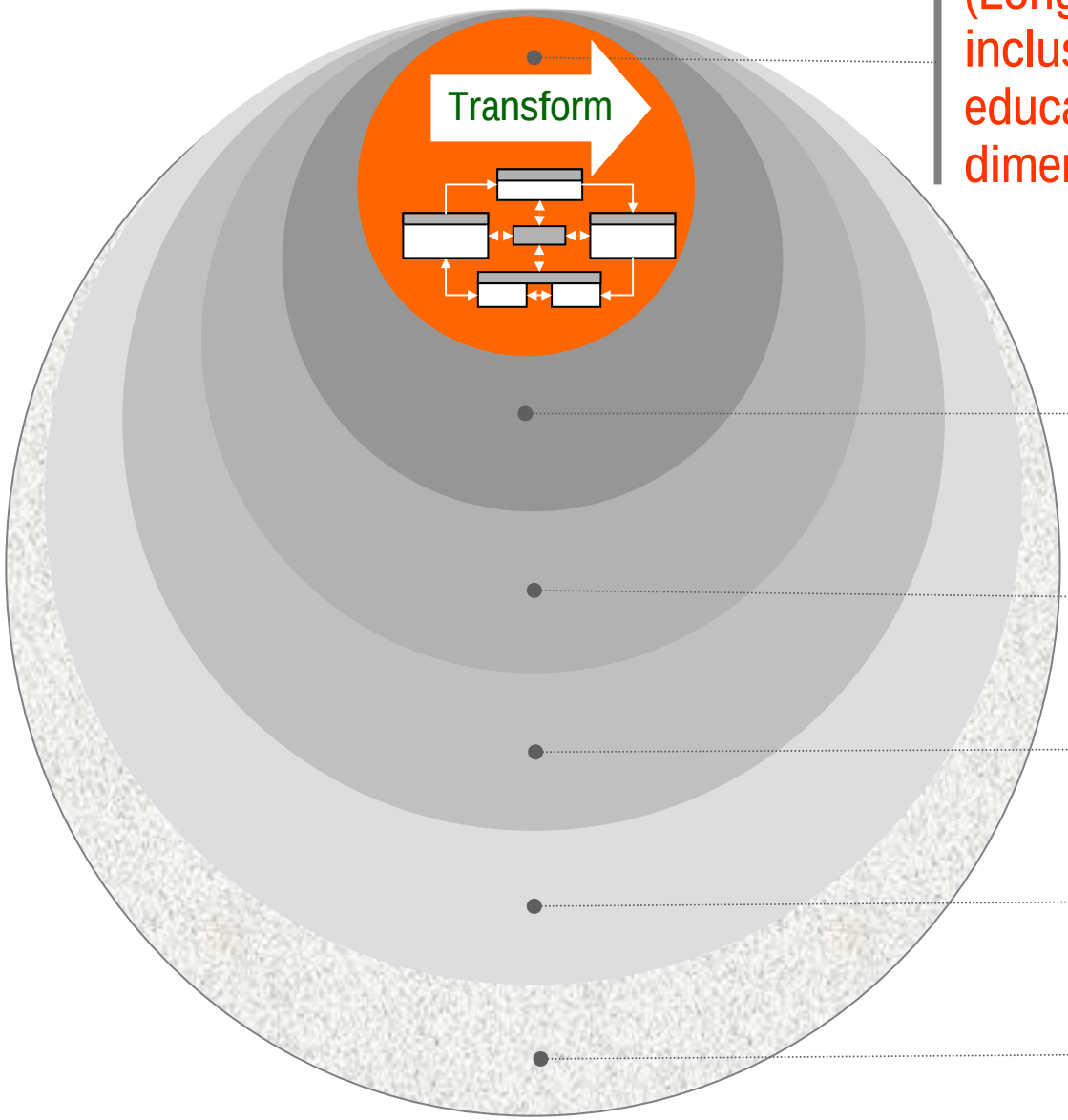
Table 2	EHS	ELSI	Education Gap	Political and Security	Human Develop.
A. Government	2	1			
B. Industry	2	-	1		-
C. R&D risk organizations	2	1			
D. NGOs	2	1+			
Summary:	**8**	**3**	**1**	**0**	**0**

Multi-level structure of NT risk governance

Implication Domain / Examples of RG activities / Implementation approach



CONVERGING TECHNOLOGIES GOVERNANCE OVERVIEW



Core Governance Process
(Long-term view, transforming, inclusive, integrate CTs, cross CT education, addressing societal dimensions, risk governance)

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

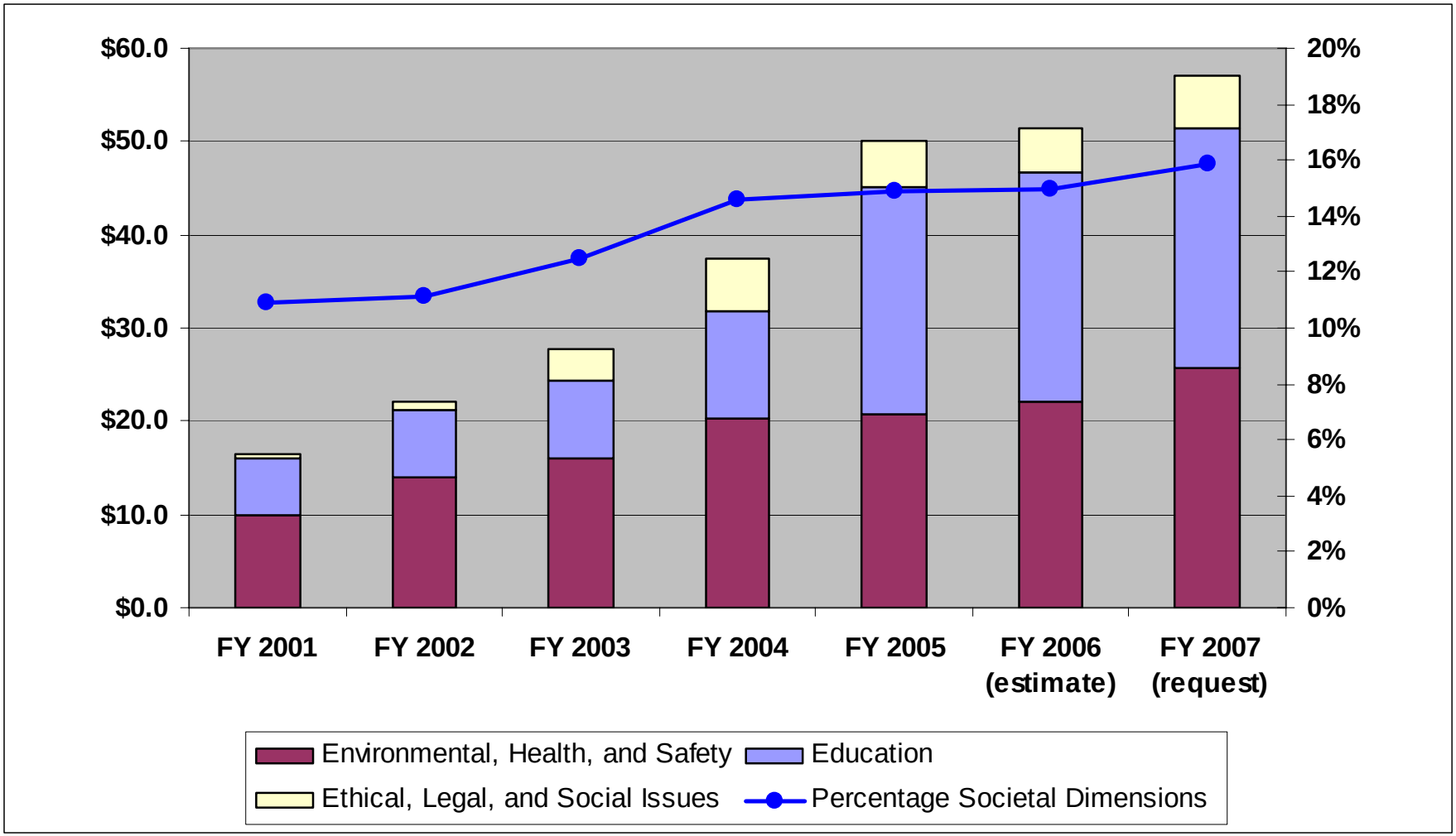
Implementation Network
(Regulators, business, NGOs, media, public)

Social Climate
(Perceived authority of science, civil involvement)

National Political Context

International Interactions

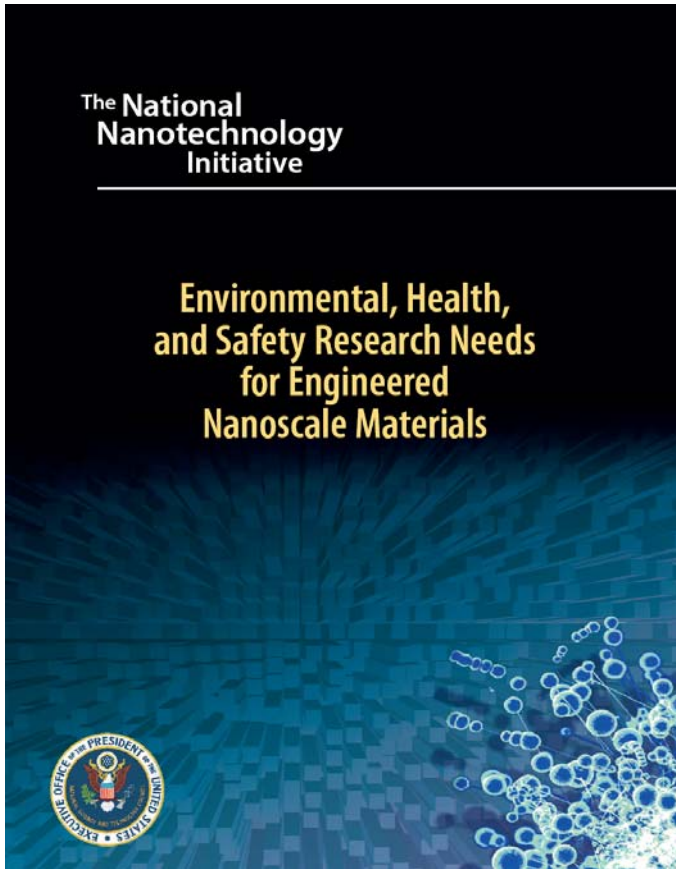
Of the total 2007 NSF / NNI request budget of $373.2 million, $59 million – or 16% – is directed toward societal dimensions This is a $7.6 million (15%) increase over the FY 2006



ENVIRONMENTAL, HEALTH, AND SAFETY RESEARCH NEEDS (NNI, Sept. 21, 2006)

Purpose

Identify for the Federal Government environmental, health, and safety (EHS) research and information needs related to understanding and management of potential risks of engineered nanoscale materials



Key topics

Instrumentation, Metrology, and Analytical Methods

Nanomaterials and Human Health

Nanomaterials and the Environment

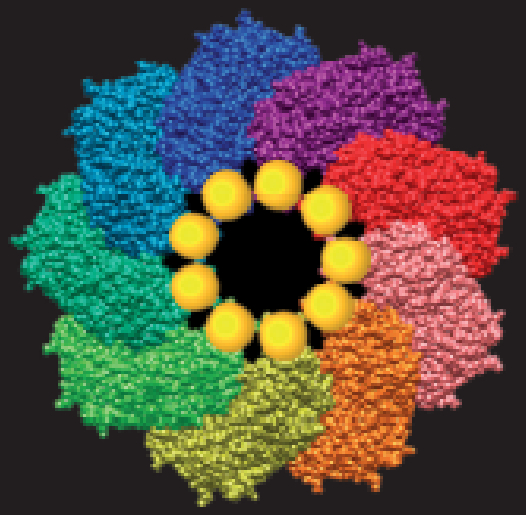
Health and Environmental Surveillance

Risk Management Methods

Nanotechnology: Societal Implications I

Maximizing Benefits for Humanity

Edited by
Mihail C. Roco and William Sims Bainbridge



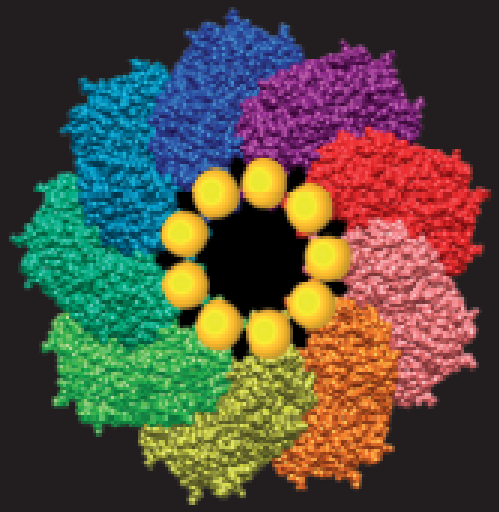
Springer

November 2006

Nanotechnology: Societal Implications II

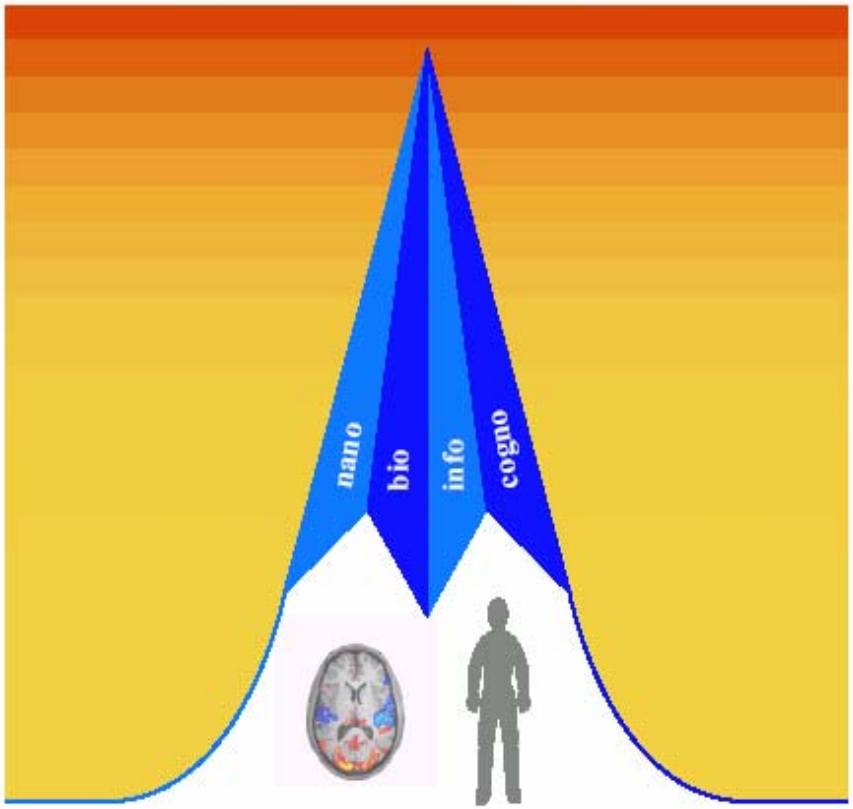
Individual Perspectives

Edited by
Mihail C. Roco and William Sims Bainbridge



Springer

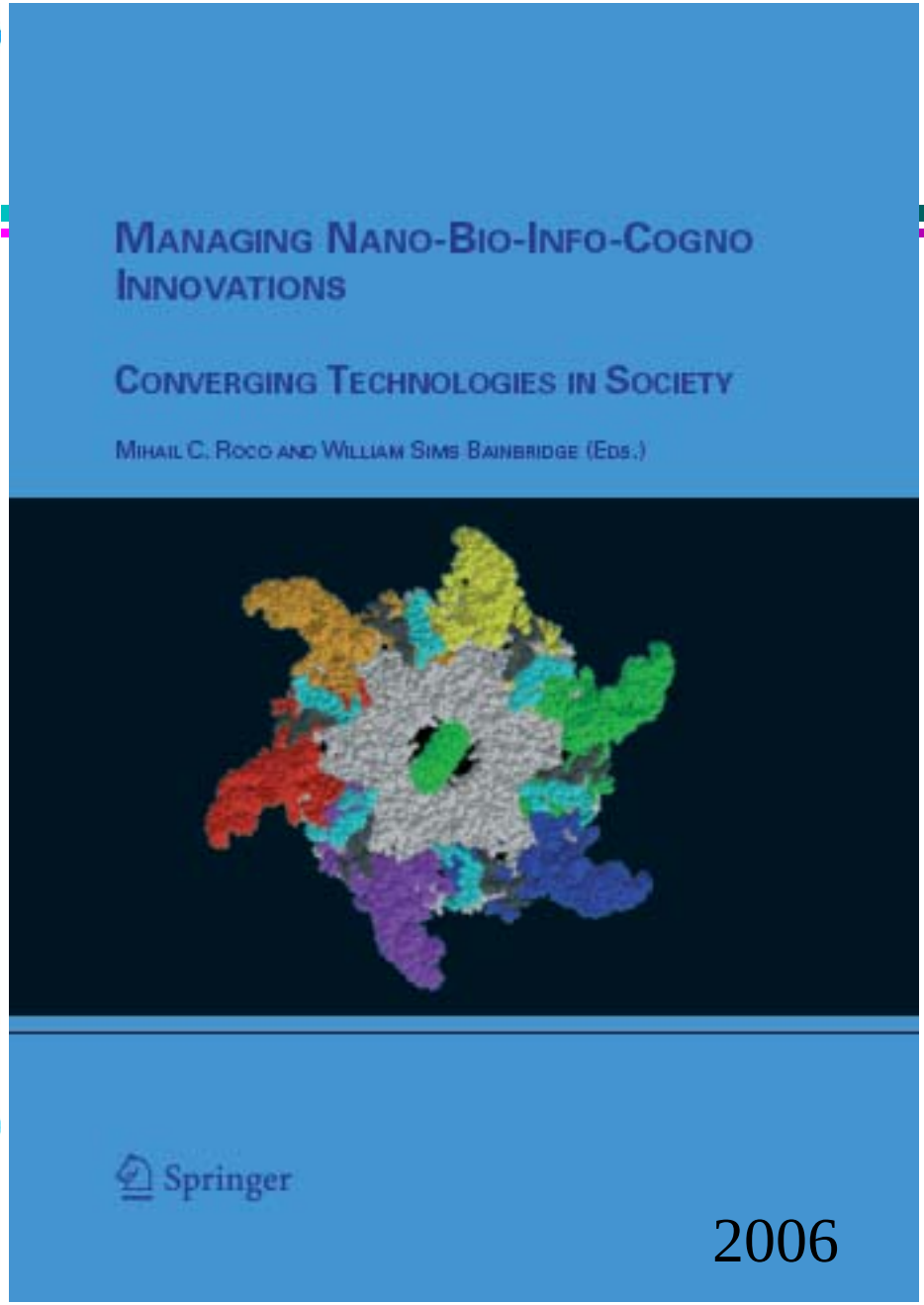
November 2006



CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

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



2006

Governance within large NT companies (Lux Research, 2004): Regional differences emerge in how corporations approach nanotechnology R&D

- US corporations more likely to adopt decentralized approaches and rely on cross-functional business / R&D steering committees

- Asian corporations more likely to have an explicit strategy, aim for first-to-market status, put a business not R&D exec in charge, and have CEO/board-level awareness of nanotechnology efforts

- European corporations have had specific nanotechnology focus for the shortest amount of time; are more likely to take a “watch, wait, and follow fast” approach rather than commit large resources now

Development of Nanotechnology

Reaching at the building blocks of matter for manmade and living systems, and access to global information system
- makes transforming tools and unintended consequences powerful

The introduction of nanotechnology is accelerating in academe, industry, medicine and business with major implications

A long-term concern is a possible instability in development, because perturbations created at the foundation of life and at the transforming tools of matter may have implications that could be difficult to control

There is a need for an adaptive and corrective governance with four key roles: transforming, responsible, visionary and inclusive

Five ways nanotechnology will change business

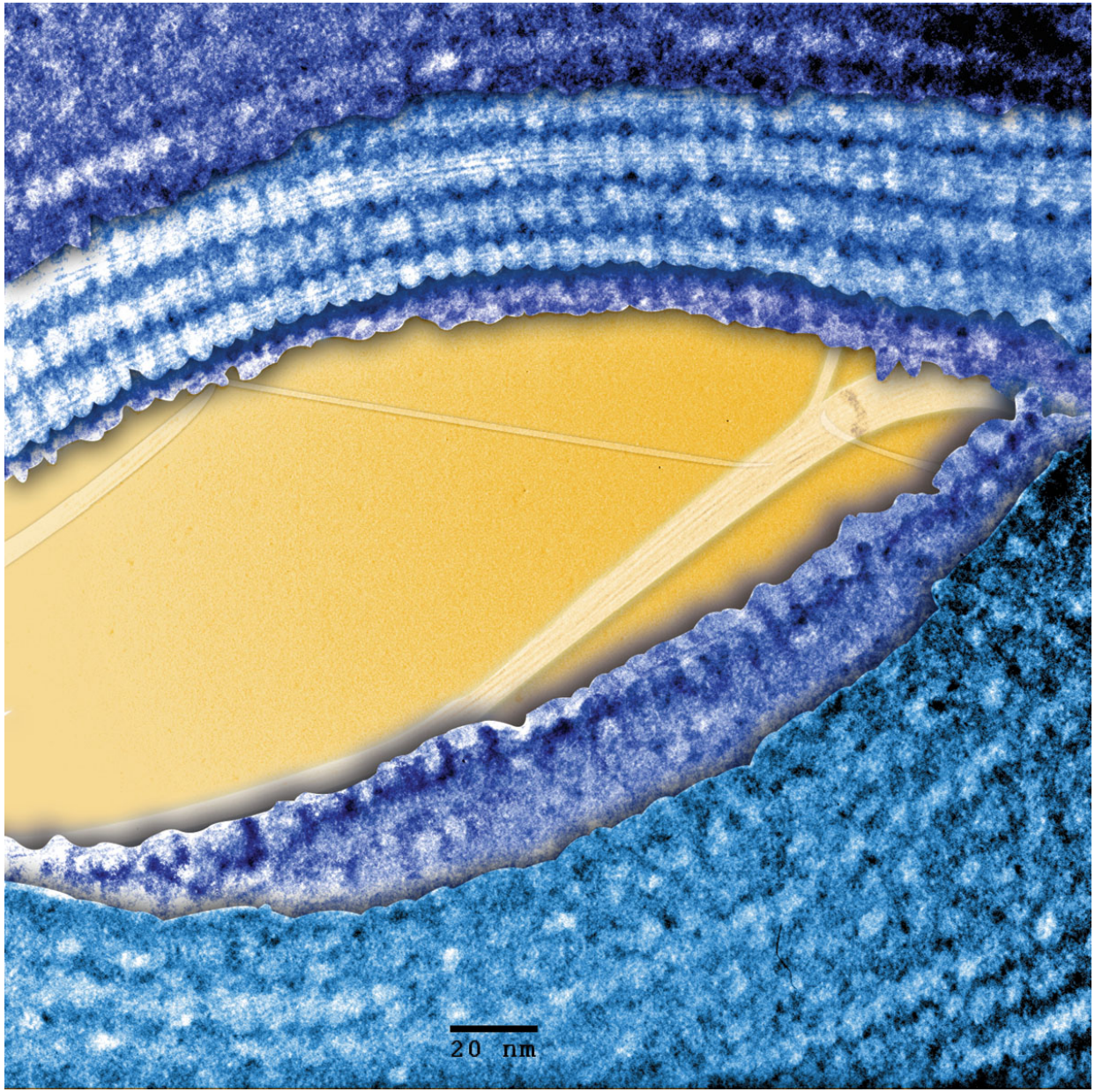
1. *Competitive advantage* by improved products now

2. *Create S&T nanotech platforms* for revolutionary new products (over 50% of new chemical/ electronic/ pharmaceutical/ advanced materials products by 2015)

3. *Opportunities for innovation*: Convergence with biomedical, electronics and cognition

4. *New organization and business models* – "horizontal" information, S&T clusters, distributed production

5. *Global governance*: strong collaboration and competition; address multi-stakeholders and responsible development



Society has an eye on emerging nanotechnology

“Blue Eye”

sees highly regular binding of lysophospholipid LPC and single-walled carbon nanotubes.

Pu-Chun Ke, Clemson U. (2006)