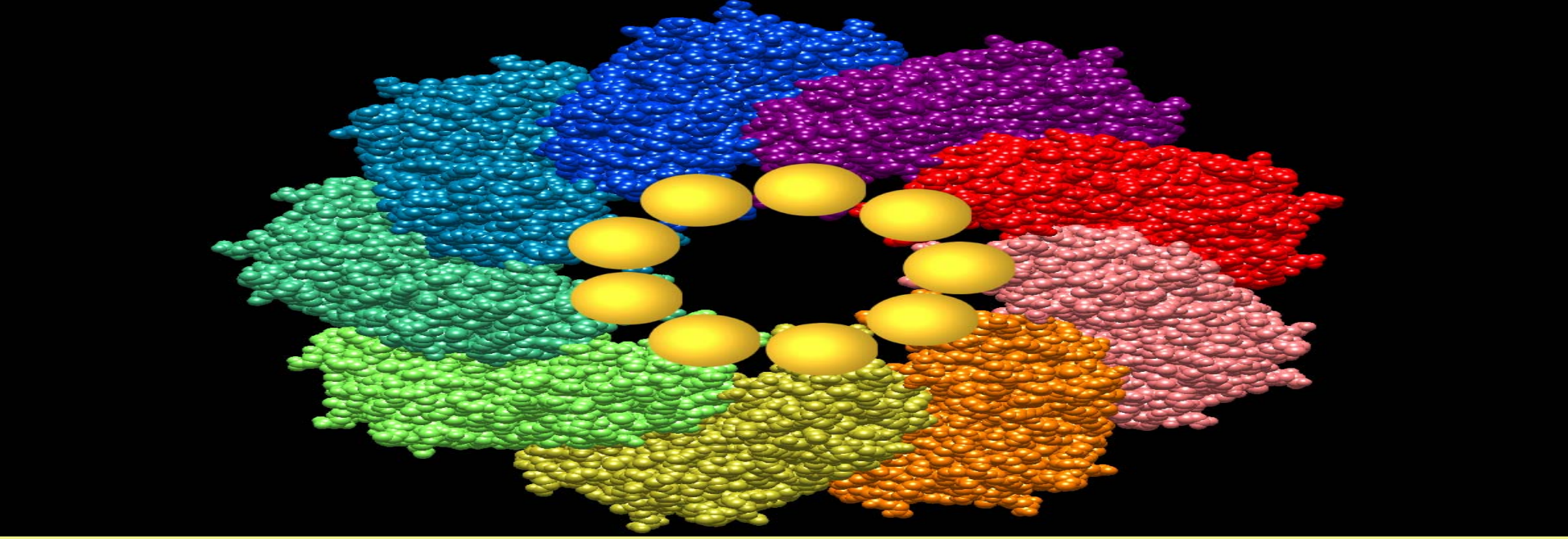


Nanotechnology

M.C. Roco

Senior Advisor for Nanotechnology, NSF,

Subcommittee on Nanoscience, Engineering and Technology (NSET),
National Science and Technology Council (NSTC)

Minneapolis, October 3, 2005

Nanotechnology

M.C. Roco,
U.S. National Science and Technology Council's Subcommittee
on Nanoscale Science, Engineering and Technology (NSET),
and Senior Advisor, National Science Foundation (NSF)

Abstract

Nanoscale science and engineering allow us to reach beyond our natural size limitation and work directly at the building blocks of matter where the properties of matter are defined and can be changed. Material structures with fundamentally new properties, new tools demonstrating nanoscale phenomena, new molecular assembling and techniques yielding control of structures at the nanoscale, are leading to a unified set of general principles and methods of investigation for a variety of disciplines and areas of application. Key engineering drivers are novel methods for creating engineered nanosystems, nanomanufacturing, and the synergism with modern biology and information technology. Several generations of nanotechnology products are expected to evolve from relatively simple nanostructures for products such as coatings and hard metals, to active components such as nanoscale actuators and transistors, followed by nanosystems with new architectures, and molecular nanosystems.

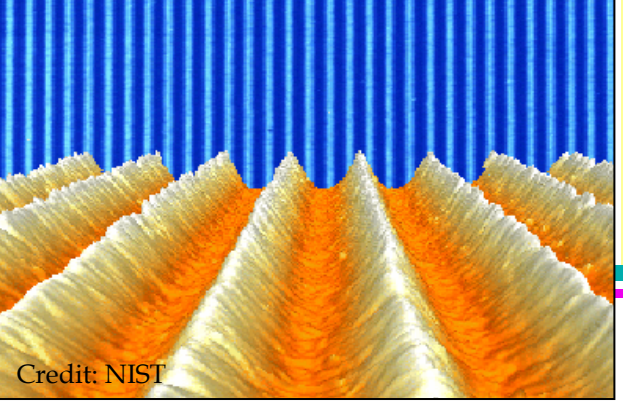
TOPICS TO BE ADDRESSED

- **A. What is nanotechnology and why it is important?**
  From new phenomena and structures to applications

- **B. Four generations of nanotechnology products**
  Nanomanufacturing; Outlook 2000-2020

- **C. NNI main objectives and examples of outcomes**
  Brief; International perspective; New frontiers

- **D. Societal dimensions**
  EHS, Education and ELSI



❑ Part A
WHAT IS NANOTECHNOLOGY
(definition 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, manipulate matter at the nanoscale* in order to change those properties and functions
  - *integration along length scales, and fields of application*

NNI - Why nanotechnology is important?

- **A. Reaching at the foundation of matter**

  Historical event in understanding, control and transformation of natural/living and manmade systems (natural threshold between discontinuous and continuous behavior; where first level organization of matter defines properties and functions)

- **B. The long term societal implications**

  Improved knowledge, quality of life, and environment
  Create foundation for a technological and industrial revolution

- **C. Higher purpose goals than development of NT**
  - More basic and unifying science and education
  - Higher efficiency processes and novel products
  - Molecular medicine
  - Extend the limits of sustainable development
  - Increased coherence/integration of S&T policies

Why moving into nanoworld ?
A. Intellectual Drive

- **Miniaturization is of interest**
  - Less space, faster, less material, less energy

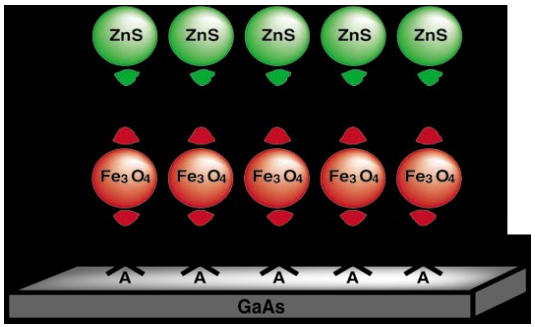
More important:

- **Novel properties/ phenomena/ processes**
  - New structures and functions; Engineering beyond nature; Manipulate quantum effects in low-dimensional structures (quantum dots, wires, wells) electronic, optical, thermal, etc.; Access new molecular effects (mechanics, electronics, recognition, …); High surface to volume ratio
- **Unity and generality**
  - At the building blocks of all natural/artificial things; Systems!
- **Most efficient length scale for manufacturing**
  - Less energy than for subatomic or macroscopic
- **Transcendent effects: at the confluence of steams**
  - S&T; Living/non-living ; Interdisciplinarity; Relevance areas

Scales: Expanding the limits of knowledge and action

Nanoworld - natural threshold

for behavior, performance,
unity, bio-inert, manufacturability



1 to 100 nm

~ 1 m
Human scale

Outer space

Over 10,000 km

Smallest Known Size

10^{-7}

10^{7}

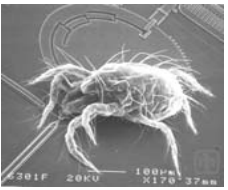
Largest Known Size

10^{-27}

10^{27}

The Scale of Things -- Nanometers and More

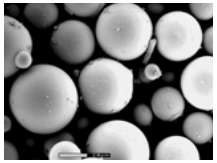
Things Natural



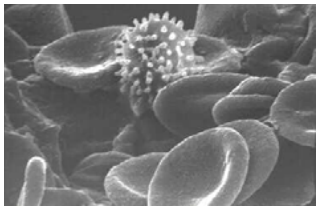
Dust mite
200 μm

Ant
~ 5 mm

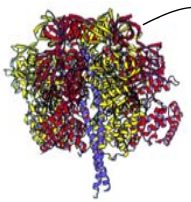
Human hair
~ 10-50 μm wide



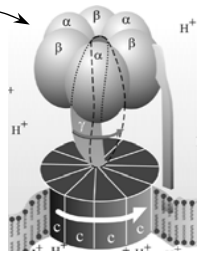
Fly ash
~ 10-20 μm



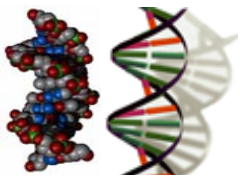
Red blood cells
with white cell
~ 2-5 μm



~10 nm diameter

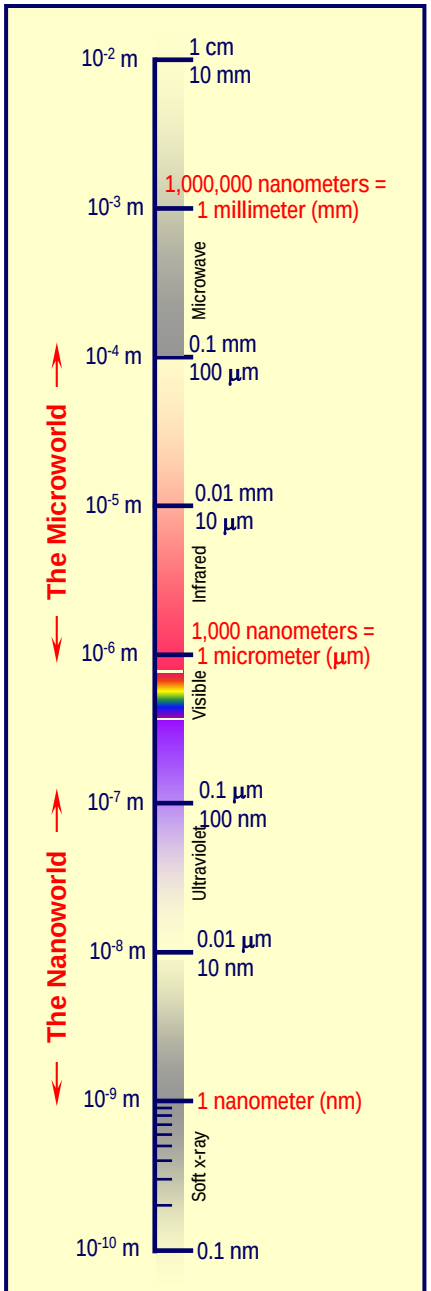


ATP synthase

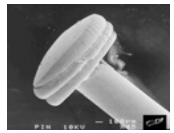


DNA
~2-1/2 nm diameter

Atoms of silicon
spacing ~tenths of nm

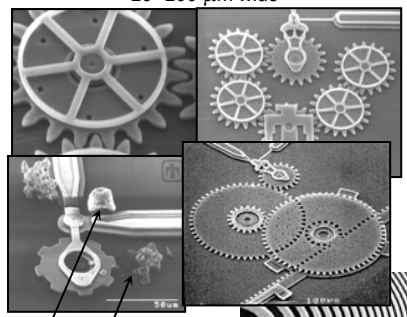


Things Manmade

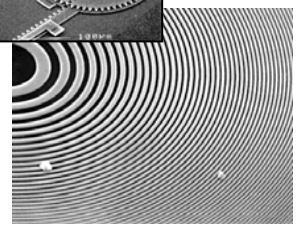


Head of a pin
1-2 mm

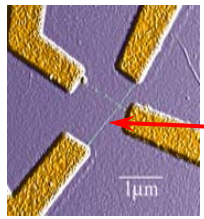
MicroElectroMechanical devices
10 -100 μm wide



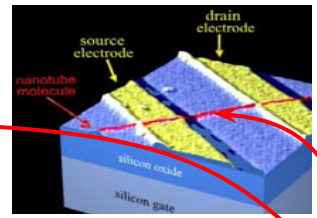
Red blood cells
Pollen grain



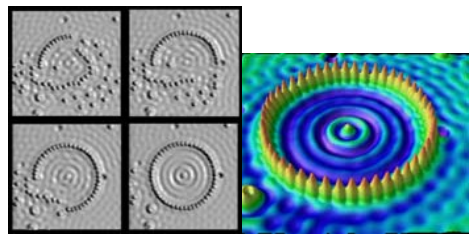
Zone plate x-ray "lens"
Outermost ring spacing
~35 nm



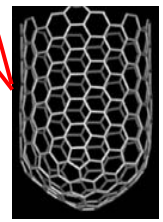
Nanotube electrode



Nanotube transistor



Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm



Carbon nanotube
~2 nm diameter

Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 03-05-02

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

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

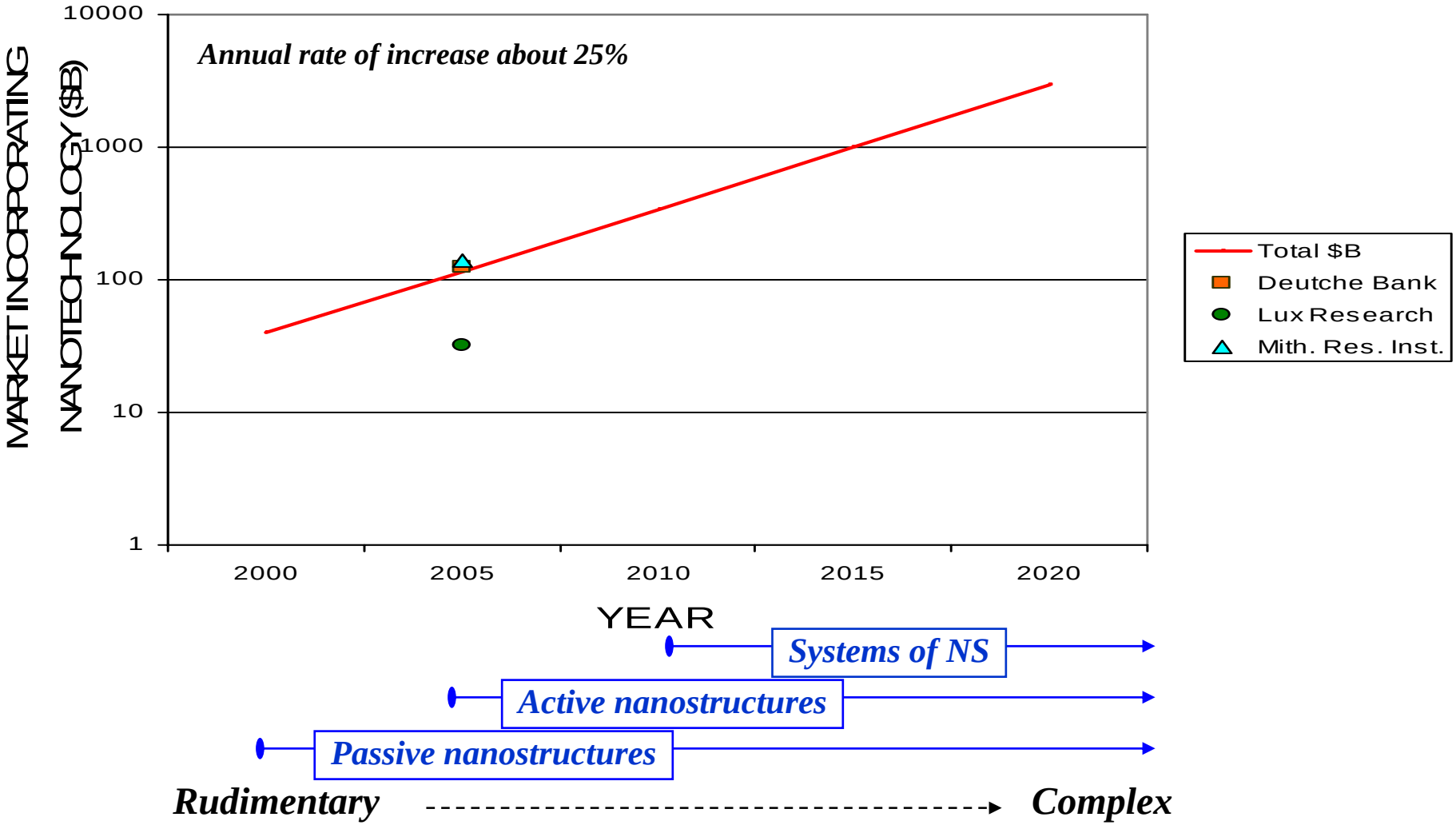
  Would require worldwide ~ 2 million nanotech workers (all ~7M)
  In U.S.: ~ 0.8 million (all with supporting jobs ~ 2.8 million)

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

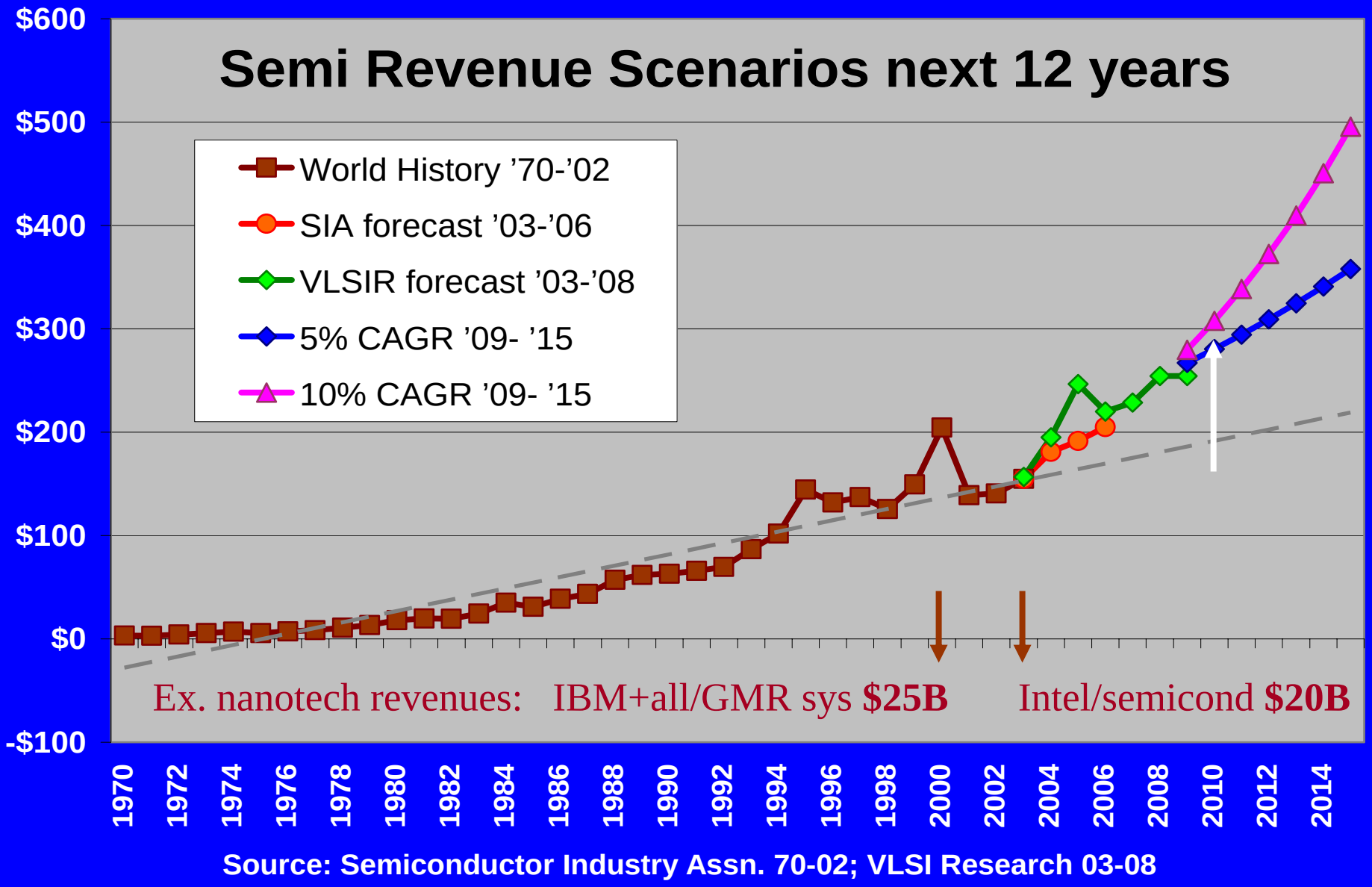
- **Sustainability**: agriculture, food, water, energy, materials, environment; ex: lighting energy reduction ~ 10% or **$100B/y**

Worldwide market incorporating nanotechnology.

Estimation made in 2000 (NSF)



Semiconductors Extrapolated to 2015 ($B)

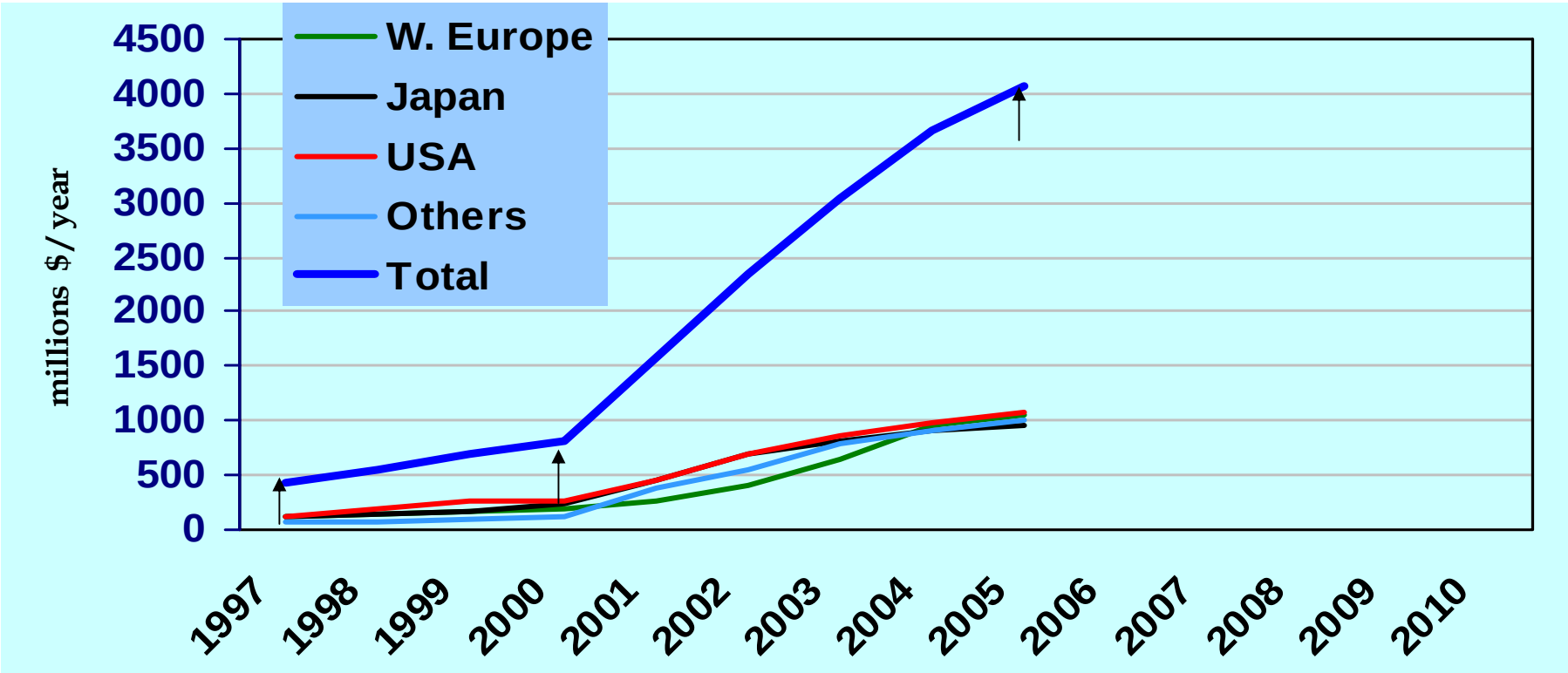


Source: Semiconductor Industry Assn. 70-02; VLSI Research 03-08

Note: $300B nanotech revenues sooner than predicted (2010 instead of 2015)

Context – Nanotechnology in the World

Past government investments 1997-2005 (est. NSF)



Seed funding (1991 -)

NNI Preparation (vision / benchmark)

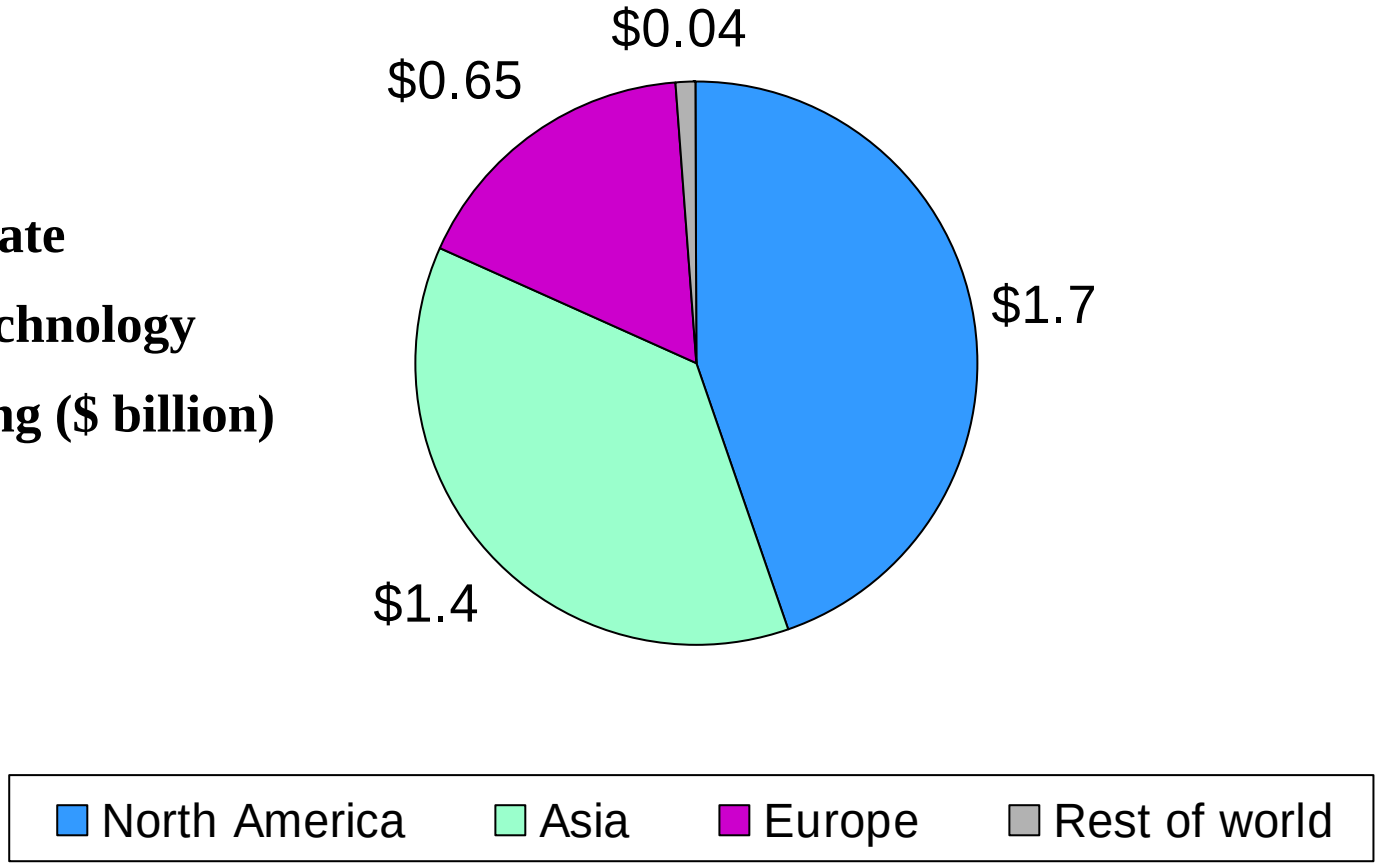
1st Strategic Plan (passive nanostructures)

2nd Strategic Plan (active ns. & systems)

Total government expenditure in FY 2004 – about $4.1 billion

Established corporations spending - > $3.8 billion globally on nanotechnology R&D in 2004

Corporate Nanotechnology Spending ($ billion)



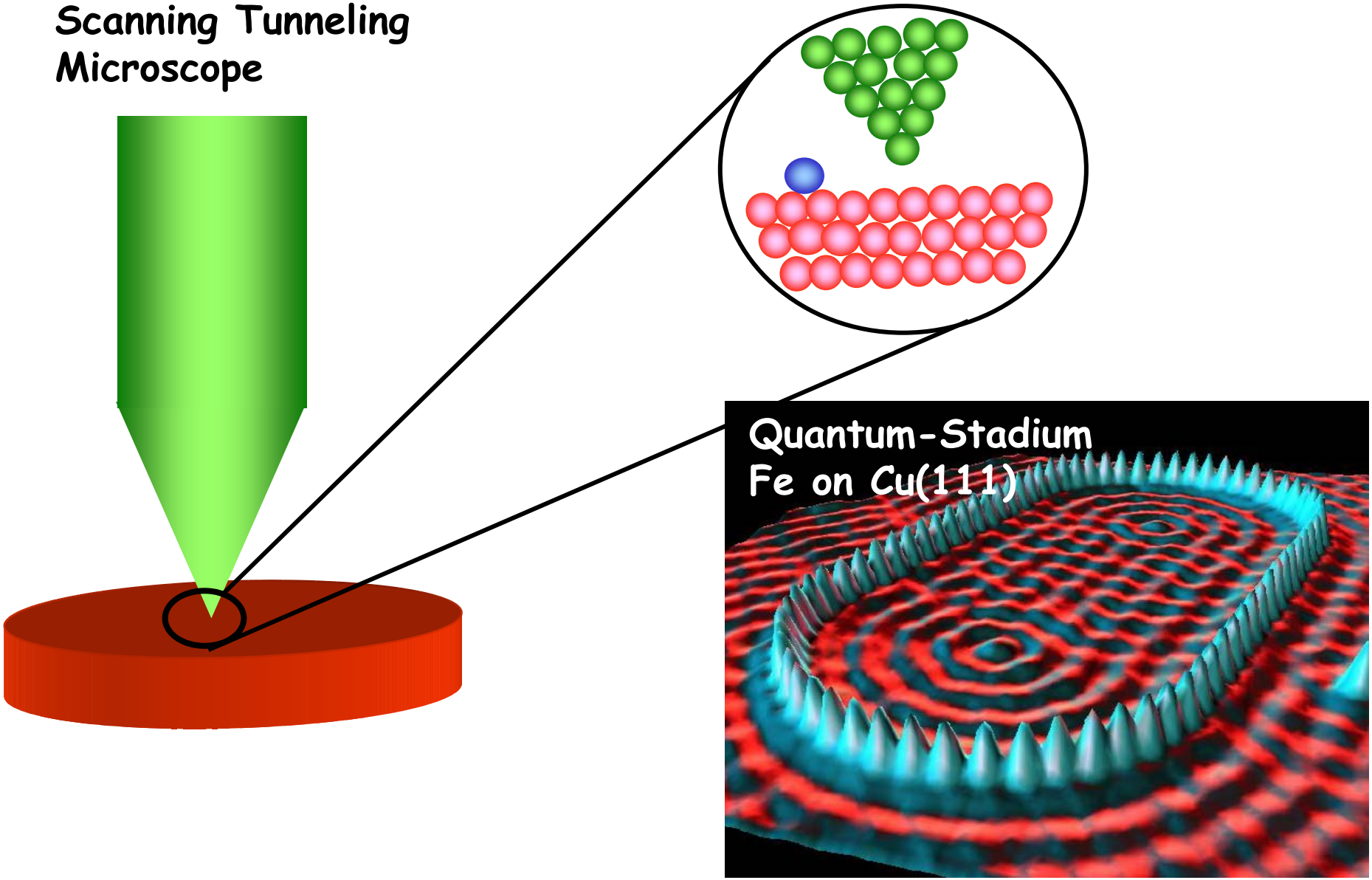
Source: Lux Research reference study “The Nanotech Report 2004;” based on published spending figures, national statistics, Lux Research analysis

Scientific Drivers

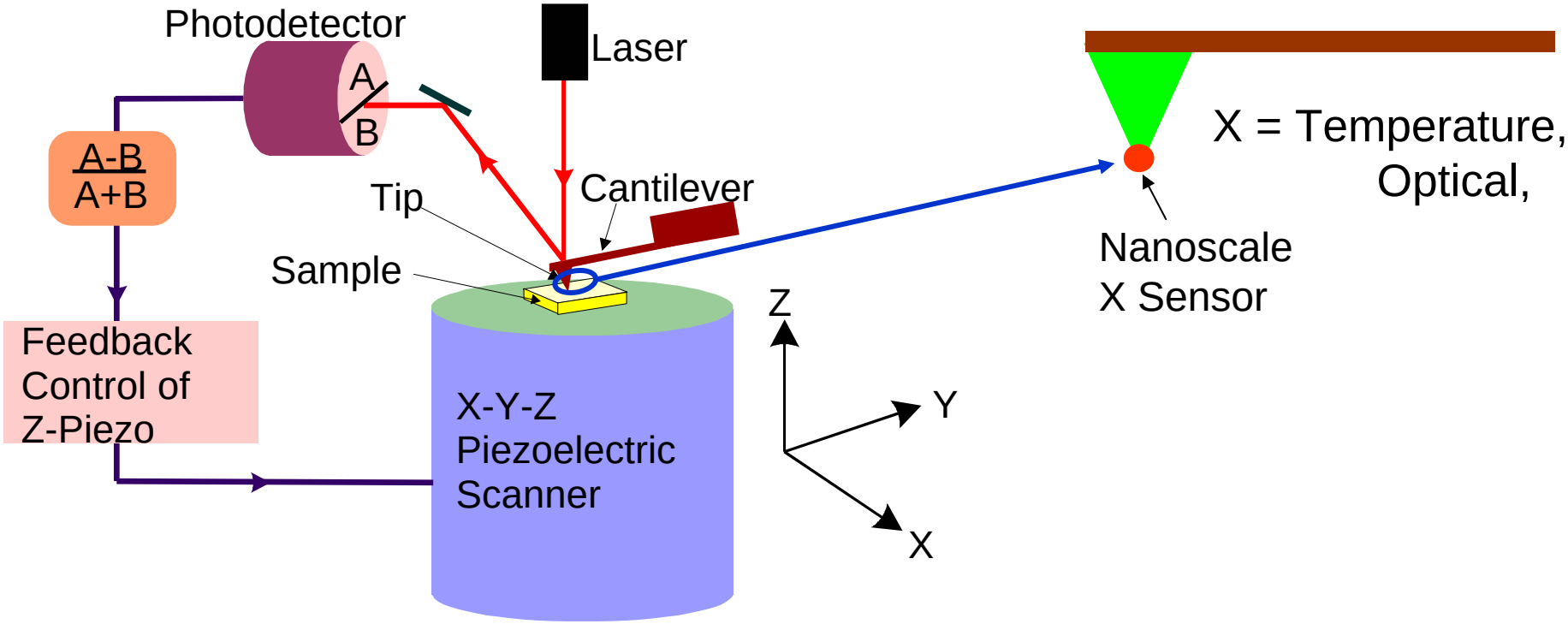
- **Phenomena at nanoscale**
  Ex. Confinement; Large surface; Quantum phenomena, at room temperature; Coulomb effect; Collective interactions
- **The science of large number of objects; systems**
- **Atomic- and molecular-scale structures and their manipulation enabled by new tools**
- **Concepts - nanostructures, devices and systems**
- **Instrumentation for single molecules and clusters**
- **Understanding the cell and modern biology**
- **Assembling and connecting at the nanoscale**
- **Unifying science and technology integration**

Nanotools

Scanning Tunneling Microscope



Courtesy: IBM Almaden Lab



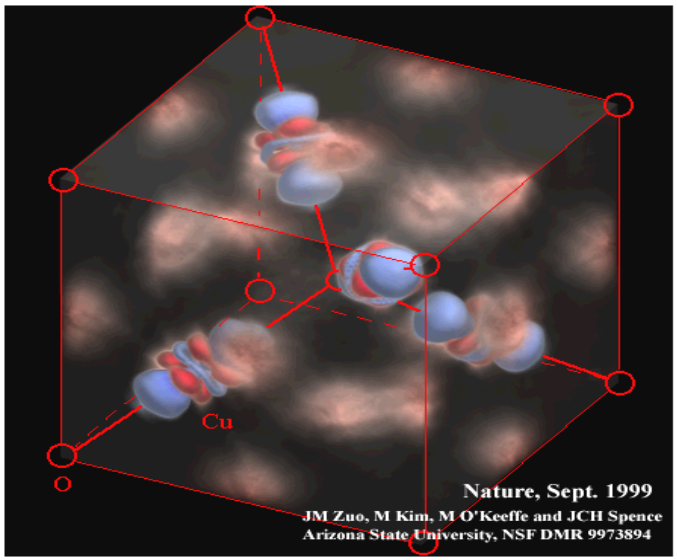
Nanotools

Atomic Force Microscope

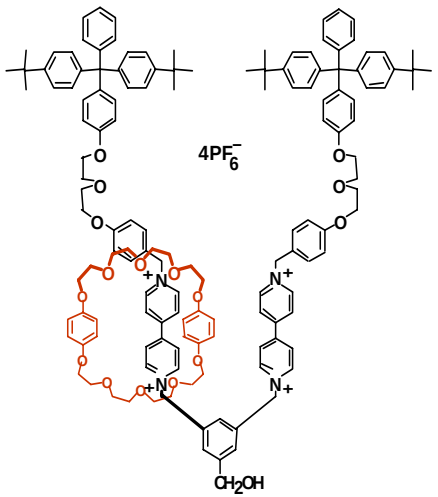
Courtesy: Li Shi, P. Kim

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

(a) One nanometer structures

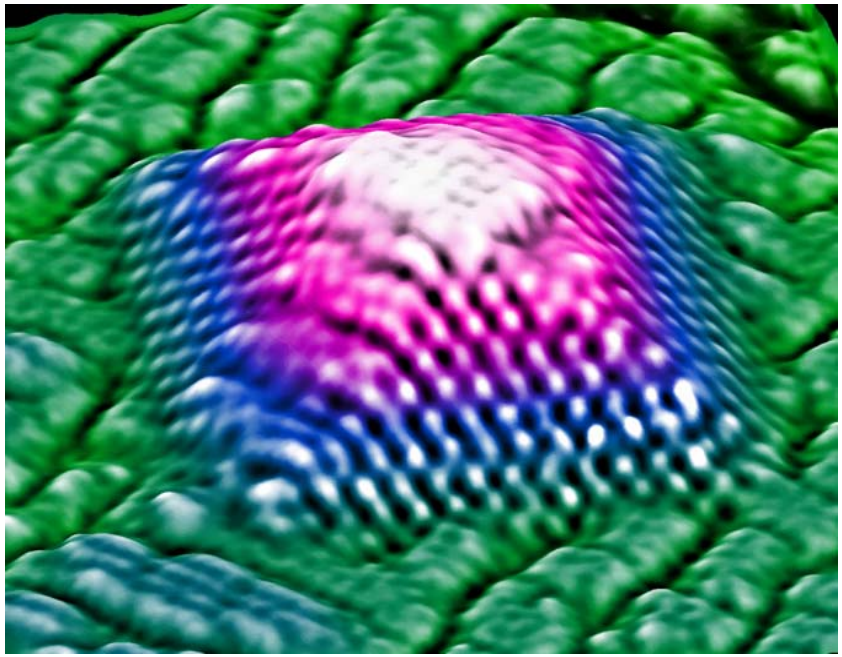


Electron orbitals have been directly observed (L ~ 1nm). For understanding molecular assembling (ASU, 1999)

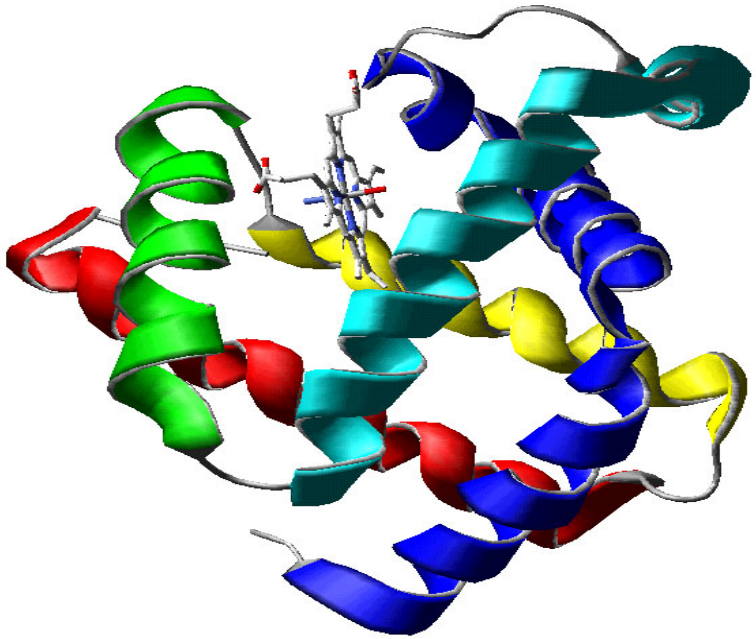


Molecular logic: switches (size ~ 1 nm) (HP, UCLA, Yale, 1999)

(b) 10 nanometer structures

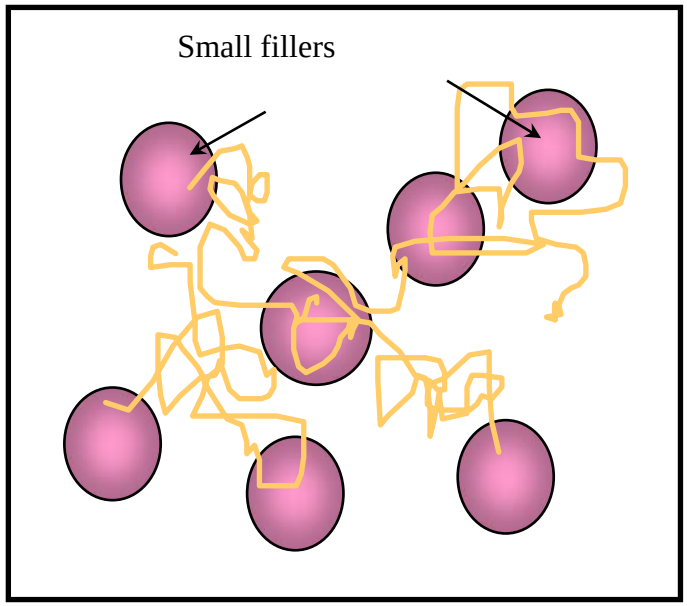


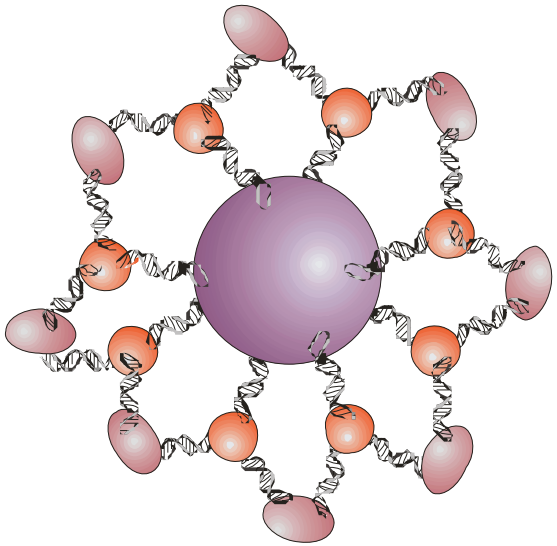
Quantum dot - self-assembled Germanium pyramid (HP, 1999)



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

(c) 10-200 nanometer structures

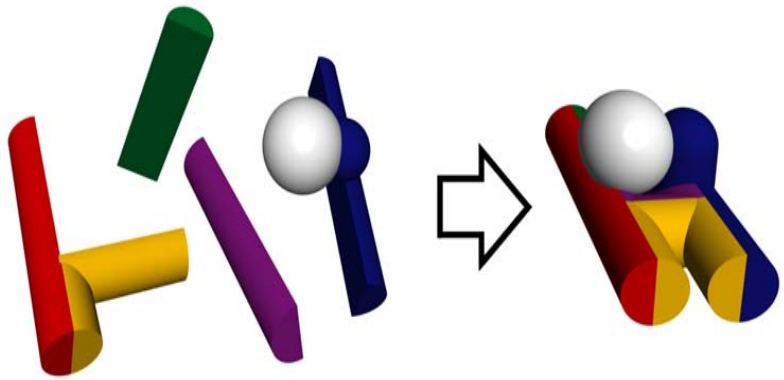




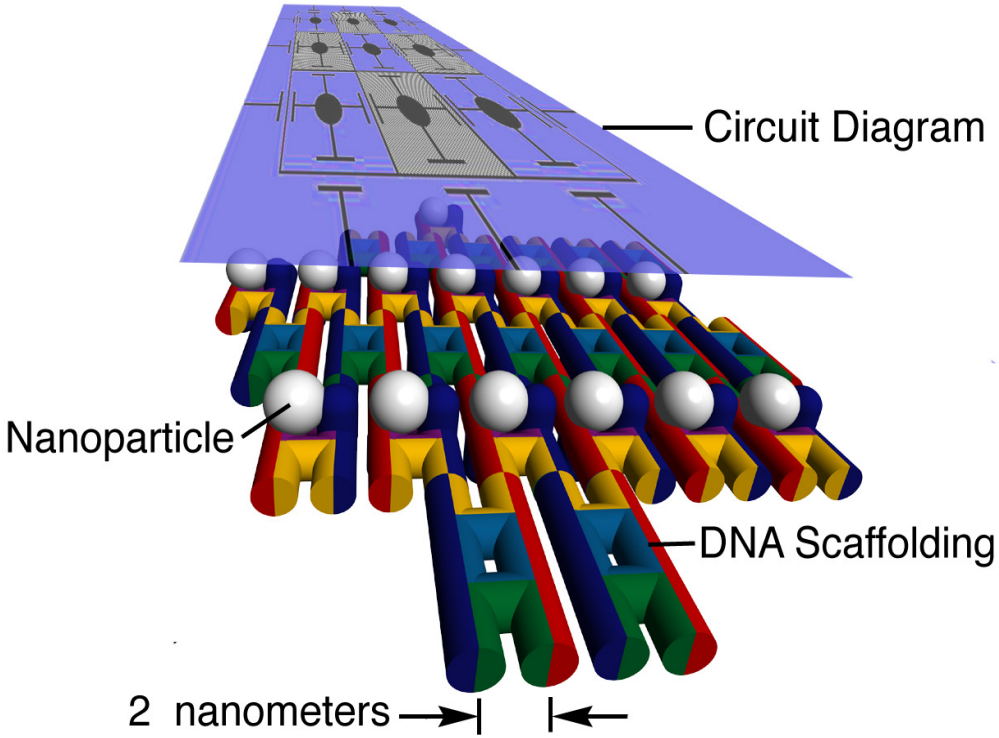
Nanocomposites
new low-cost, high-strength materials for automotive parts (RPI, 1999)

DNA-based Nanoparticle Building Blocks
(NWU, 1999)

(d) Three-dimensional assembling - synergism Nano - BIO - IT - (University of Minnesota, 1999)



Selfassembled DNA synthetic strands and nanoparticles



3D architecture
for a nanoscale electronic circuit

From synthesis to use of nanostructures

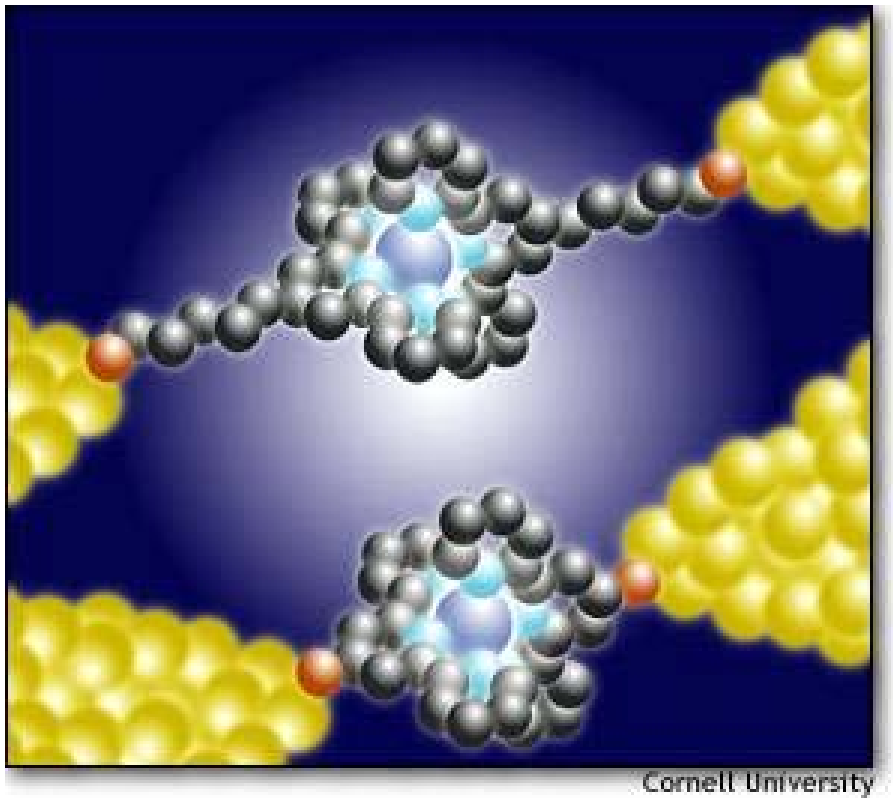
Examples of new functions

Single Electron Molecular Transistor

F. Di Salvo and D. Ralph, Cornell University, 2002

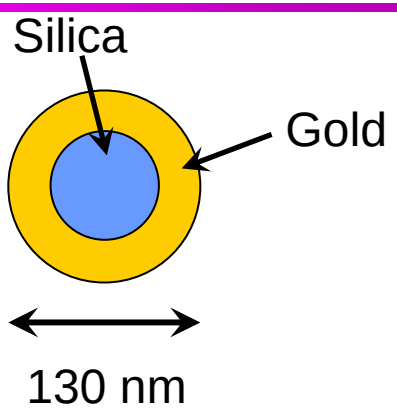
- The two molecules contain a central cobalt atom and differ in their length -- the shorter of about 2 nm one exhibits less resistance. At low temperature, the longer molecule functions as a single electron transistor, and the shorter molecule exhibits both transistor action and the Kondo effect.

- The electrical characteristis of the transistor can be varied systematically by making chemical changes to the molecule.



Example of Nanoscale Device/System: Product under Development for Treating Cancer

- **Gold nanoshells (10 nm shell thickness) formed by depositing metal on silica spheres**
- **Size is *critical***
  - **For reaching tumor**
  - **For absorbing IR energy (dT=37°C)**
  - **For optimal transmission through tissue**
- ***In-vivo* study in mice showed promising results**
- ***In-vitro* study in human breast carcinoma cells also promising**
- **Technology developed at Rice Univ. with funding from NSF; start-up company formed to commercialize**

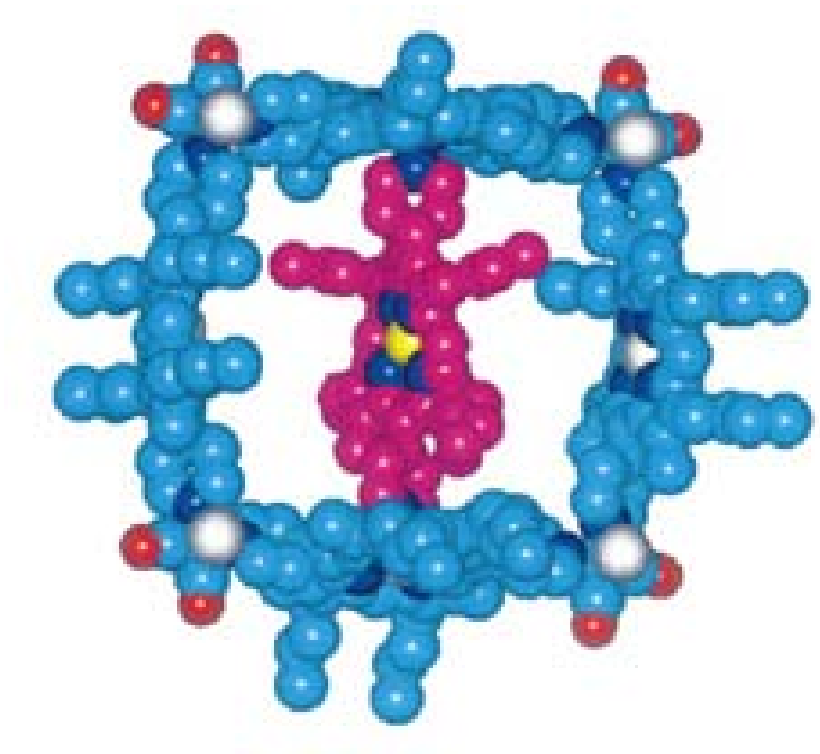


LR Hirsch, RJ Stafford, JA Bankston, SR Sershen, B Rivera, RE Price, JD Hazle, NJ Halas, JL West - Rice Univ. PNAS 23 11/11/2003

(C) Selective Membranes

J. Hupp, S.-B. Nguyen and R. Snurr, Northwestern University, 2002

- Membranes that allow the passage of some substances while blocking others. A network of these supramolecules can act as a molecular filter and catalyst
- The thin-film material with nanometer-sized cavities can be manipulated to allow the passage of certain molecules but not others depending on size, shape and other properties
- Chemically transforming molecules can be placed within these cavities



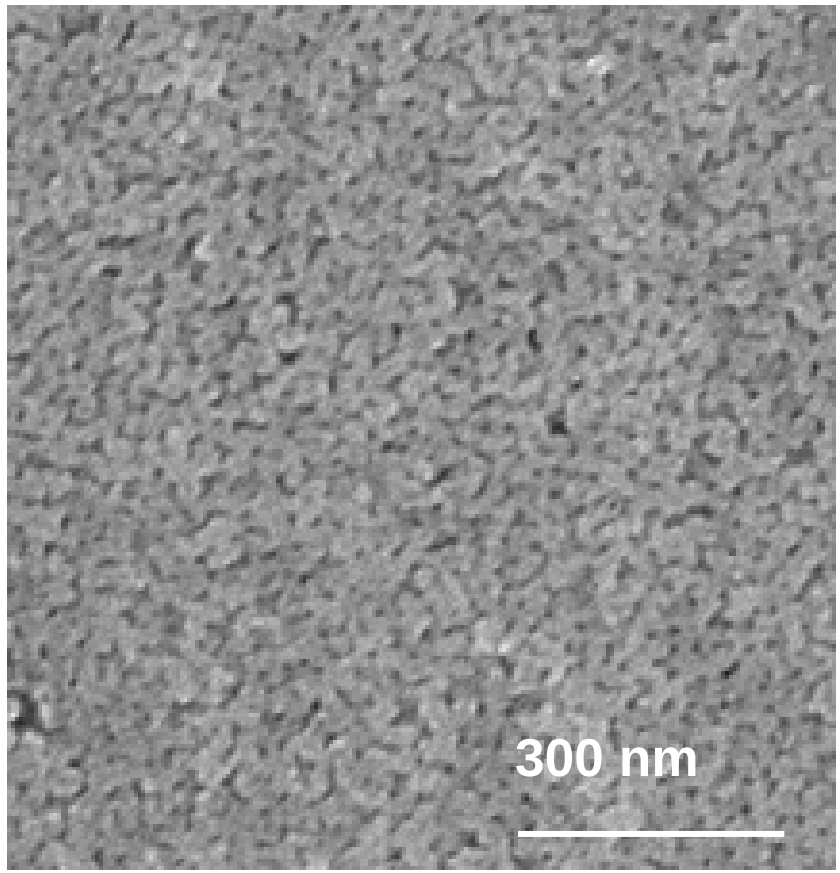
Nanoengineering

Issues

- Three dimensional material/device/system spatial/temporal architecture
- Directed assembling/patterning/templating
  for heterogeneous nanosystems
- Hybrid and bio nanosystems for medicine and manufacturing
- Energy conversion and transfer
- Multiphenomena, multiprocesses, multiscale design
- Large scale atomistic modeling and simulation
- Integration of nanoscale into larger scales:
  use of intermediary standard components
- Thermal and chemical stability
- Operational and environmental safety
- Reliability and reproductivity at the nanoscale

Several NNI centers are focused on nanoengineering.
Ex: Cornell, NWU, Sandia, ORNL

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

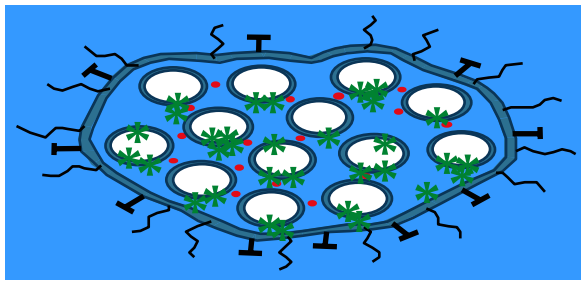


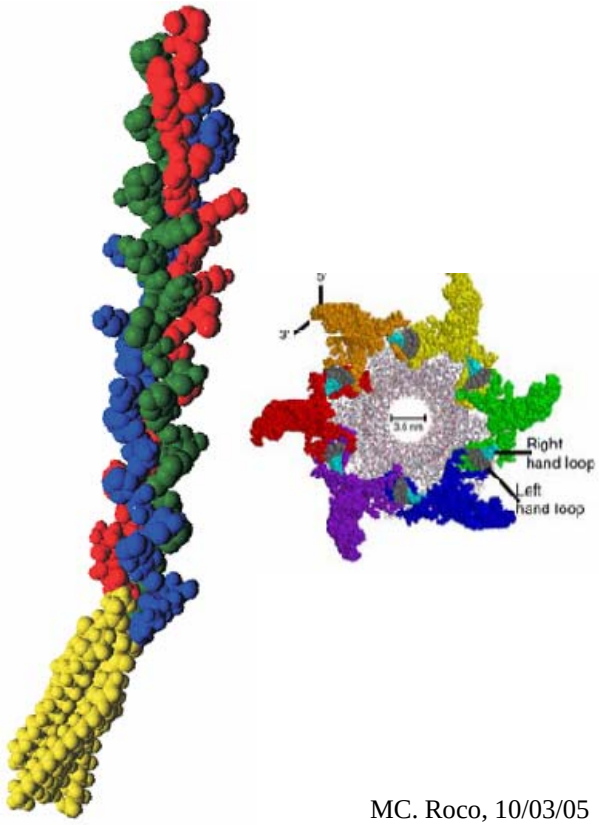
Example:

Synthesis and control of nanomachines

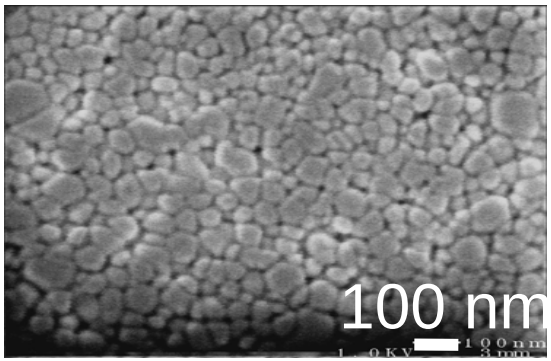
(examples NSE in 2004, www.nseresearch.org - 300 projects)

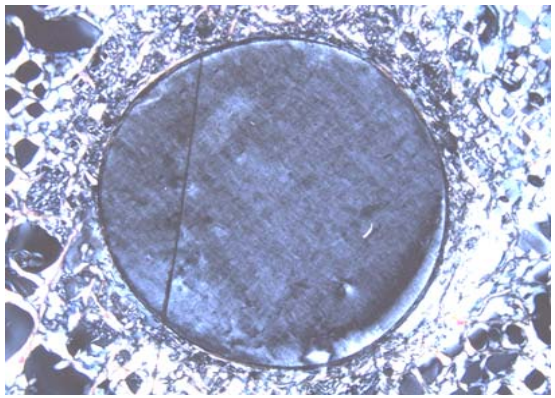
- **Self-assembly processing** of nanoscale bio-materials and devices for micromachines components (UCSB)
- Chemistry to synthesize components of **nano machines to work on surfaces** and b activated by external electromagnetic fields (UCB)
- **Light driven molecular motors** (U. Nevada)
- **Combinatorial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





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

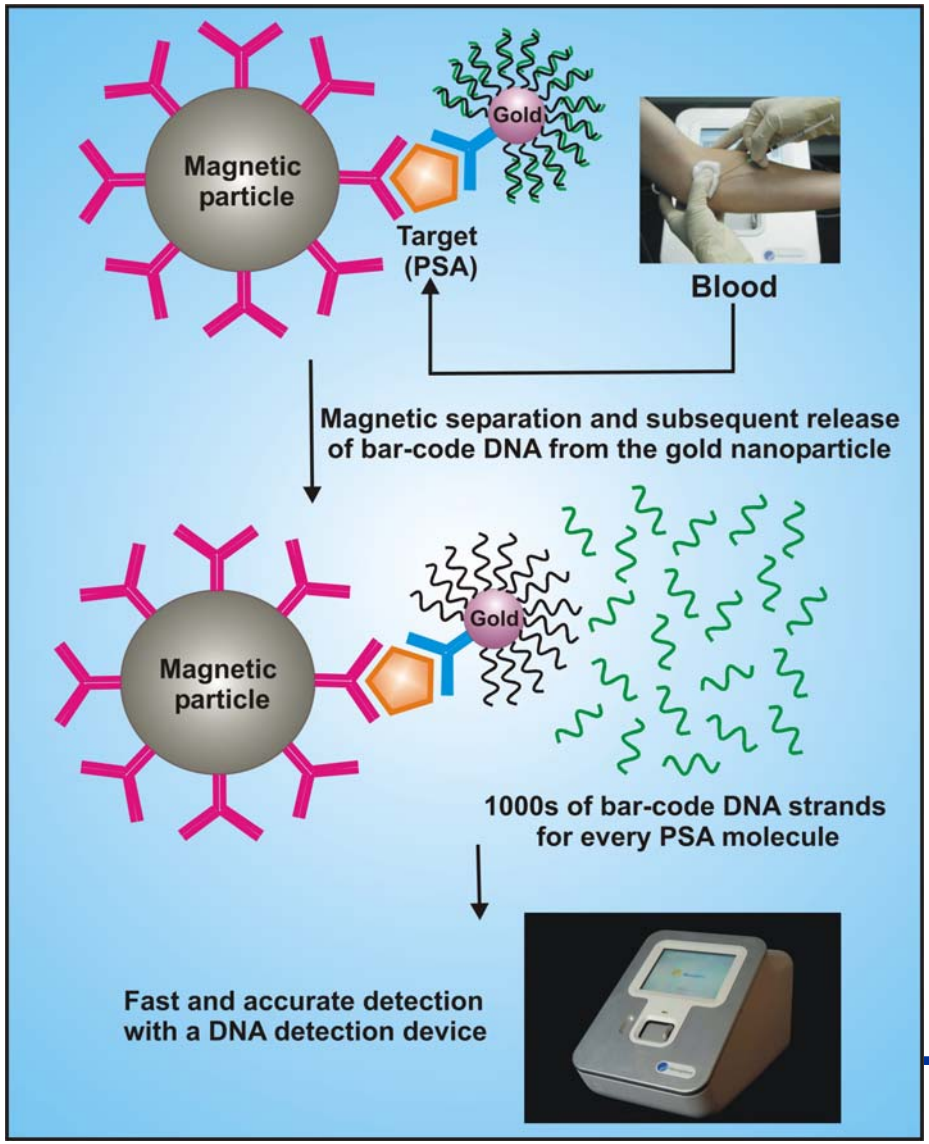
Bone bonding in 2 weeks and osteointegration in 4 weeks because the nanostructure closely match that found in human bone

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

The product received "marketing clearance" from FDA in 2005

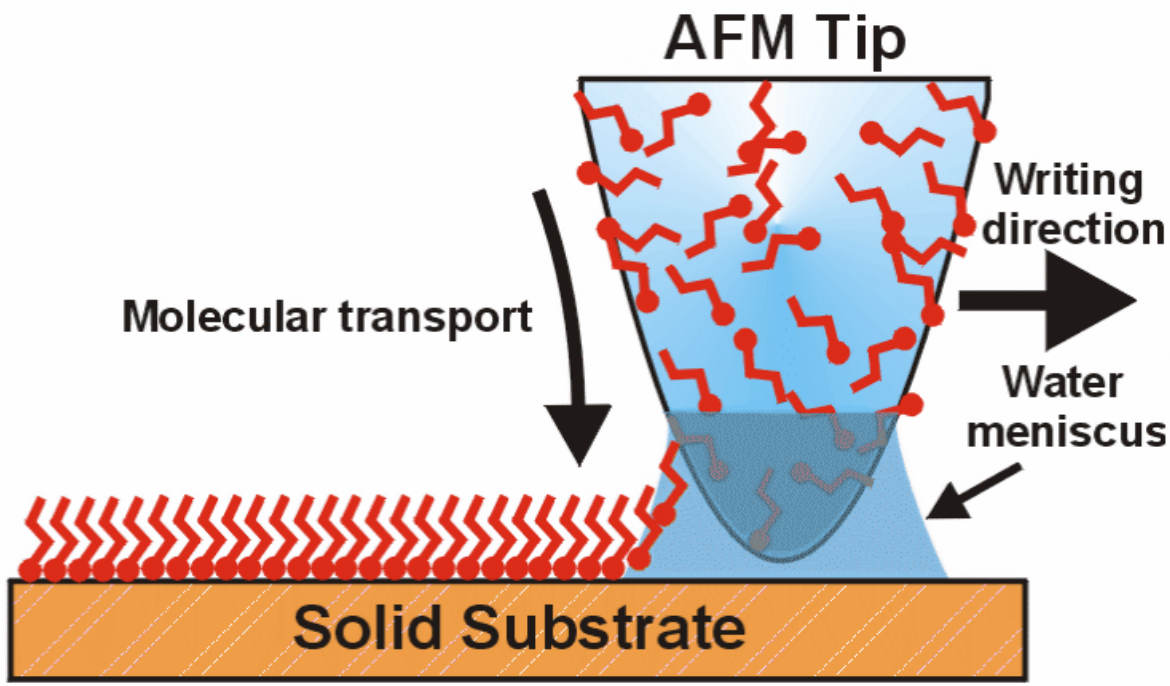
Example: NanoBio-Bar-Code Assay,

Chad Mirkin (NU 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**

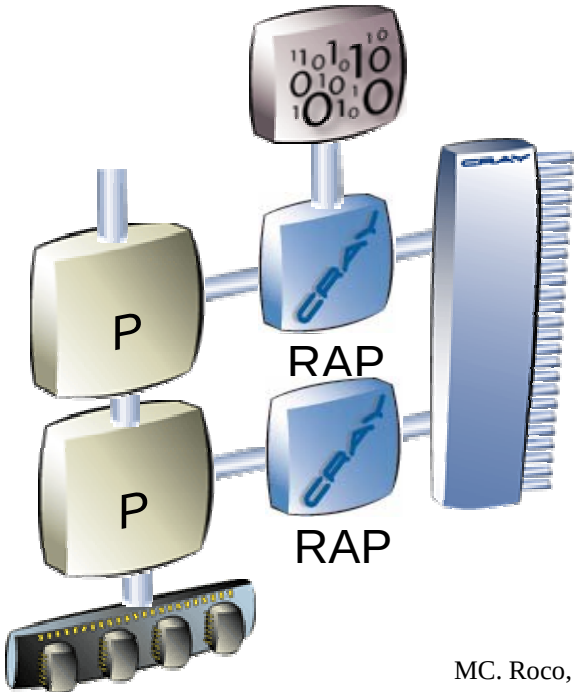
Example: Dip Pen Nanolithography (DPN)



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

Using nanotechnology to build the highest speed processors

Using fast computers and reconfigurable computing for nanoscale S&E "application acceleration"
(for 100x potential speeedup)

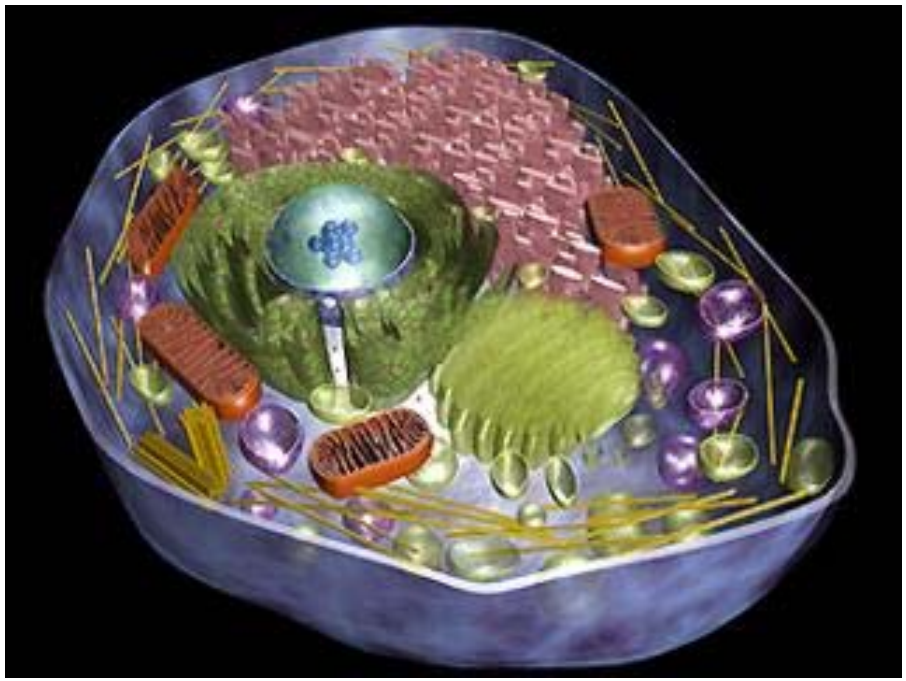


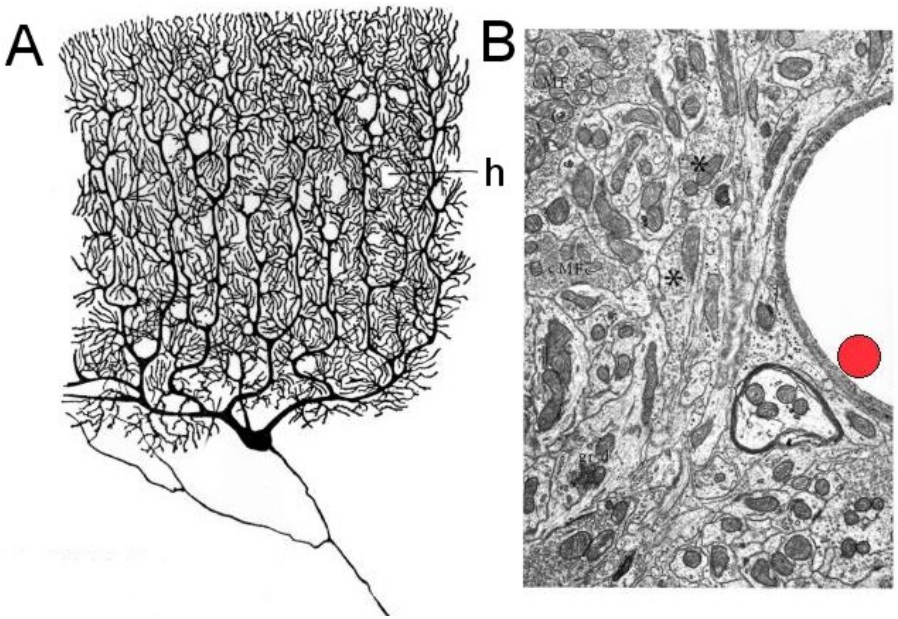
Capability 2004 (Cray X1):
50+ TFLOPS (fastest computer in the world)

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

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

Challenge 2015: 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, . . .

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)

Revolutionary technologies, 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**

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, Flextronics, 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

- issues -

Energy conversion

- Fuel cells; Photovoltaics, space harvesting systems
- Photo or electro-catalytic reduction of CO2 to produce a liquid fuel

Storage

- H2 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.

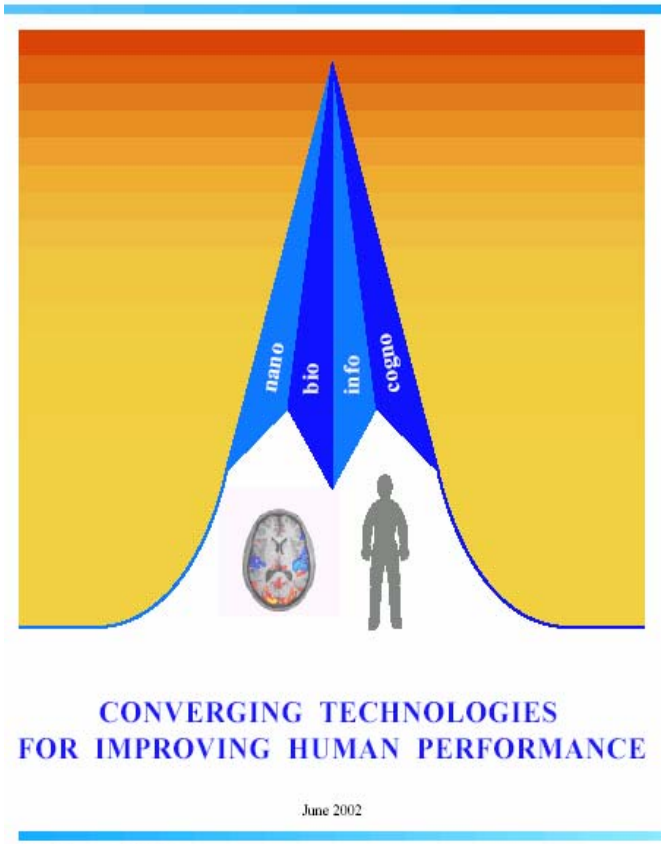
Nanotechnology holds major implications in the environment

- Nanoscale manufacturing will in the long term provide the means for sustainable development. By increasing production capacity for the same useful 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

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)

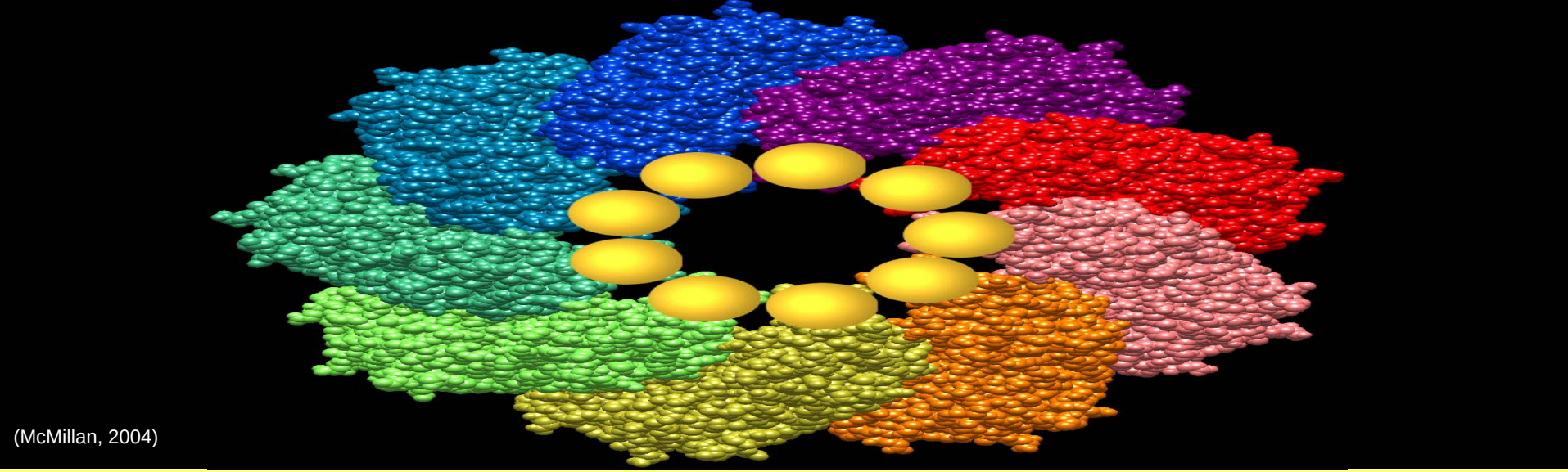
Online www.nsf.gov/nano,
also Kluwer Academic Publ

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
- NNI support for nanomanufacturing
- Planning for the future

Minneapolis, October 3, 2005

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**

Manufacturing at Nanoscale
- typical bottom-up processes -

- Nucleation and growth
  - Aerosol and colloidal dispersions; deposition on surfaces
- Selfassembling
  - Natural process in living systems and biomimetics
  - Chemistry/chemical manufacturing
  - Guided by electric, magnetic, optical fields, DNA controlled ..
- Templating
  - Al and carbon nanotubes; Substrate patterning; local reactors
- Engineered molecules and molecular assemblies
  - Designed molecules as devices: Wires, switches, logic devices..
  - New molecular architectures by design: several scales, dynamic
- Bio methods
  - Selectivity, selfassembling, synthetic biology, ..

Manufacturing at Nanoscale
- other typical processes -

- Lithography:
  - Optical, ultraviolet, electron-beam (1-10 nm)
  - Scanning probe microscope based (1-10 nm)
- Nano-machining
- Nano-manipulation
  - Atoms and molecules (ex: IBM), nanoparticles (ex: USC)
  - 1D, 2D and 3D structures; assembling of nanodevices
- Fragmentation: mechanical milling, spark erosion, etc.
- Sintering of nano precursors
- Thermal treatment of metals, ceramics, composites
- Mixing of nanocomposites and their processing
- Nanoscale robotics
- Evolutionary approaches, ..

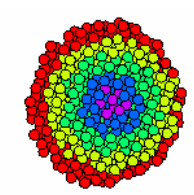
Defining Nanomanufacturing (2)

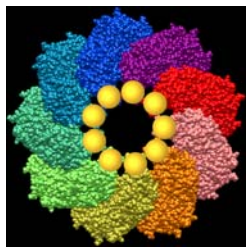
- Fragmentation
- Patterning
- Restructuring of bulk
- Lithography, ..

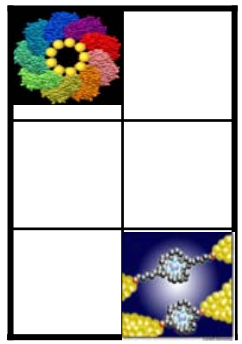
- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

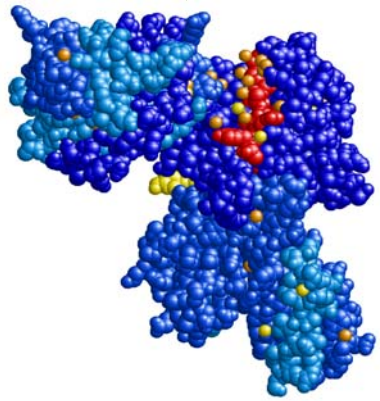
- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration..









Assembling

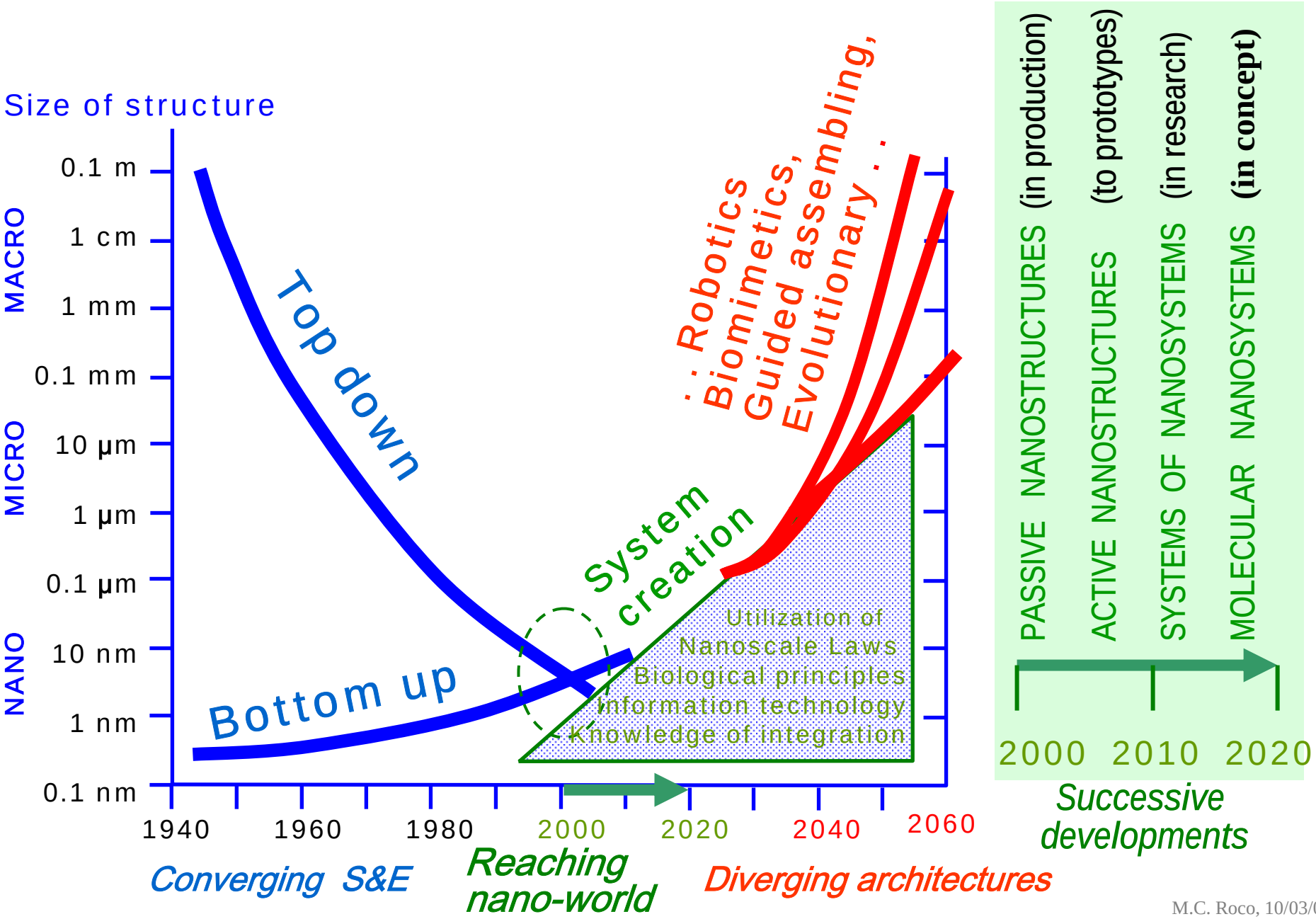
- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

- Molecules as devices,
- Quantum control,
- Synthetic biology..

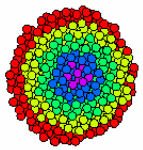
PASSIVE NANOSTR. - ACTIVE NANOSTR. - SYSTEMS OF NANOSYSTEMS - MOLECULAR NANOSYSTEMS

Reaching nano-world and system creation



M.C. Roco, 10/03/05

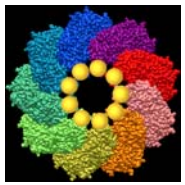
Timeline for beginning of industrial prototyping and nanotechnology commercialization: Four Generations



1st: Passive nanostructures (1st generation products)

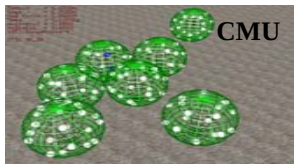
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2000



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

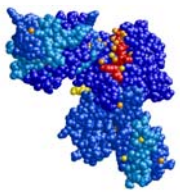
~ 2005



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

Nanoelectronics:
Example of Enablers for Successive Product Generations

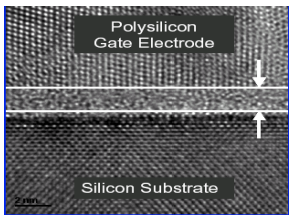
- First generation: Scaling down "masked-lithography of thin-films" approach (the cost-per-function trend is threatened); Nanoscale comp. (ex: layers) w/ new physics
- Second generation:
  - Manufacturing technique to lower the cost of: capital equipment, pattern generation, and "atomic-level" process control will be required. Possible solution - "directed self-assembly" leading to CMOS scaled to its ultimate limits (5-10 nm).
  - New devices/circuits that extend the industry's historical rates of improvement in energy-delay product and standby power. CMOS is already being scaled into a regime where the tradeoff between performance and power consumption forces significant compromise. Possible in the medium term - "post-CMOS" (but still "charge-based") with carbon-nanotube, single-electron "transistors", others.
- Third generation: Charge-based devices tend to remain limited by most of the interconnect charge-transport issues (e.g., parasitic capacitance) and near-equilibrium thermodynamic constraints that afflict CMOS. Possible solutions in devices based on state variables other than electric charge (e.g., electron-spin, nuclear-spin or photonic states).
- Fourth generation: Molecular and supramolecular components "by design"

Reference: 2002 edition of the International Technology Roadmap for Semiconductors; R. Doering

Challenge 2015: Transistor beyond/integrated CMOS under 10 nm

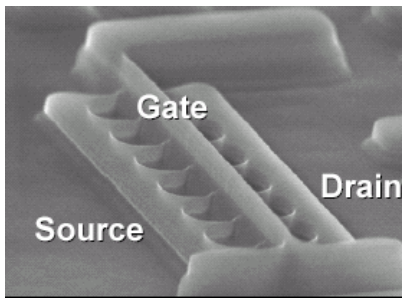
- In the 70s, 80s and 90s
  Geometrical scaling was the major driver

- 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

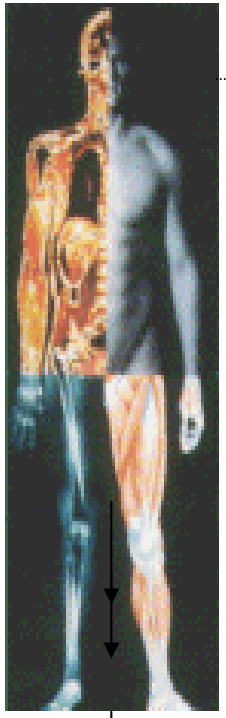
In addition, to explore beyond CMOS:

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

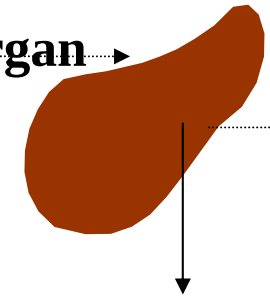
Examples of levels for intervention of nanobiotechnology

in human life extension: 4 generations of products

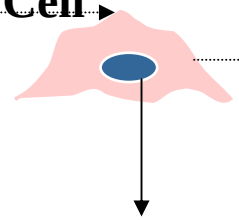
Human



Organ



Cell



Molecule

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

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

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

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

(NBIC Report, 2002)

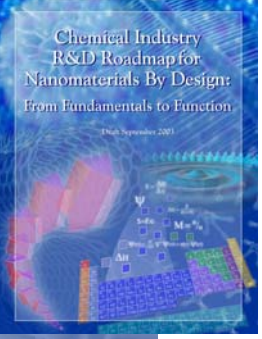
First generation of products: passive nanostructures (~ 2000 –)

- 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

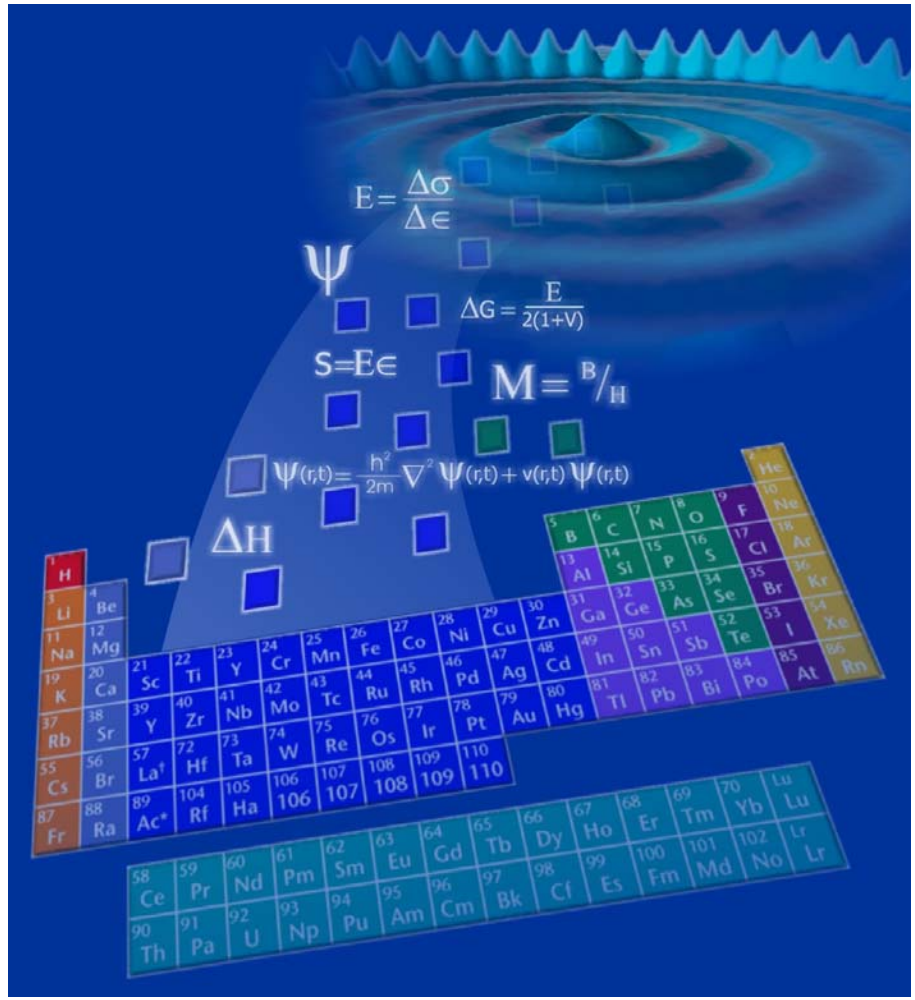
- **R&D focus:** on new properties of materials and new tools
  Ex.: grain boundary simulation, nanomechanics



Nanomaterials By Design

www.ChemicalVision2020.org and NNI

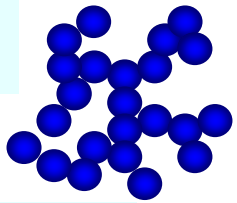
The ability to employ scientific principles in deliberately creating structures with nano-scale features (e.g., size, architecture)
that deliver unique functionality and utility for target applications



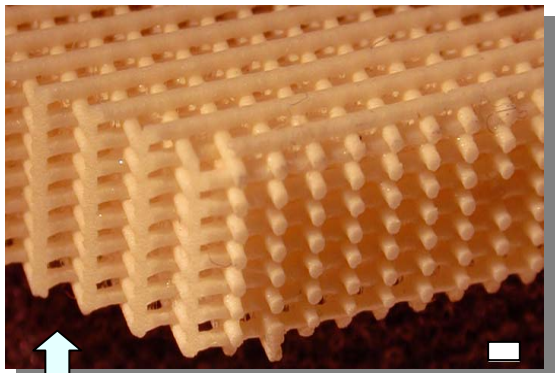
Directed selfassembling

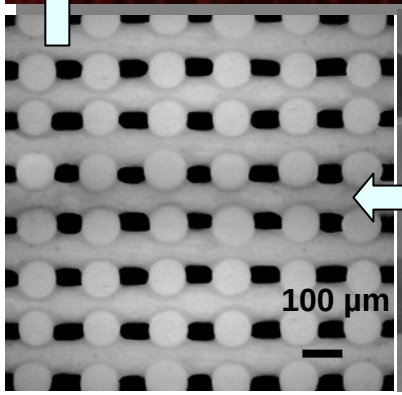
Ex: Robotic deposition of nanoparticle/polymer gels (RPI)

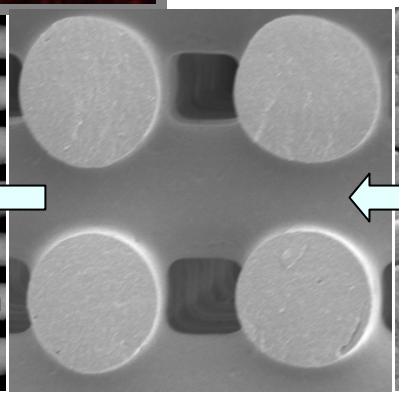
nanostructured inks

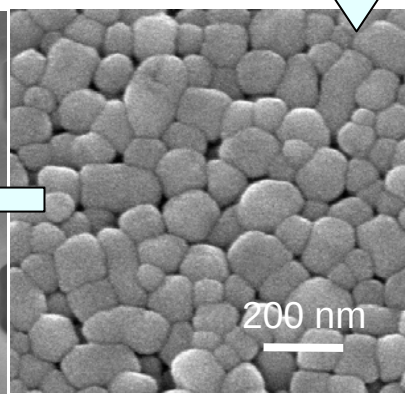


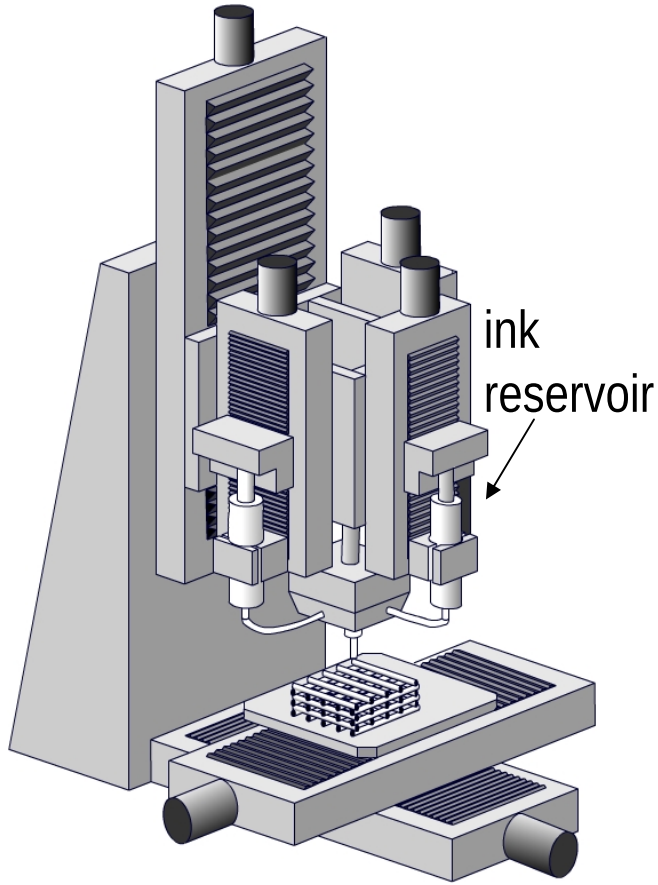
direct-write assembly of 3-D structures with builds rates ca 1 mm/s
D nozzle: 1µm -1mm
Lewis et al. (2003)







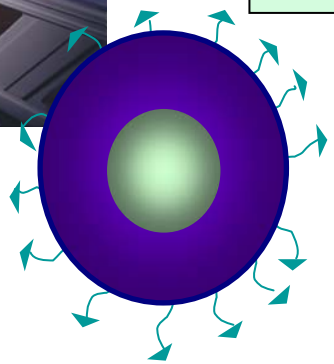




Goal: Design nanostructured inks with controlled rheology and create materials with 3-D features on multiple length scales

Aircraft Engines

Healthcare



Nanotechnology Platform

NanoTubes and NanoRods

NanoParticles

NanoCeramics

NanoStructured Metal Systems

Hybrid Materials

Water

Energy

Nanotechnology at General Electric

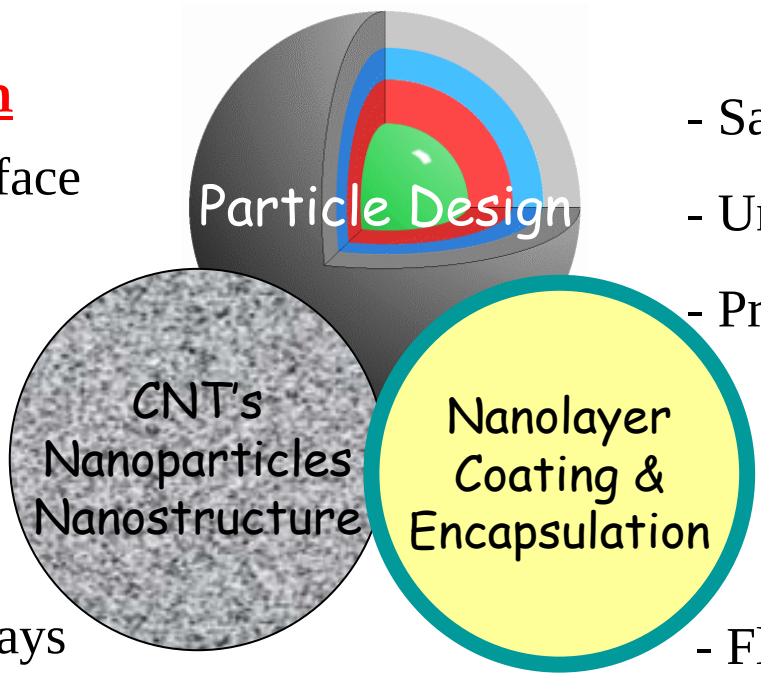
DuPont: Process Engineering & Manufacturing

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 of today's technology:

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)

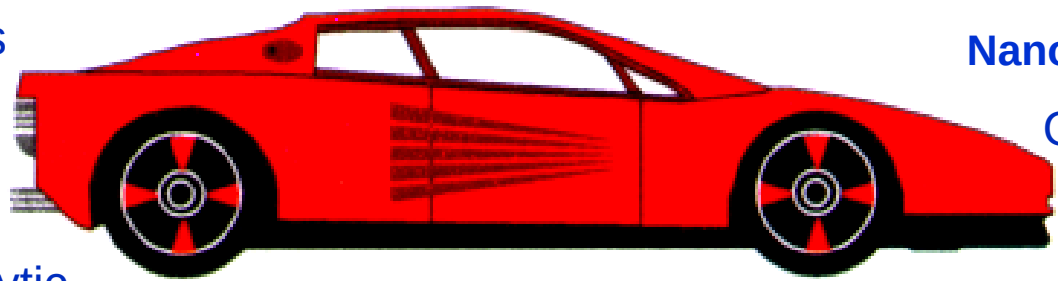
Ex: "Nano in Cars" consortium in Germany - 6 car manufacturers, 10 suppliers, and 26 R&D university and laboratories

Nanoparticle reinforced polymers, metals, filters

Windows with UV/visible light absorber layer

Amorphous nanostructured alloys for engines

Paint pigments



Nanojet injection

Emission probe

GPS navigation

Angle sensor

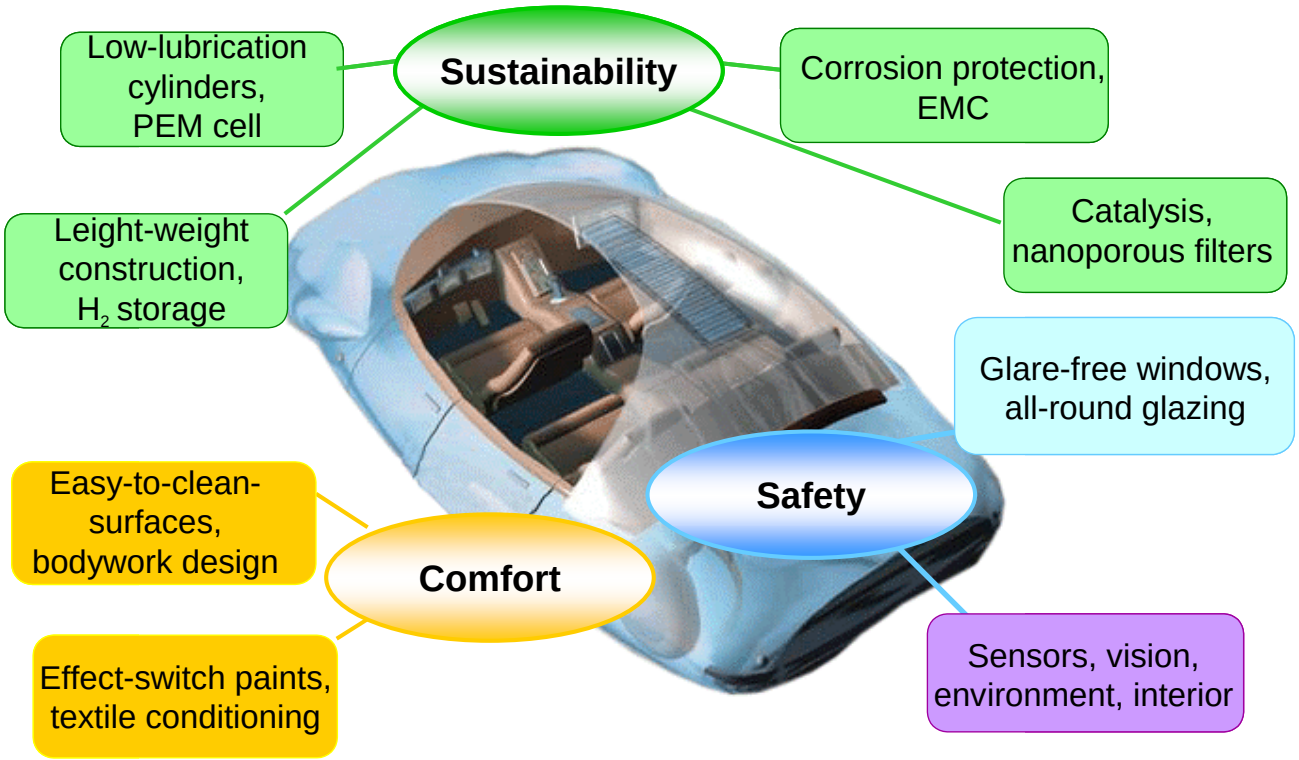
Catalytic converter

ABS sensor

Nanoparticles in rubber

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

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

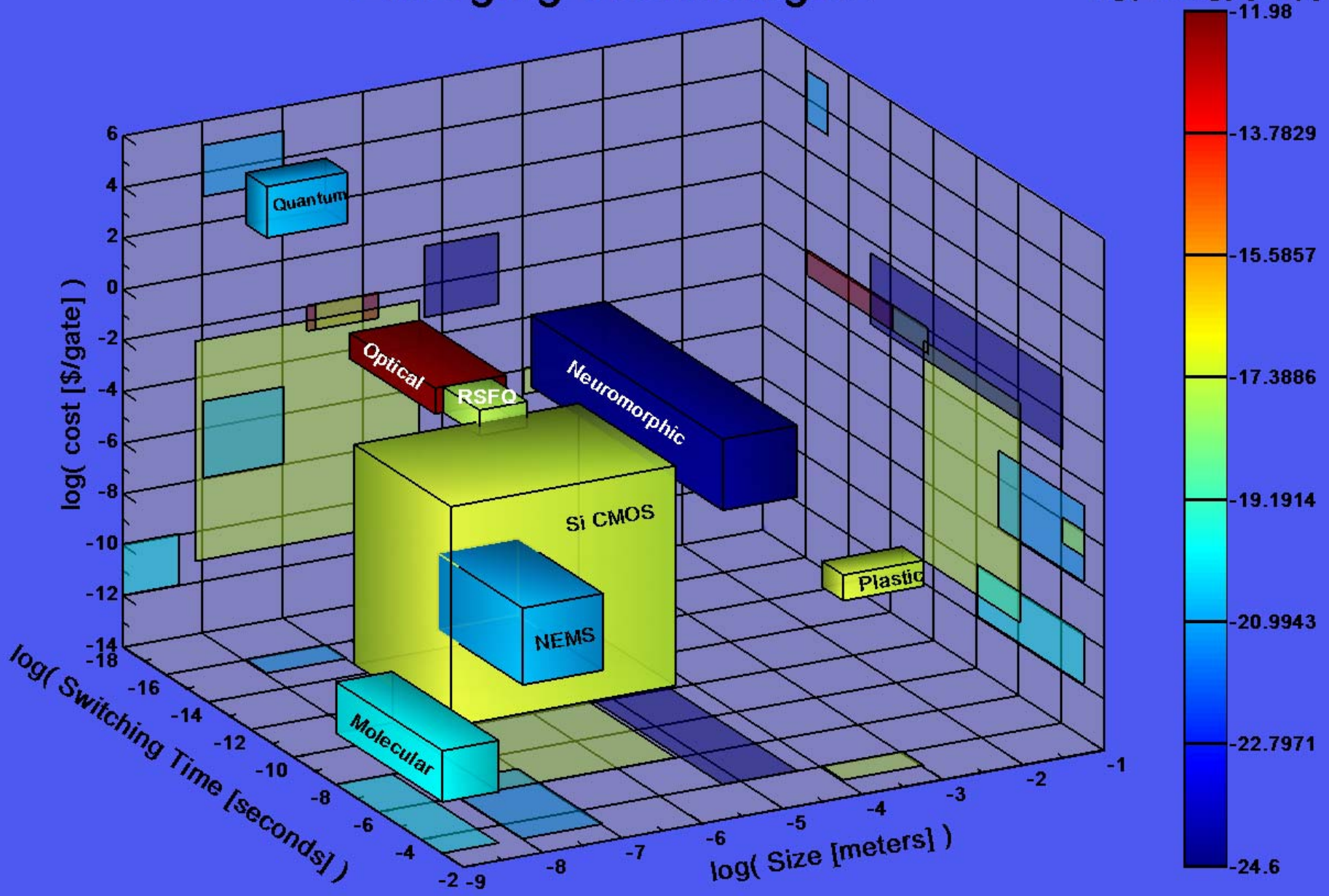
- IN DESIGN -

- **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

Emerging Technologies

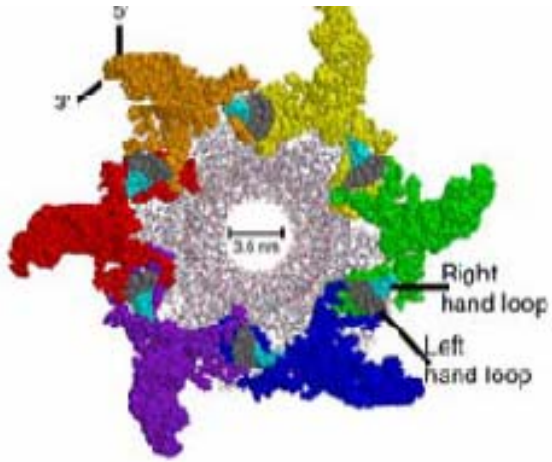


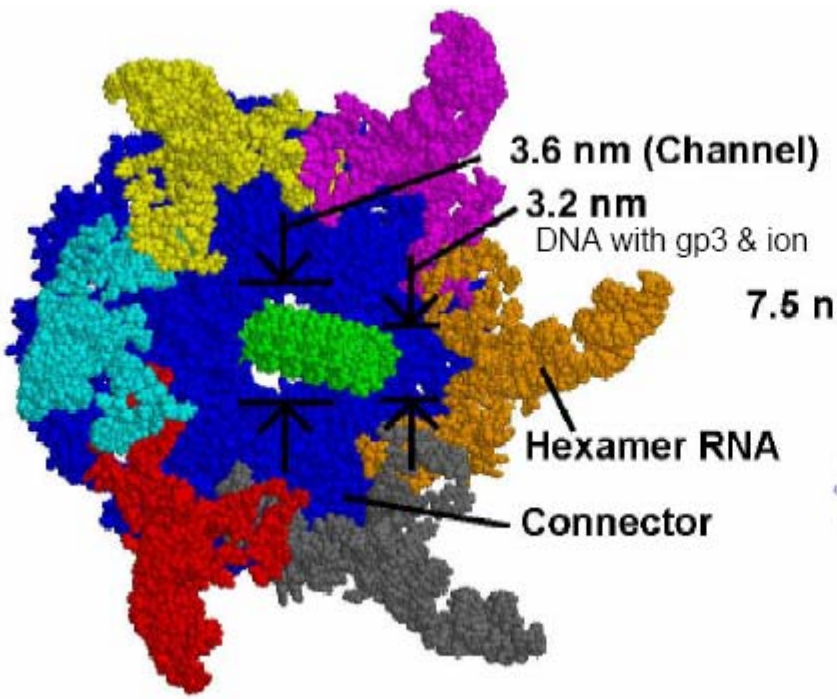
Motivation for hybridizing other devices with CMOS

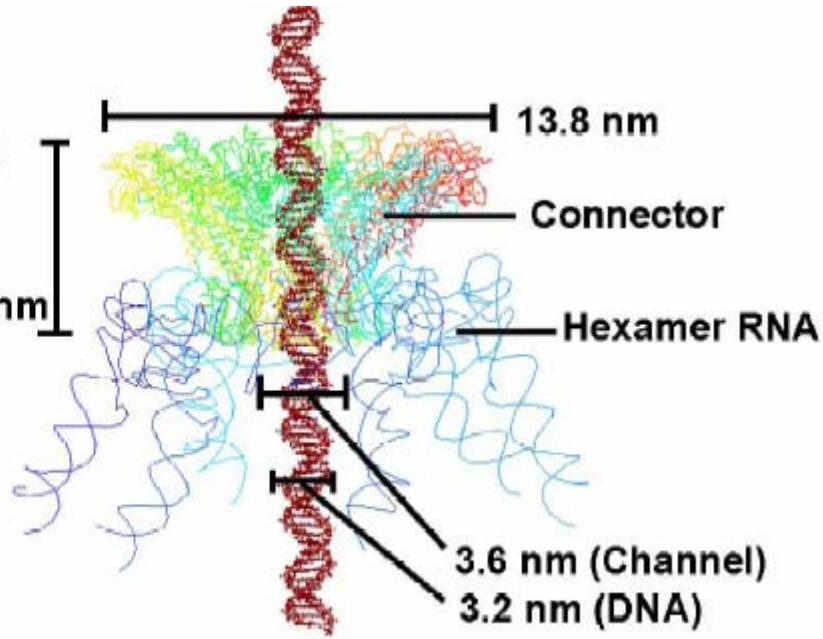
Example:

Construction of a Viral Nanomotor Driven by a Synthetic RNA

P. Guo, Molecular Virology,
Purdue University, 2004







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

- IN RESEARCH -

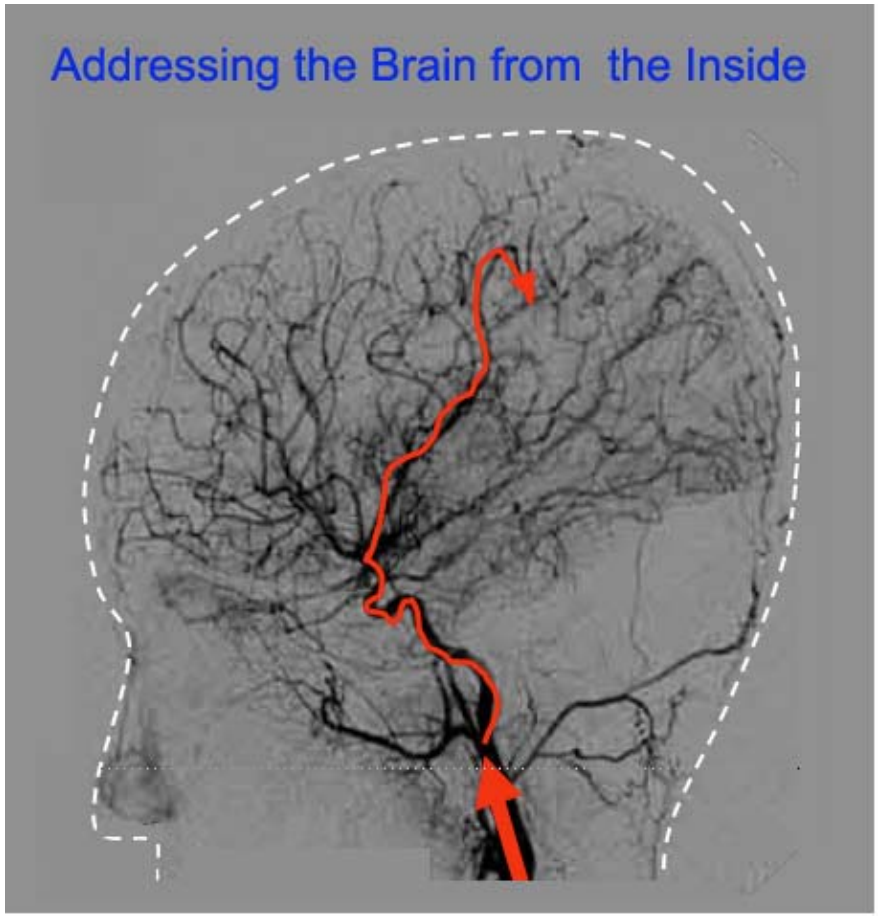
- **Goal:** engineer and manufacture 3D nanosystems with heterogeneous components, systems of nanosystems; typically for nanoscale assemblies and systems

- **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

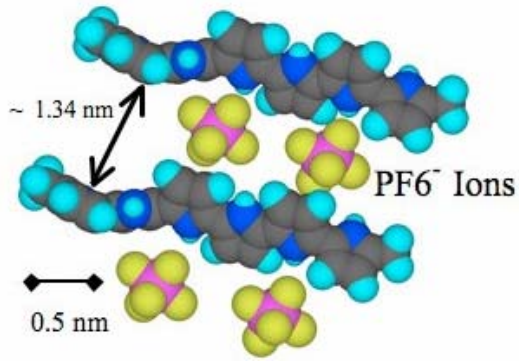
Example: Neuro-vascular Central Nervous Recording/ Stimulating System: Using Nanotechnology Probes

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

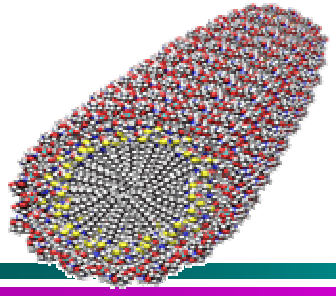
Fourth generation of products: molecular nanosystems (~2020?)

- 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

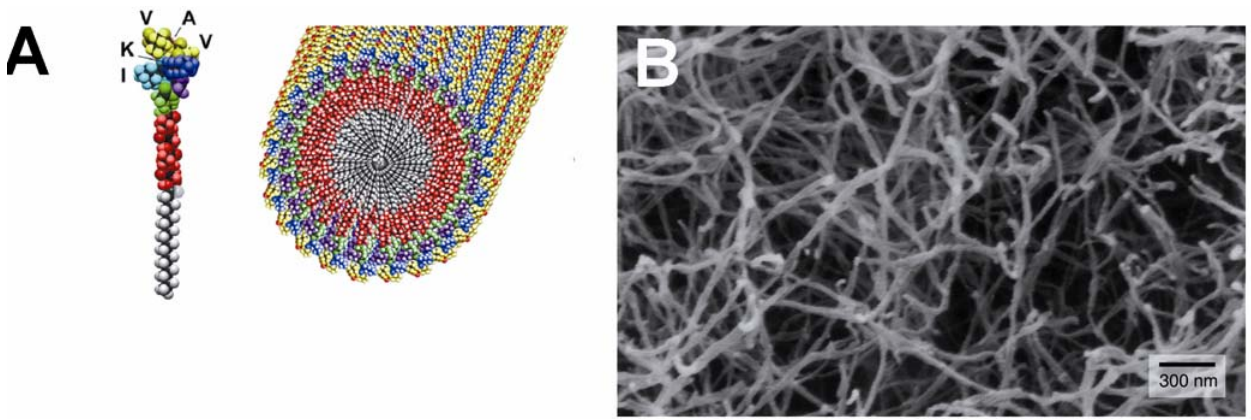
- **R&D focus:** atomic/molecular design, collective behavior and chemical-mechanical interaction of molecules, tissue nanoengineering, nano-bio-info-cognitive convergence, neuromorphic engineering

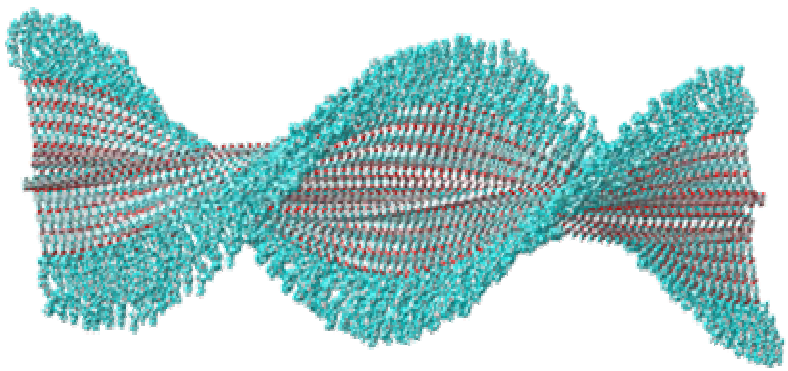


Designing molecules for hierarchical selfassembling

EX: SAMUEL I. STUPP, *Northwestern University*

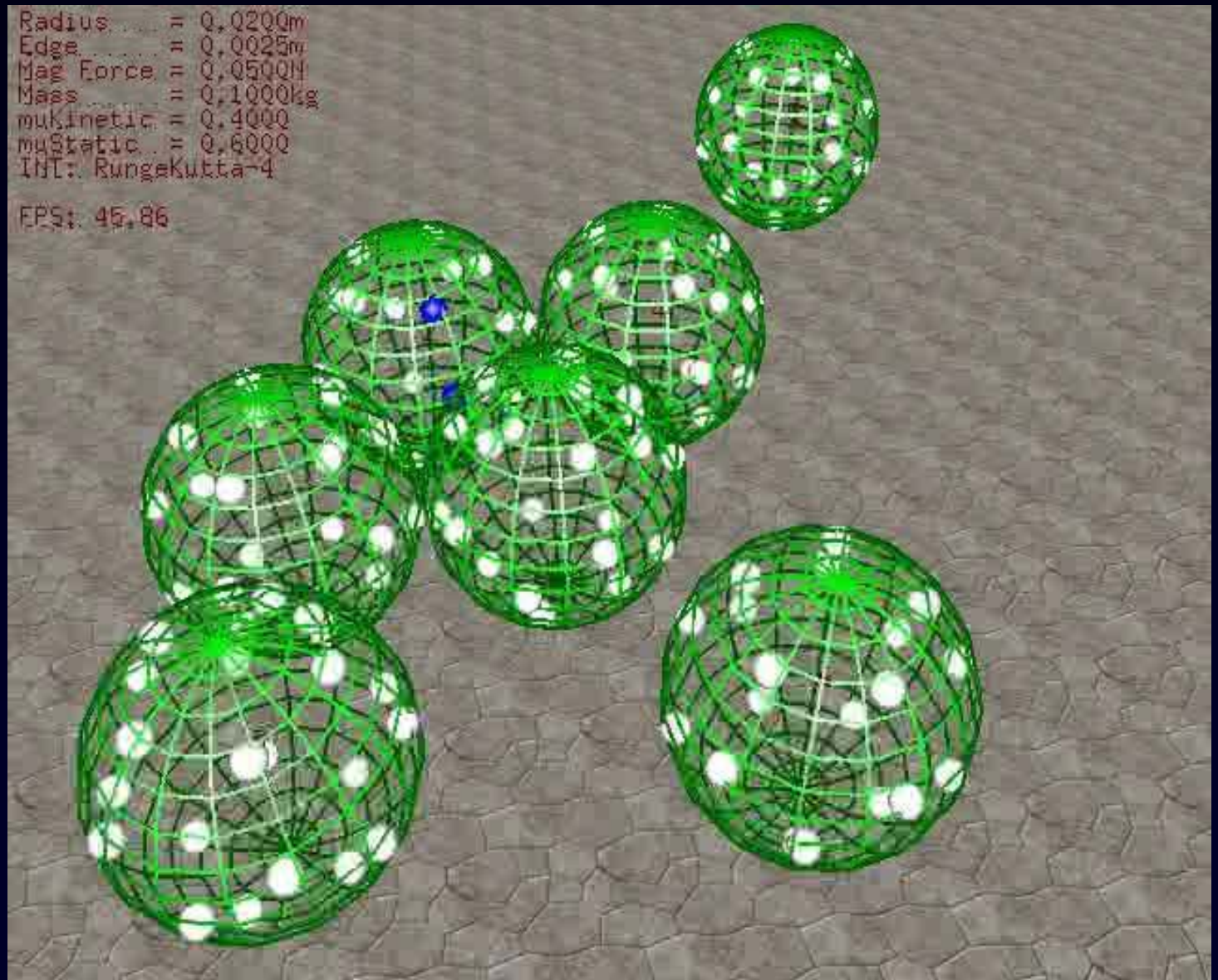
Application: biomaterials for human repair, reactive filters, others





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

(Seth Goldstein, CMU)



Manufacturing at Nanoscale

- several challenges -

- Efficiently create structures in the 0.1-100 nm range
- Combine top-down and bottom-up approaches
- Integration along scales with larger systems
- Large scale production and economical scale up: different concepts and principles?
- *Interaction non-living and living structures*
- *Replication (ex: lithography, thermodynamic cycle)*
  Self-replication (ex: bio, DNA-based)
- *Revolutionary processes envisioned (open system)*
  Extend existing manufacturing capabilities if possible

Nanomanufacturing: Several key issues

- Evolutionary vs. revolutionary technologies
- Specific nanotechnology processes and equipment;
  Expand on existing infrastructure?
- Need for specific instrumentation, metrology, manu. tools
- Integrating length scales in 3-D, time scales, materials,
  functionality (mechanical, electromagnetic, thermal,
  biological, chemical) of manufacturing processes;
  from nanoscale to micro- and macro-scales
- Scaling up / high rate production requirements
- Environmental/Health/Safety requirements
  and research needs
- Intellectual property issues: time scale, coverage, etc.

NNI and Nanomanufacturing 2000 - 2005

- **Nanomanufacturing - initial goal of NNI**
  (included in the nanotechnology definition,GCs and SBIR)
- **Aiming at a progressive approach:**
  exploratory research, design, prototyping, applications
- **A new NNI Grand Challenge since FY 2002**
  Lead agencies: NSF (basics - $22M; new program on Nanomanufacturing and theme in solicitation) and NIST (applied)
- **About 1/3 NNI budget has relevance to**
  nanomanufacturing (crossing the 5 modes of support); to continue for all four generations of nanomanufacturing
- **Workshops** (ex. Report on interagency meeting, 2004)
- **Working group focused on nanomanufacturing** (12/2003)
- **Outcomes:** R&D, Facilities, SBIR, Partnerships, Growth

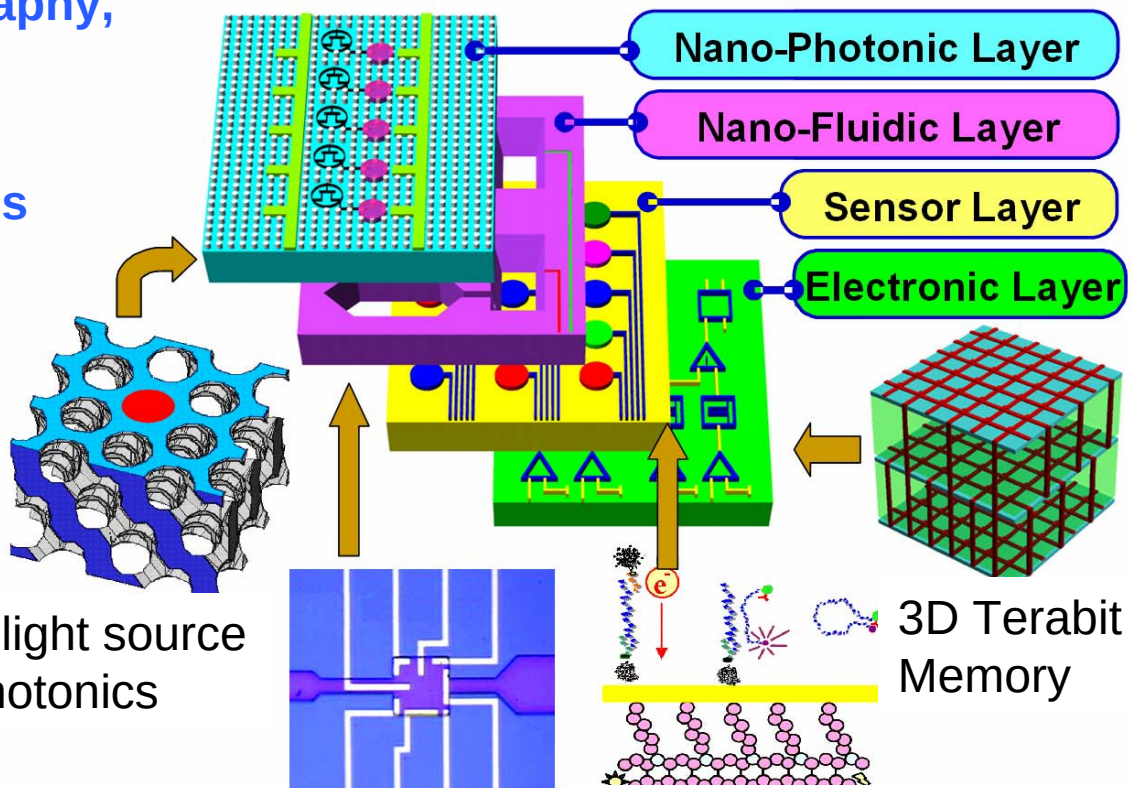
Center of Scalable and Integrated Nanomanufacturing

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

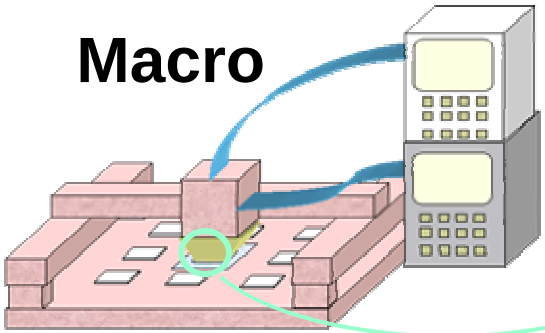
Nano Fluidic Circuits

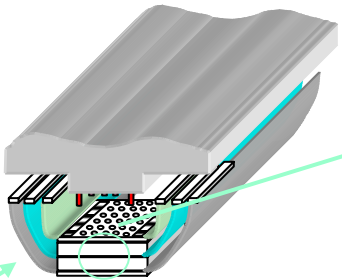
Ultra Sensitive Bio-sensor

3D Terabit Memory

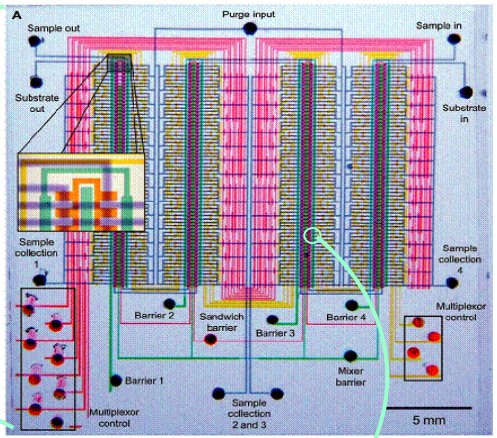
Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, UIUC, NCSU, Caltech

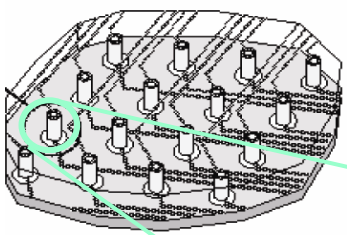
Macro

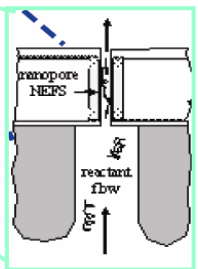




Micro







Nano

Goals - control of composition at nanoscale

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

Research Thrusts

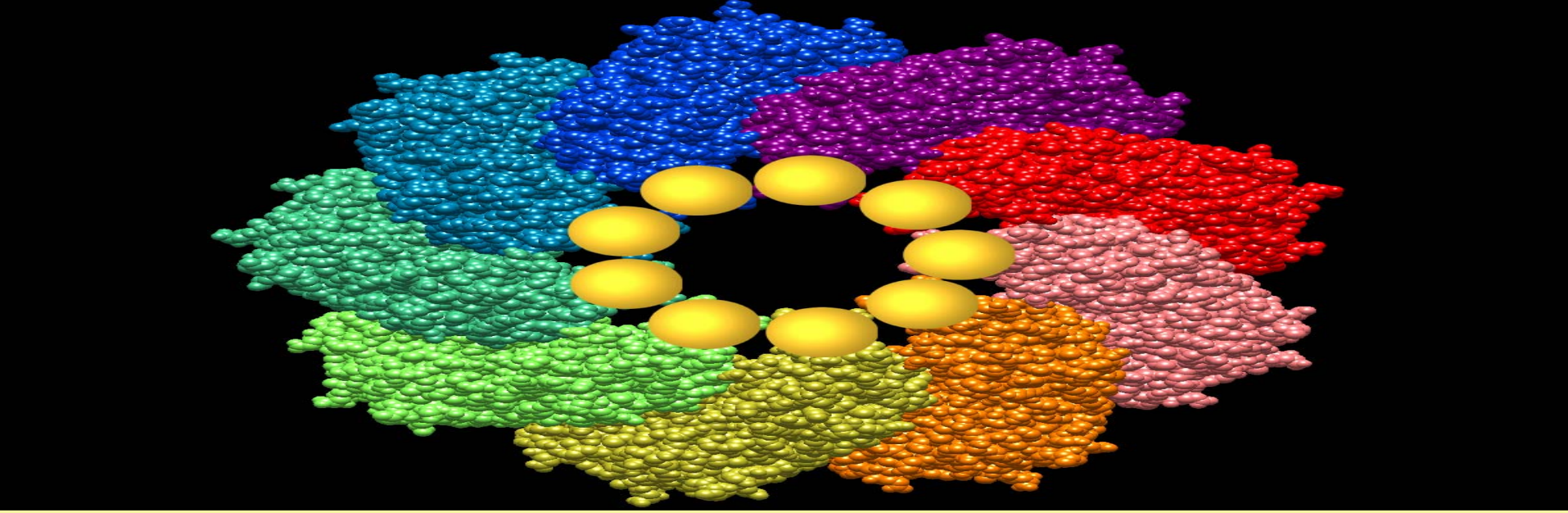
Micro-Nano Fluidic Network Toolbit

Process Sensing and Control

Manufacturing Systems

Highlights of the FY 2006 Budget Request - Nanomanufacturing -

- Establishment of a network for nanomanufacturing based on 4 NSF centers lead by the Center on Hierarchical Nanomanufacturing, a DOD MURI and the NIST National Nanomanufacturing and Nanometrology Facility
- New projects funded by the Nanomanufacturing Program at NSF, DOD MANTECH program, NIST metrology and characterization tools for manufacturing, DOE and NASA
- Increased SBIR activities in nano (~$80 million in 2006)
- NSET Working Group to promote innovation and liaison with industry
- Collaboration with the NSTC Working Group on Manufacturing R&D

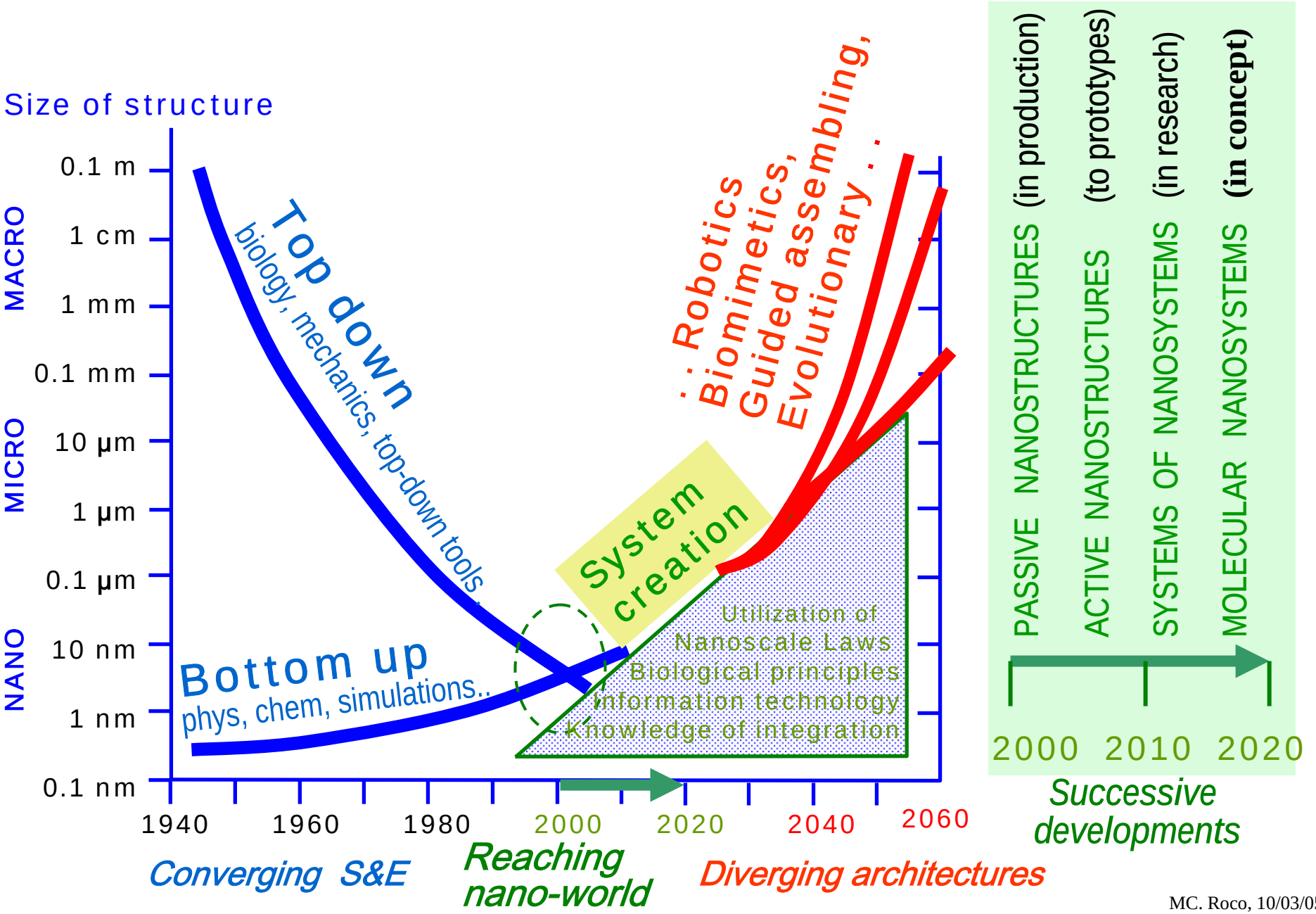


Part C
National Nanotechnology Initiative: The Long-term View

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

Minneapolis, October 3, 2005

Reaching nano-world and system creation



MC. Roco, 10/03/05

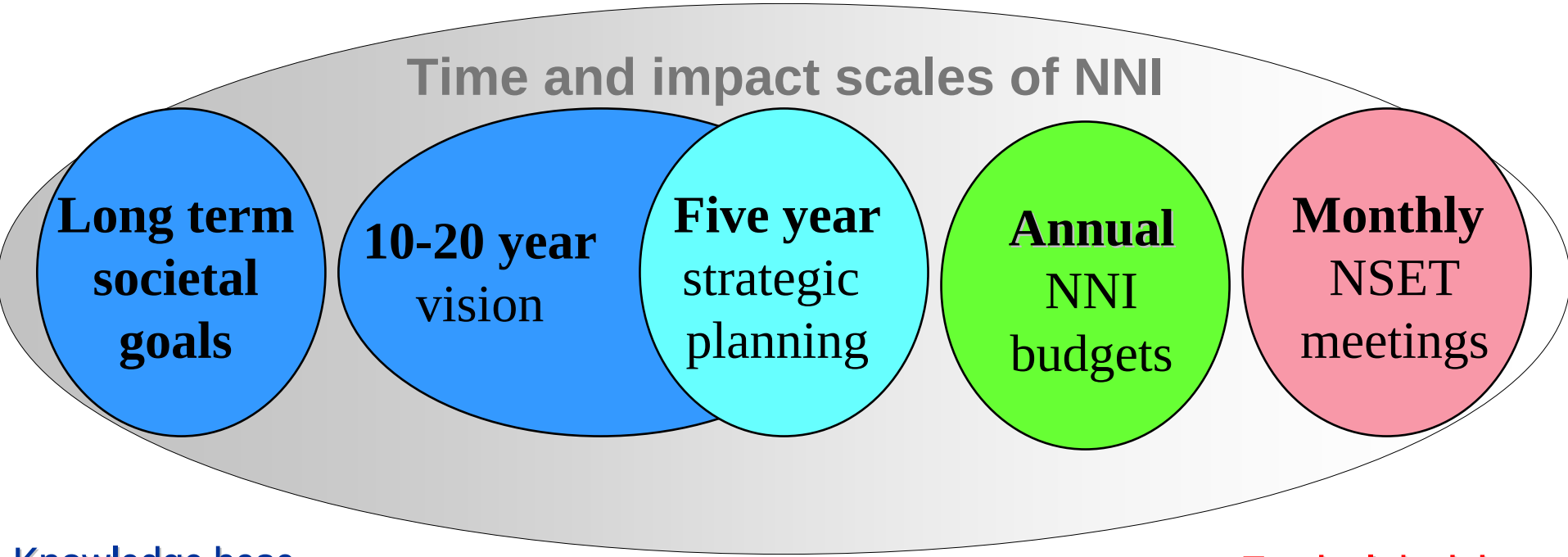
R&D towards the Next Industrial Revolution

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



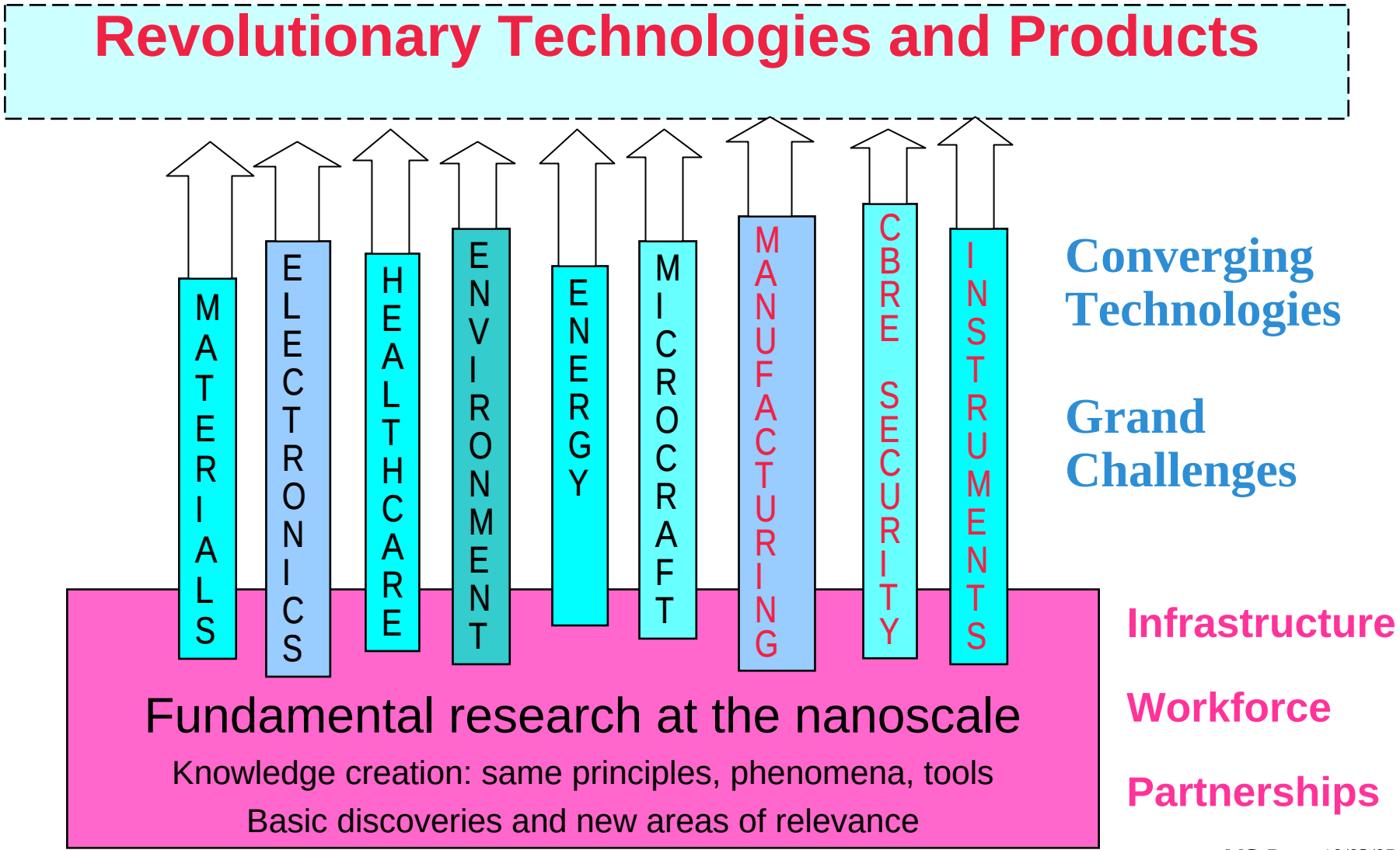
Knowledge base
Economy
Quality of life
Responsible NT
World context

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



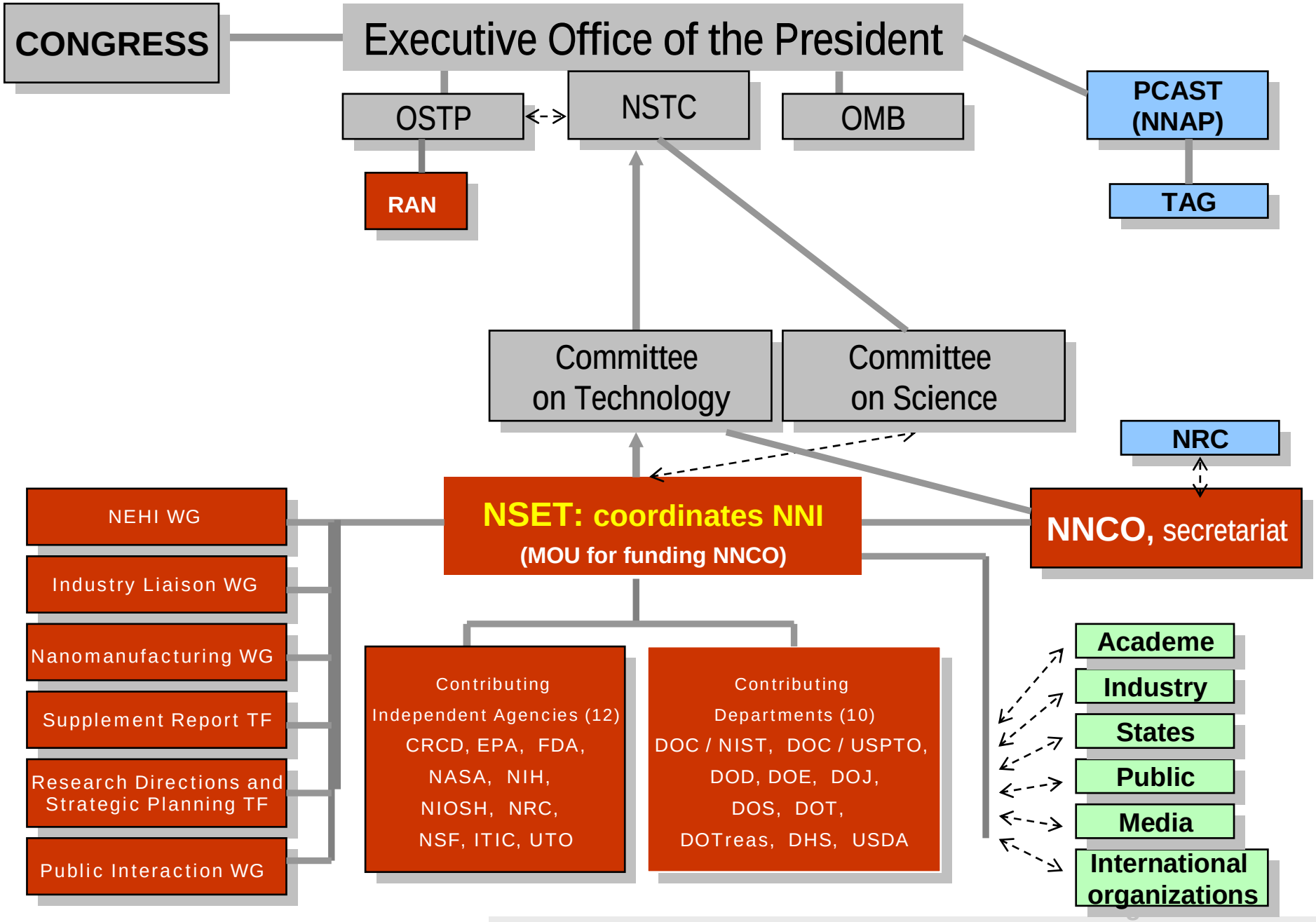
MC. Roco, 10/03/05

NATIONAL NANOTECHNOLOGY INITIATIVE

First NNI strategic plan (2001-2005): R&D funding by Agency

Fiscal year (all in million $)	*2000* Actual	*2001* Enact/Actual	*2002* Enact/Actual	*2003* Enact/Actual	2004 Req./Actual	2005 Req/Est.
National Science Foundation	97	150 /150	199 /204	221 /221	249 /256	305/338
Department of Defense	70	110 /125	180 /224	243 /322	222 /291	276/257
Department of Energy	58	93 /88	91.1 /89	133 /134	197 /202	211/210
Health and Human Services	32	39 /39.6	40.8 /59	65 /78	70 /106	89/145
NASA	5	20 /22	35 /35	33 /36	31 /47	35/45
NIST	8	10 /33.4	37.6 /77	66 /64	62 /77	53/75
EPA	-	/5.8	5 /6	5 /5	5 /5	5/5
Homeland Security (TSA)	-		2 /2	2 /1	2 /1	1/1
Department of Agriculture	-	/1.5	1.5 /0	1 /1	10 /2	5/3
Department of Justice	-	/1.4	1.4 /1	1.4 /1	1.4 /2	1/2
Congressionally-directed to DOD		25	40	80	103	150
TOTAL	270	422 /490	600 /737	770 /942	849 /1092	982/1231
Average annual rate: 38%		+82%	+50%	+28%	+16%	+ 13%

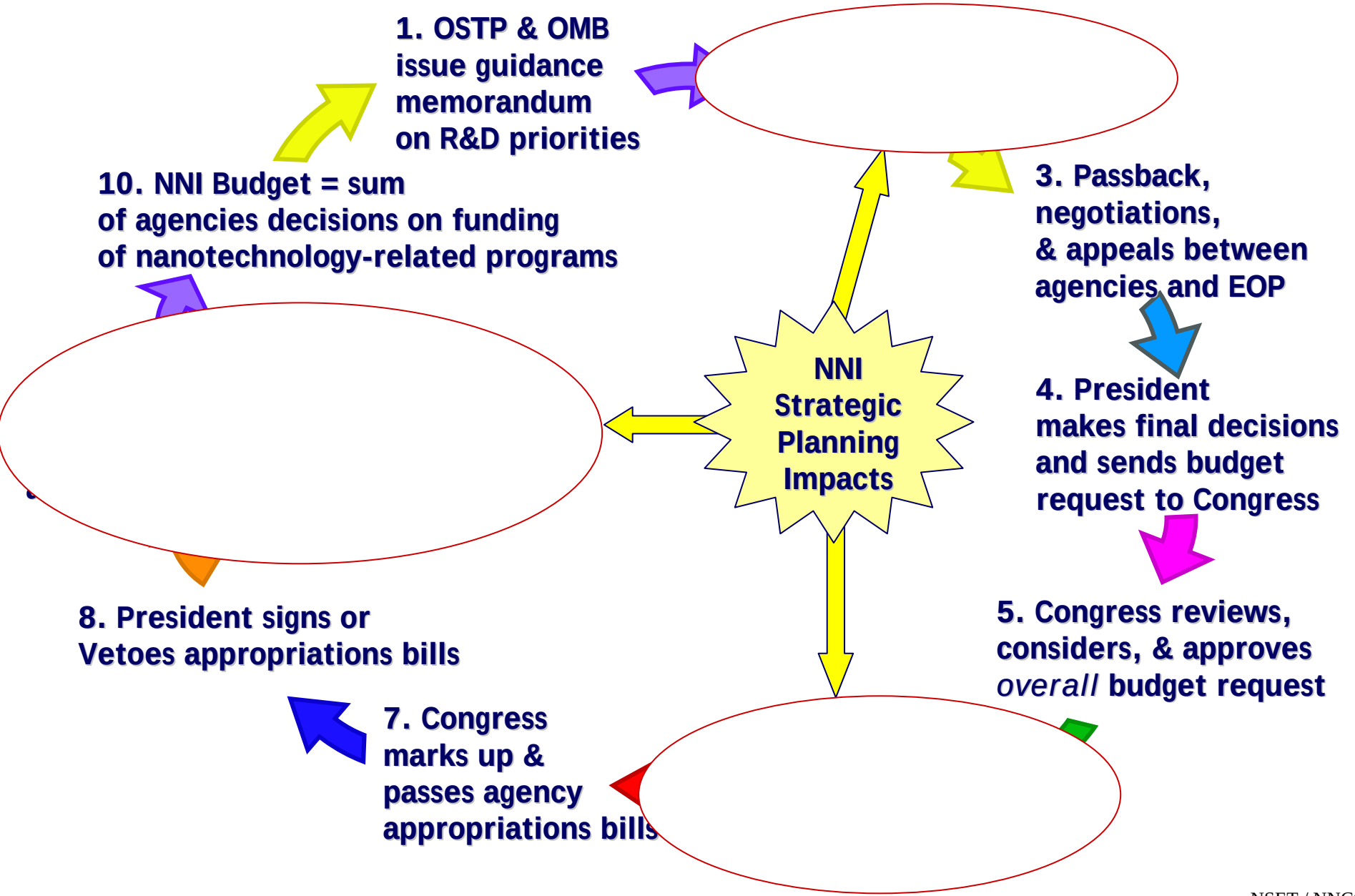
- Industry, state and local organizations: about 2 times NNI budget in 2004
- 2004 NNI budget: 65% to academia; 25% - R&D labs; 10% - industry (7% SBIR)



Organization chart of the NNI

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

Simplified Portrayal of NNI Budget Development



Accomplishments (1)

- Developed foundational knowledge for control of matter at the nanoscale:
  over 2500 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.
  Small Times reported ~ 1645 US nanotech companies in March 2005;
  In 2004, roughly half of companies were small businesses,
  and NNI SBIR/STTR investment was ~$70 million
- Infrastructure:
  over 35 new large nanotechnology research centers, networks and user facilities; about 6,300 users in 2 academic-based networks

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

Accomplishments (2)

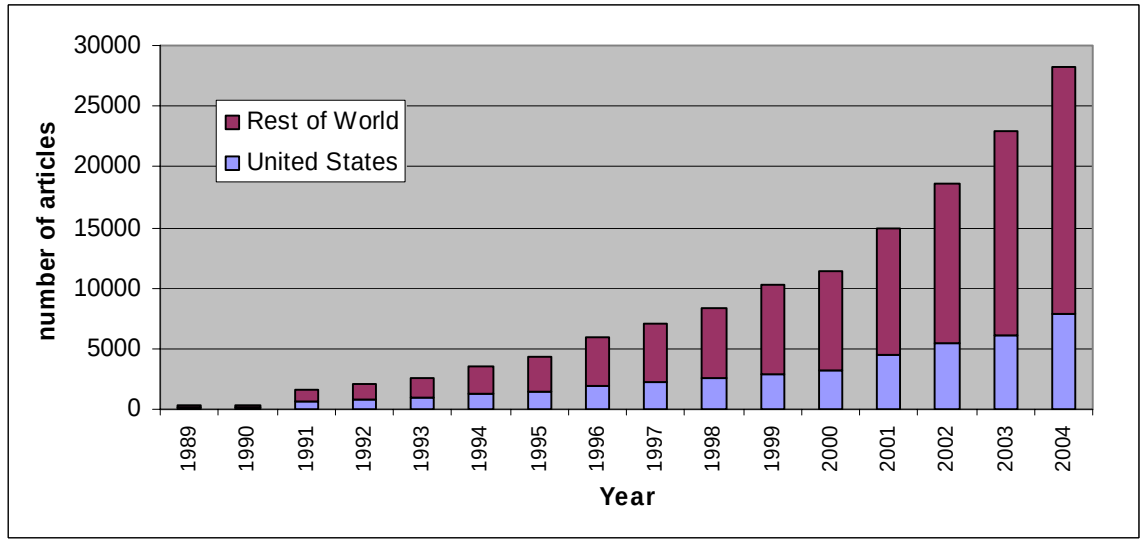
- Partnerships: with industry (Consultative Boards for Advancing Nanotechnology - CBAN), regional alliances (22), international (over 25 countries), numerous professional societies
- Societal implications and applications - from the beginning, about 10% of 2004 NNI; addresses environmental and health, 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; 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.

Exponential growth; About half of the highly cited papers in key journals originate in U.S.

("nano*" keyword search, after NNI Supplement Budget Report, 2006)

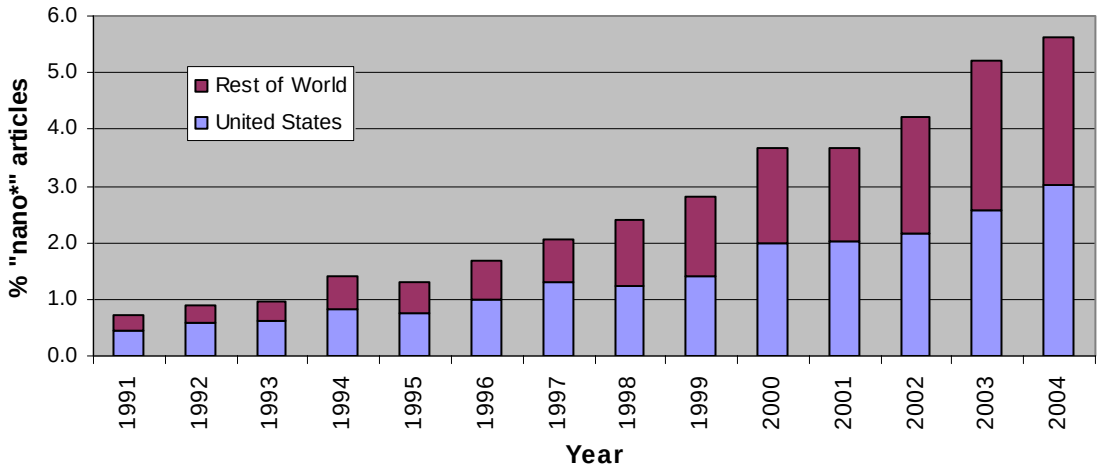
ISI Web of Science Database with 5400 professional journals

- U.S. about 30% for all journal articles in 2004



- U.S. about 50% in high-impact articles (UCLA NanoBank)

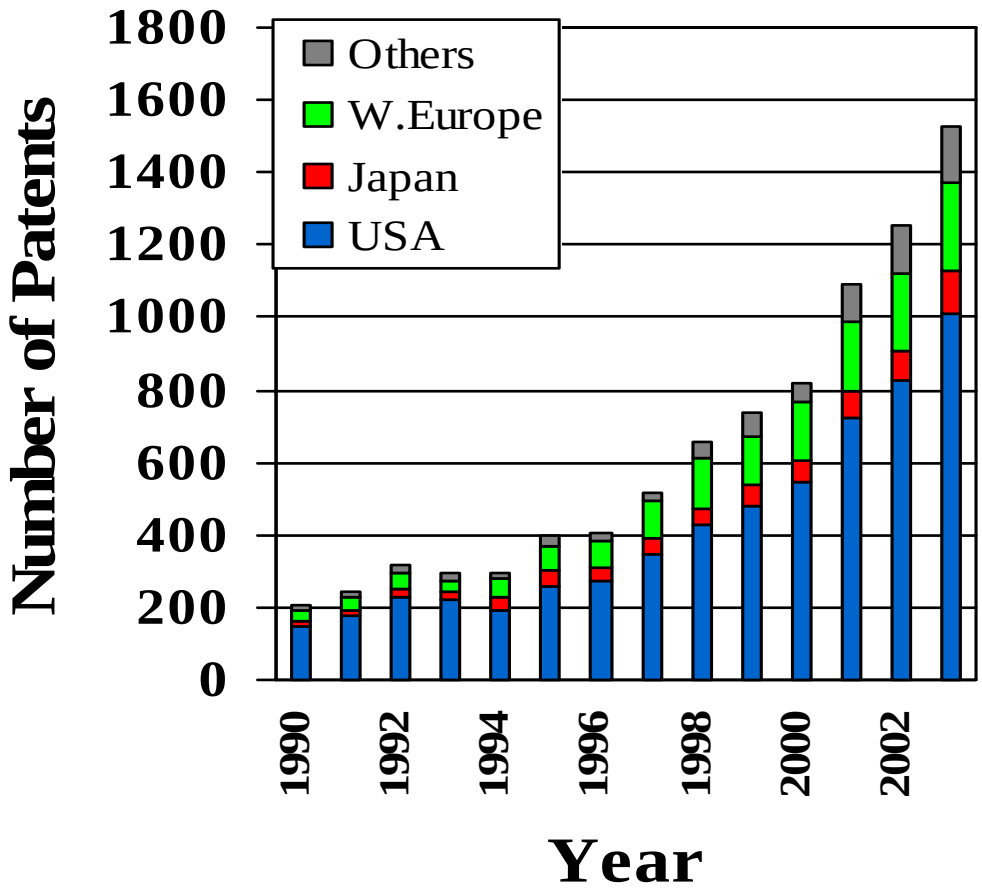
Ex: recent survey on Nature, Science, and Physics Review Letters



US has about 61% of world NT Patents (USPTO database)

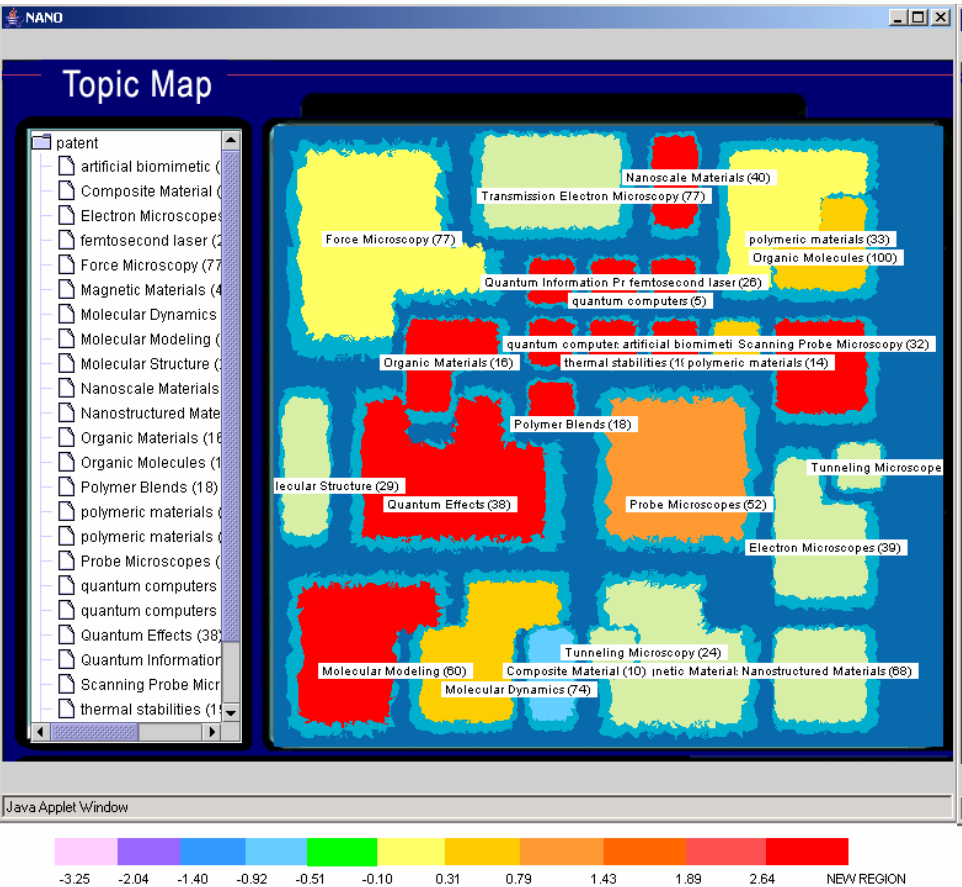
using "Title-claims"and "Full-text" search for nanotechnology by keywords
(using intelligent search engine, after J. Nanoparticle Research, 2004, Vol. 6, Issue 4)

Using "Title-claims" search:
nanotechnology claims

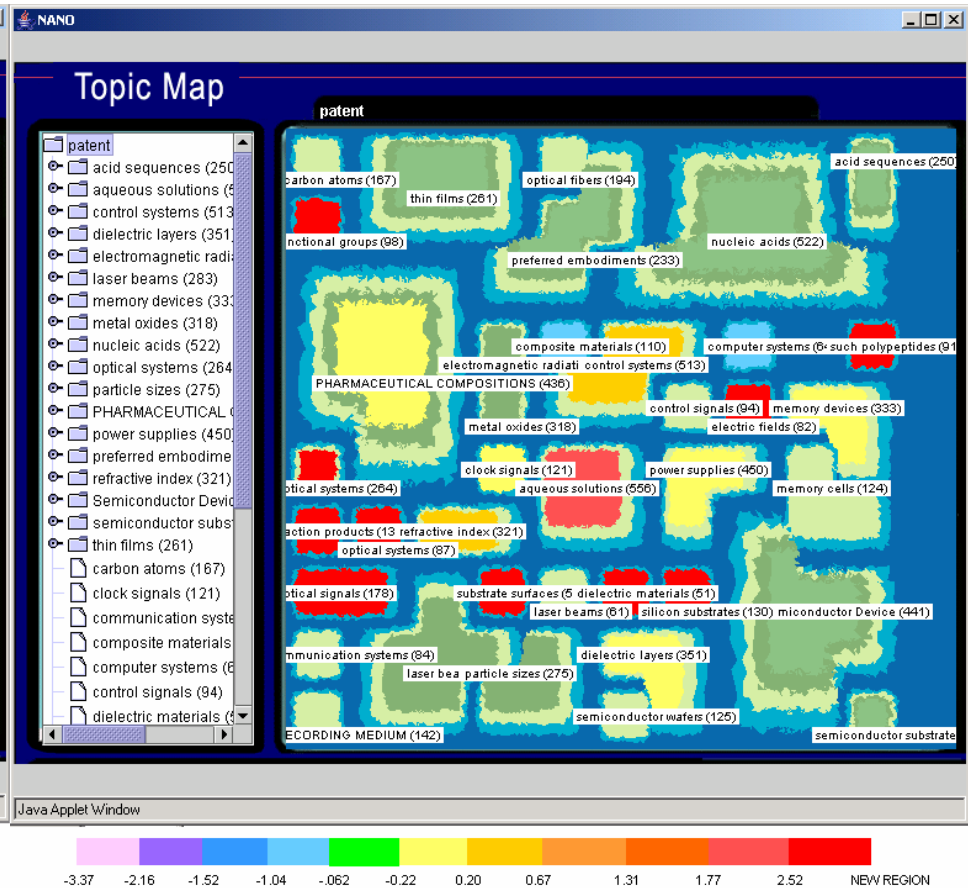


NSE content map analysis
grant – patent topic association

NSE Grant Content Map (2001-2002)



NSE Patent Content Map (2001-2002)



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

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

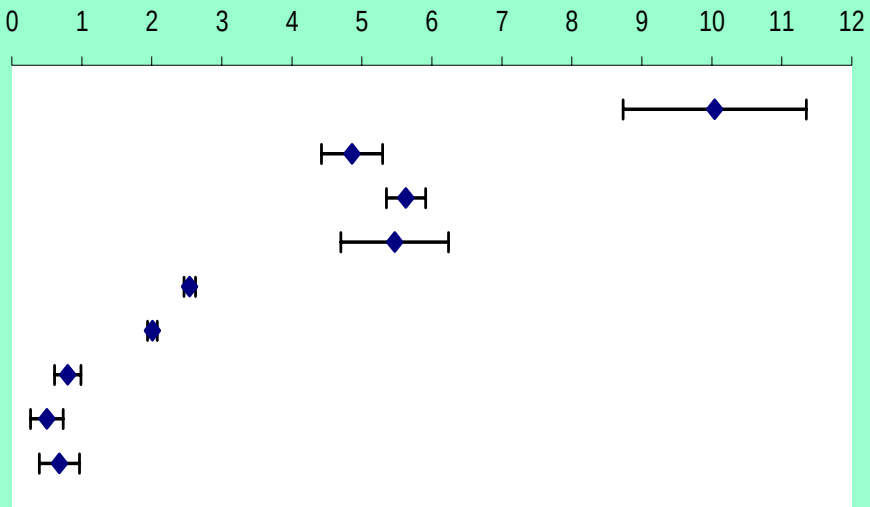
MC. Roco, 10/03/05

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

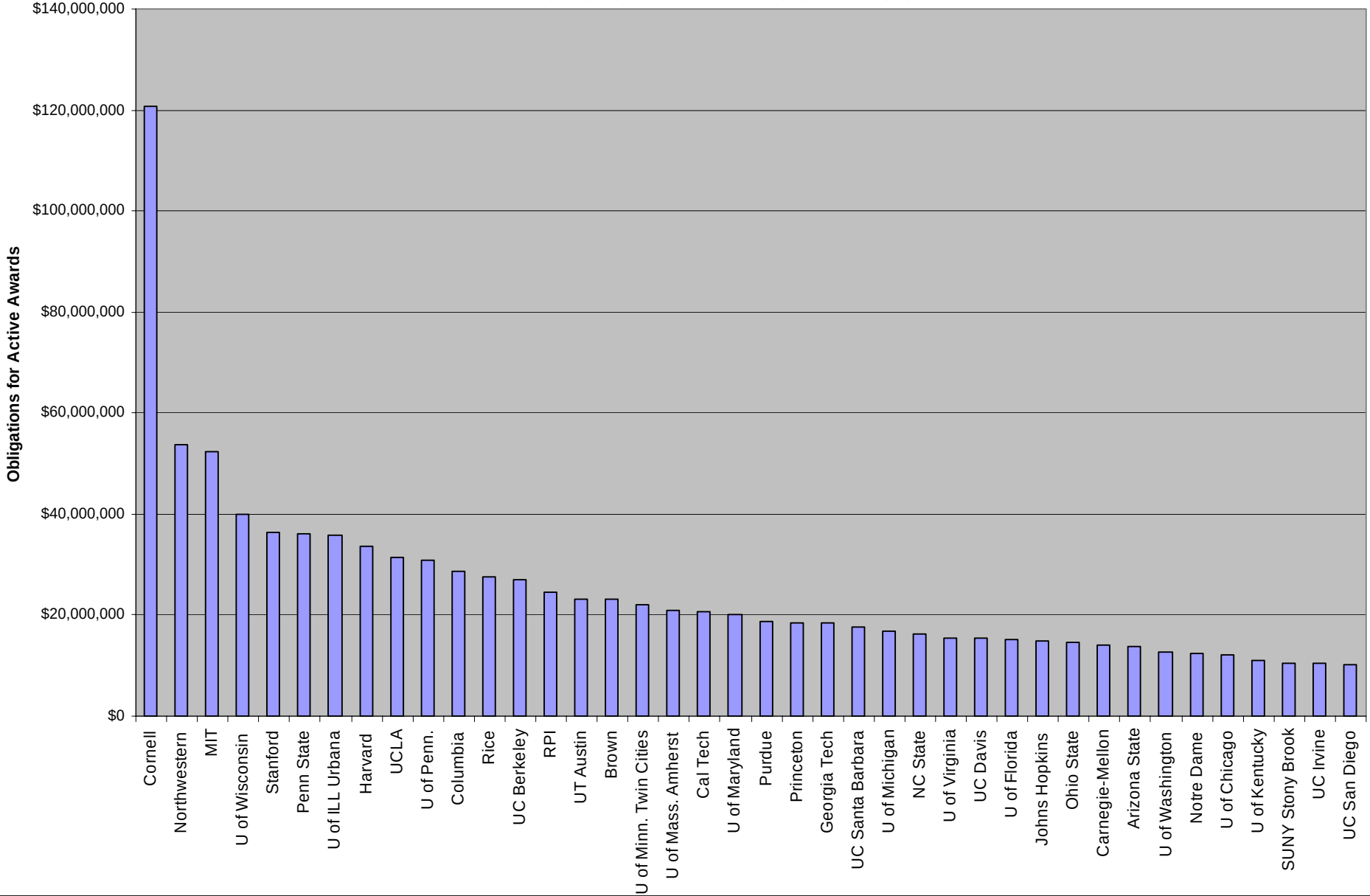


Pooled StDev = 11.70

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.

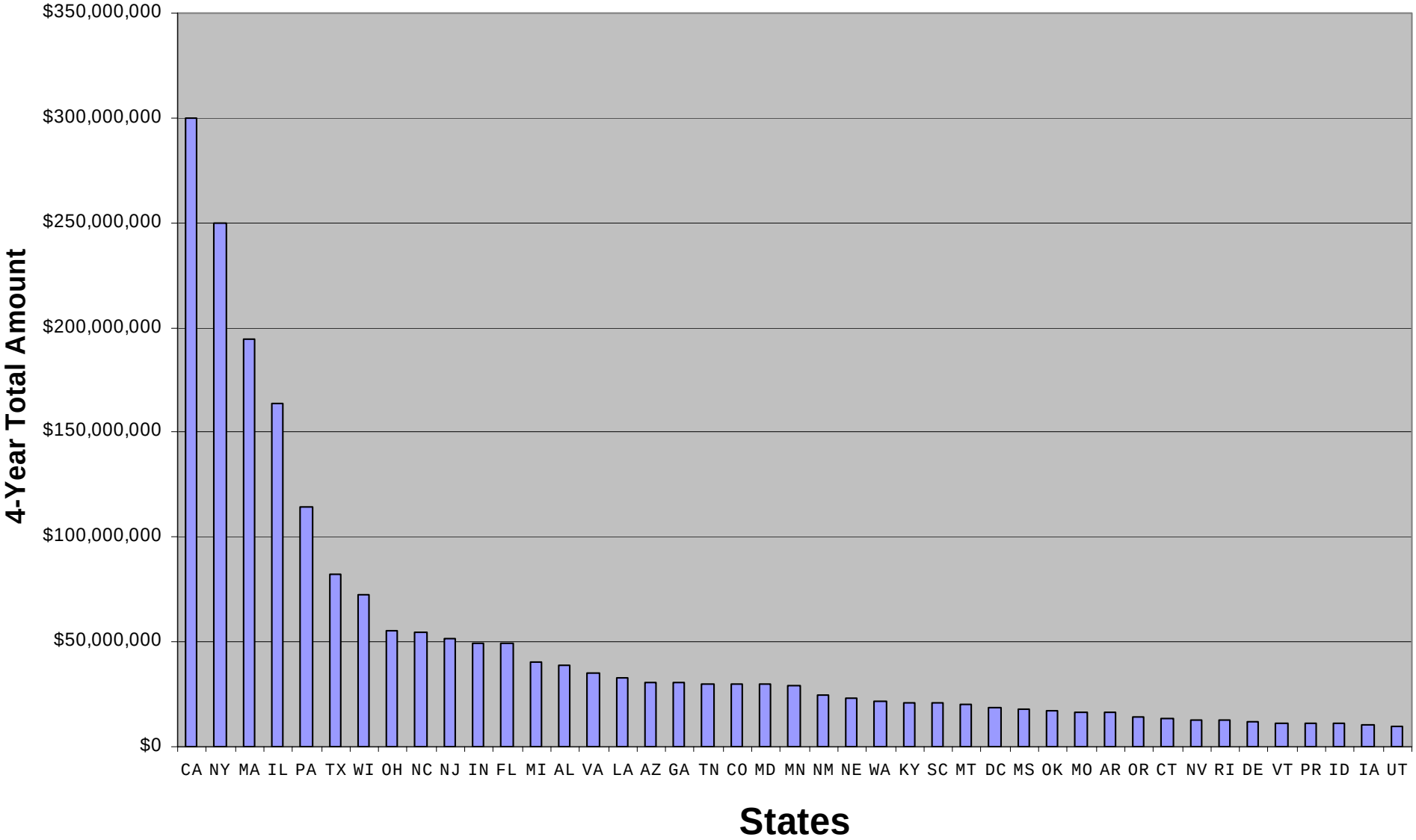
(from J. Nanoparticle Research, 2005, Issue 3)

40 Universities with more than $10 million in active NSF awards in FY 2001-2004



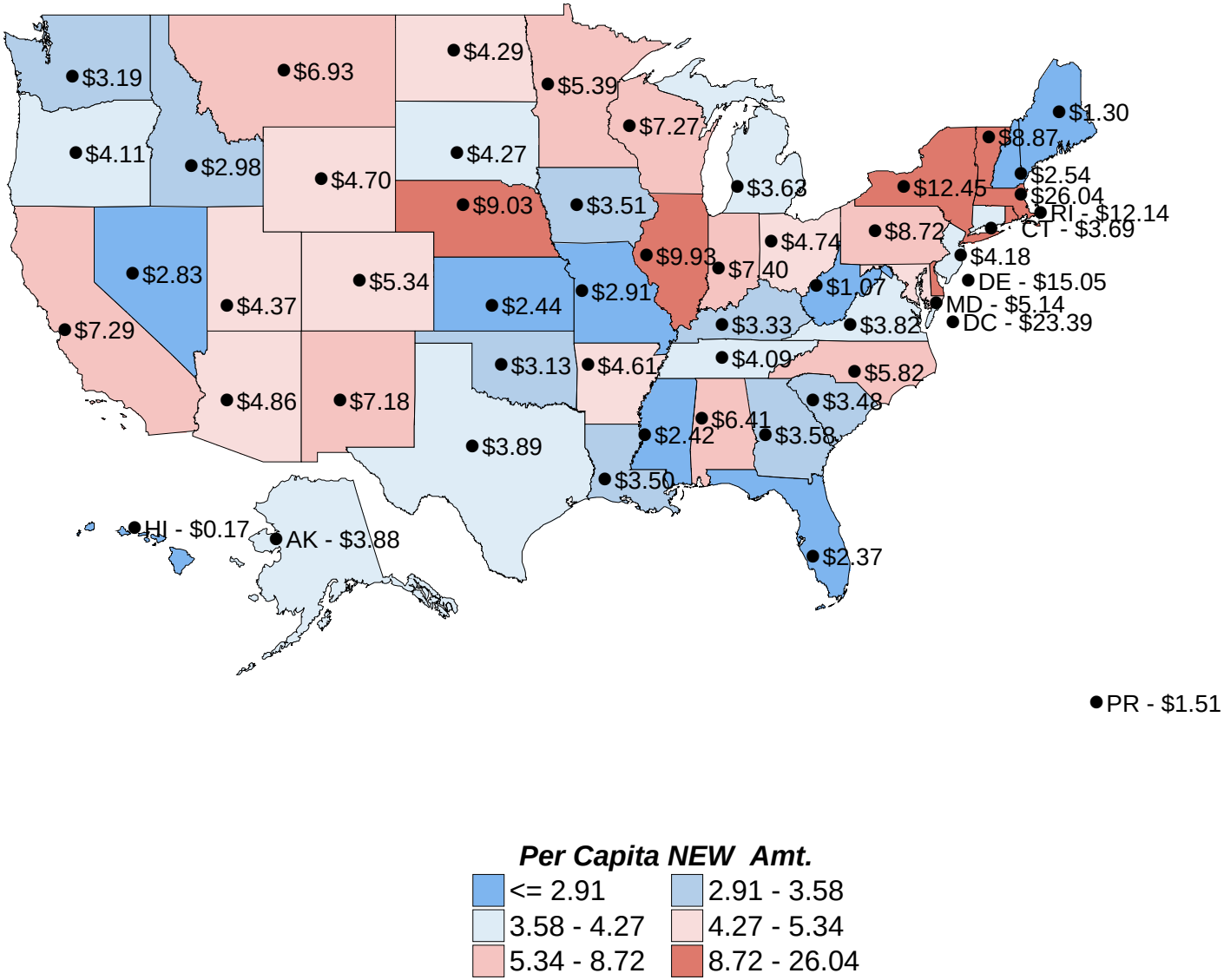
MC Roco, 10/03/05

States (US) Awarded $10 Million or More by NSF for NEW Research Grants in FY 2001 - 2004



MC Roco, 10/03/05

Per Capita NEW NNI Award Amount by State
NSF, FY 2001- 2004



MC. Roco, 10/03/05

Infrastructure 2001-2005: 40 R&D Centers, Networks and User Facilities

Nanobiotechnology, Cornell (STC)

Network for Computational Nanotechnology, Purdue (7)

Oklahoma Nano Net, OK

Nanoscale Systems in Information Technologies, Cornell

Nanoscience in Biological and Env. Eng., Rice

Integrated Nanopatterning and Detection, NU

Electronic Transport in Molecular Nanostructures, Columbia

Nanoscale Systems and their Device Applications, Harvard

Directed Assembly of Nanostructures, RPI

MRSECs on nanostructures

Integrated and Scalable Nanomanufacturing, UCLA

Nanoscale Chem., Electr., and Mech. Manu. Systems, UIUC

Extreme Ultraviolet Science and Technology, Colorado St.

National Nanotechnology Infrastructure Network (13)

Integrated Nanomechanical Systems, UCB

High Rate Nanomanufacturing, NE U.-Boston

Affordable Nanoeng. of Polymer Biomedical Devices, Ohio St.

Nano/Bio Interface, U. PA.

Probing the Nanoscale, Stanford

Templated Synthesis and Assembly at the Nanoscale, UW-Ma

Nanotechnology Center for Learning and Teaching, NU (10)

2000

Funded by NSF (24), DOD (3), NASA (4), DOE (5), NIST (2), DHHS (2)

New in 2005 (NSF): Nanotechnology in Society; NISE (museums); Hierarchical Nanomanufacturing

2001

Institute for Soldier Nanotechnology, MIT

Nanoscience Innovation for Defense, UCSB

Nanoscience Institute, NRL

2002

Institute for Cell Mimetic Space Exploration, UCLA

Institute for Intelligent Bio-Nanomaterials & Structures for Aerospace Vehicles, Texas A&M

Bio-Inspection, Design, and Processing of Multi-functional Nanocomposites, Princeton

2003

Institute for Nanoelectronics and Computing, Purdue

2004

Operation 2005-2007

Molecular Foundry, LBNL

Center for Integrated Nanotechnologies, SNL

Center for Nanophase Materials Sciences, ORNL

Center for Nanoscale Materials, ANL

Center for Functional Nanomaterials, BNL

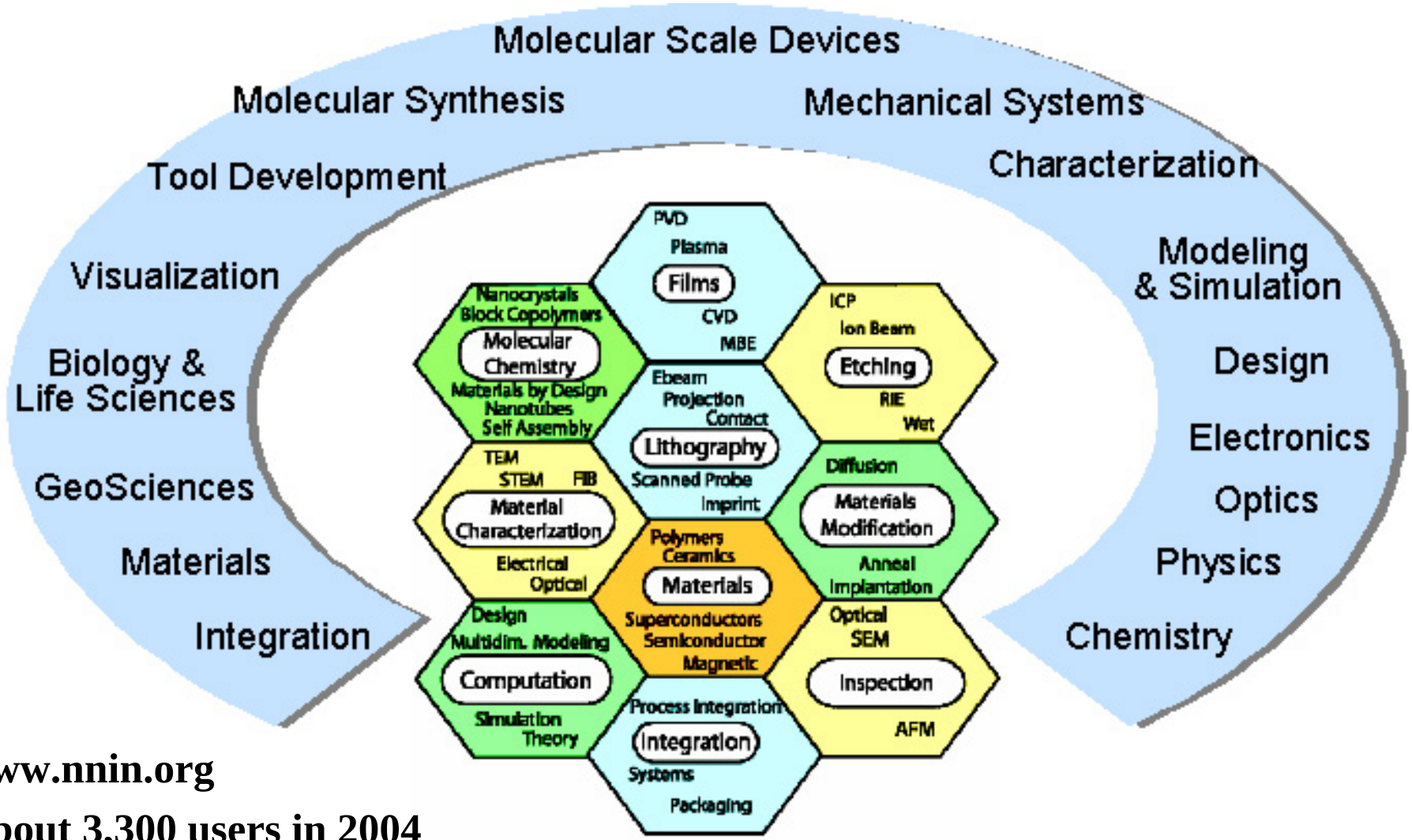
2005

Nanotechnology Labs, NIST at MA and CO

Nanotechnology Characterization Lab, NCI

NIOSH

NSF NNIN Scope and Activities
(13 nodes, lead Cornell University)



www.nnin.org

About 3,300 users in 2004

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

SBIR/STTR funding FY 2003-2004
(estimation)

	2001		2002		2003	
	Total Funding	Total Projects	Total Funding	Total Projects	Total Funding	Total Projects
DOD	20.9	104	32.2	157	32.2	144
DOE	4.5	34	1.0	2	5.8	30
NASA	5.5	31	12.8	48	2.4	28
HHS (NIH)	6.4	32	8.1	19	14.1	43
NSF	9.4	51	8.1	62	14.0	84
DOT	0.3	2	0	0	N/A	N/A
EPA	0.3	4	0.3	4	0.5	6
USDA	0.1	1	0.5	4	0	0
DOC	0.1	1	0.5	4	0.2	3
Totals	47.5	260	63.5	300	69.2	338

Funding - in million $

About 7% of the NNI R&D budget in FY 2003

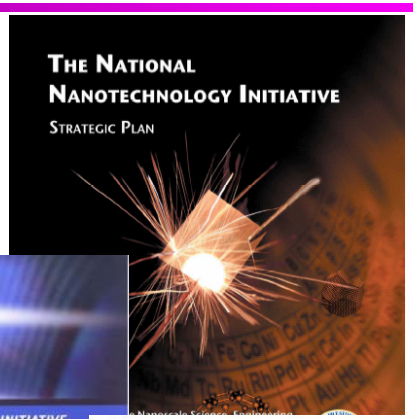
About 3.5% of funding for all SBIR/STTR topics, all agencies

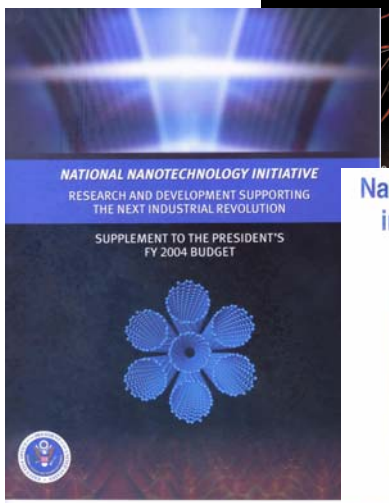
Defining the vision for the second strategic plan (II)

National Nanotechnology Initiative

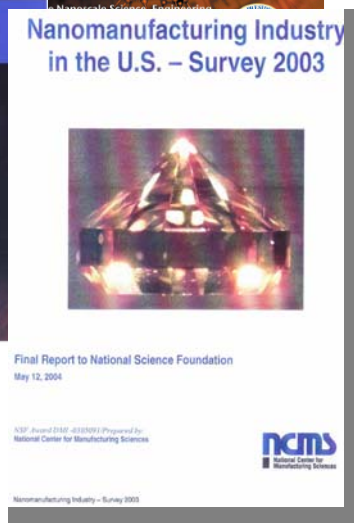
2004

2004:
10-year
vision/plan



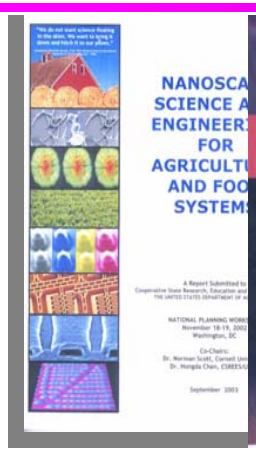


Government
Plan (annual)

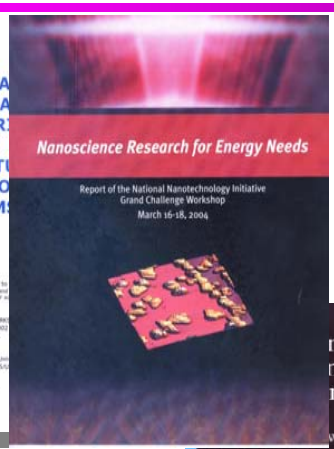


Survey
manufacturing

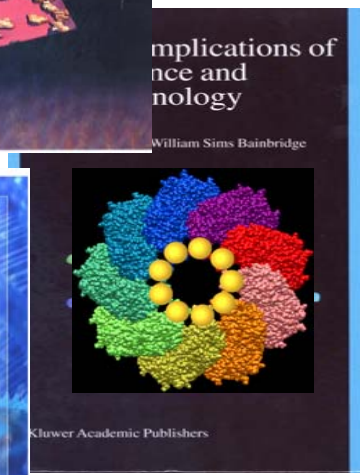
Agriculture
and Food



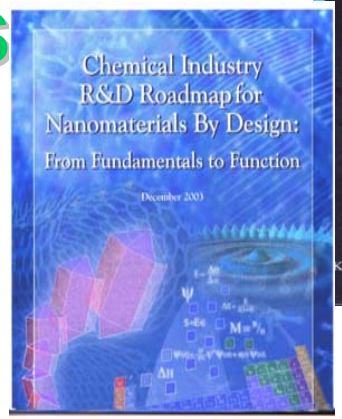
Energy



Societal
Implications
2004



Reports



Other topical reports
on www.nano.gov

Dec. 2004: Update 10 year vision, and develop strategic plan

Second NNI strategic plan (2006-2010): Goals / Activities

Four main goals *(including areas of new focus for next 5 years)*

- Maintain a world-class research and development program aimed at realizing the full potential of nanotechnology *(Support R&D for active nanostructures and nanosystems)*
- Facilitate transfer of the new technologies into products for commercial and public benefit *(Increase funding for technological innovation and multidisciplinary R&D platforms)*
- Develop educational resources, a skilled workforce, and the supporting infrastructure and tools needed to advance nanotechnology *(Access to research facilities and educational opportunities in nanoscale science and engineering for half of the undergraduate and graduate students by 2010)*
- Support responsible development of nanotechnology thru societal, environmental and health implications R&D, and interaction with the public *(Address sustainability and life cycle of products)*

After 3 years of NNI:
New R&D potential targets for 2015 (ex.)

2004 **2015**

Nanoscale visualization and simulation of 3D/m domains

= Micro domains with nano space and time resolutions

Transistor beyond/integrated CMOS under 10 nm

New catalysts for chemical manufacturing

No suffering and death from cancer when treated

Control of nanoparticles in air, soils and waters

After 3 years of NNI:

New R&D potential targets for 2015 (2)

2004 **2015**

Advanced materials and manu.: ½ from molecular level

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

NNI agencies and collaborations - Illustrations for FY 2006 -

- Nanomanufacturing (main partners NSF, DOD and NIST)

  NSF's Center for Hierarchical Nanomanufacturing will become fully operational in 2006, as will the complementary DOD MURI, and the NIST N^3F. NSET will also coordinate its activities in this area with the NSTC Interagency Working Group on Manufacturing Research and Development.

- Environmental, Health, and Safety (EHS) Research

  EPA, NSF, NIOSH, and USDA plan an expanded joint extramural research program The National Toxicology Program's initiative; NIOSH's "recommended practices" for safe handling of nanomaterials; NEHI monthly meetings

- Industry Liaison in Support of Technology Transfer and Commercialization

  The NSET Subcommittee will expand its activities to reach out to U.S. industry NSF's "Silicon Nanoelectronics and Beyond" activity DOD will place a new emphasis in 2006 on moving research innovations into applications in support of the DOD mission. NSET's informal working group on industry liaison will help to coordinate this interagency thrust.

- Standards Development

  Partner: American National Standards Institute's Nanotechnology Standards Panel (ANSI-NSP)

- Infrastructure Development

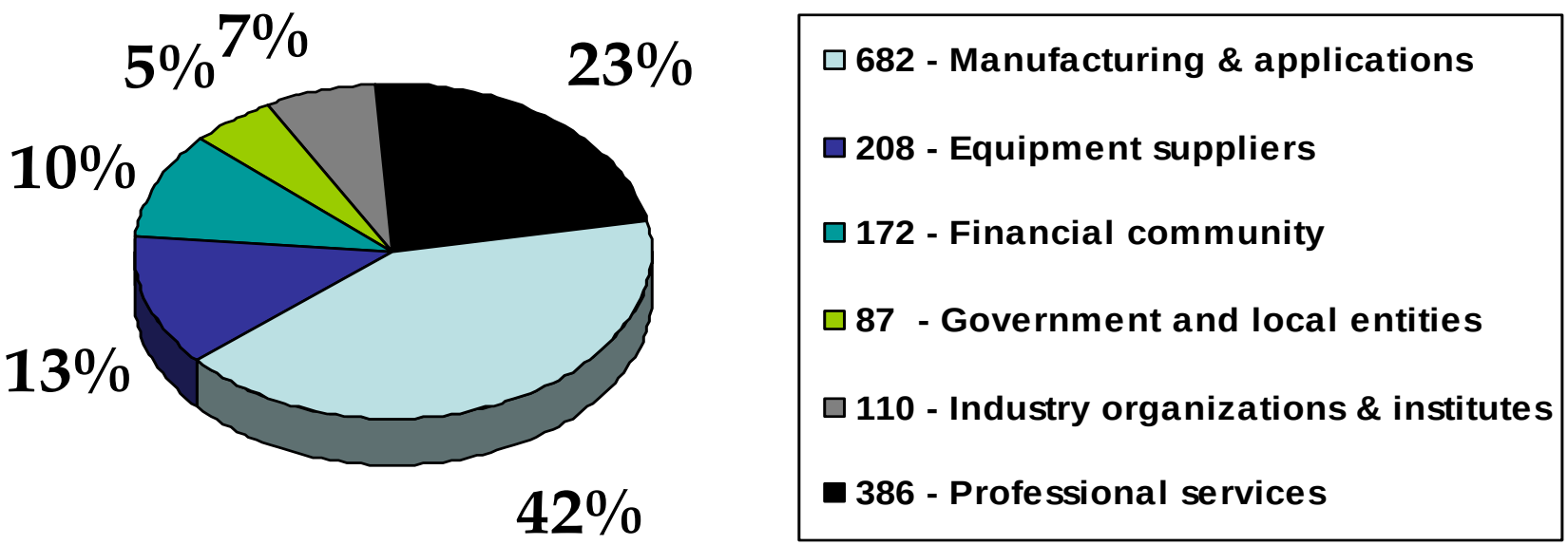
  Among R&D centers (NSECs, NNIN and NCN, centers and network with DOD, NASA and DOE);

  Modeling and simulation and nanoelectronics (DOD, NASA and NSF).

Industry surveys (1)

Companies working in nanotechnology
(Survey by Small Times in 2004, based on individual contacts and direct verification; partial NNI support)

- In March 2004: 775 nanotech companies
  (475 products in 215 companies; 23,000 new jobs in small companies)
- In March 2005: 1455 nanotech companies (730 products)



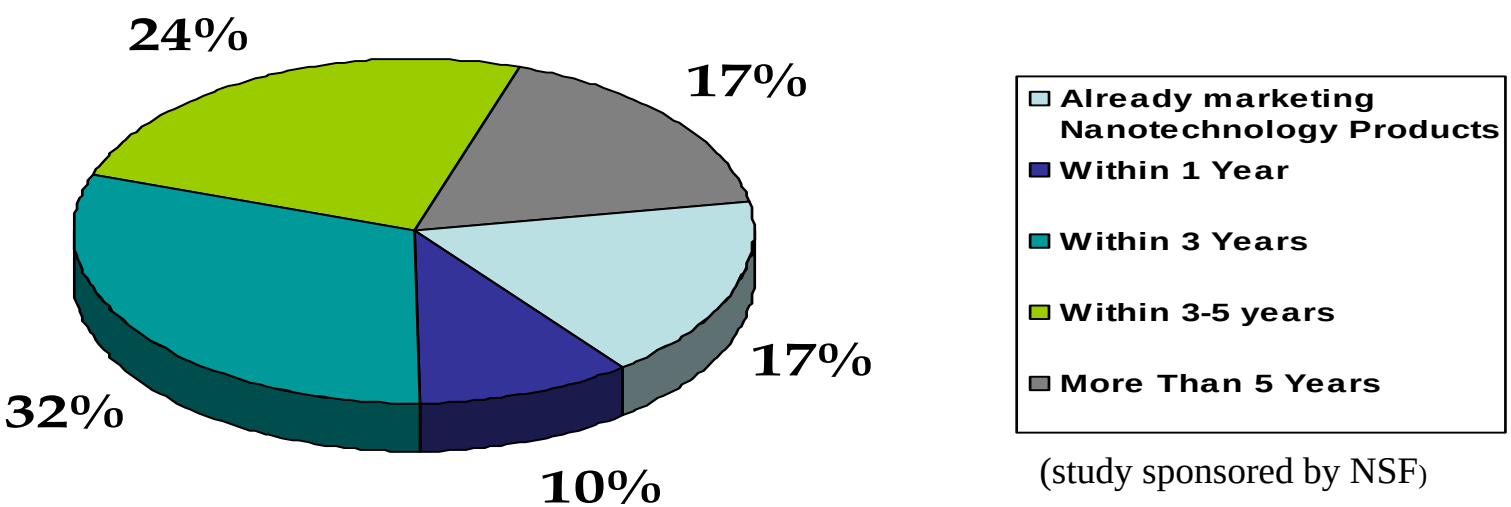
Industry surveys (2)

- 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)

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)

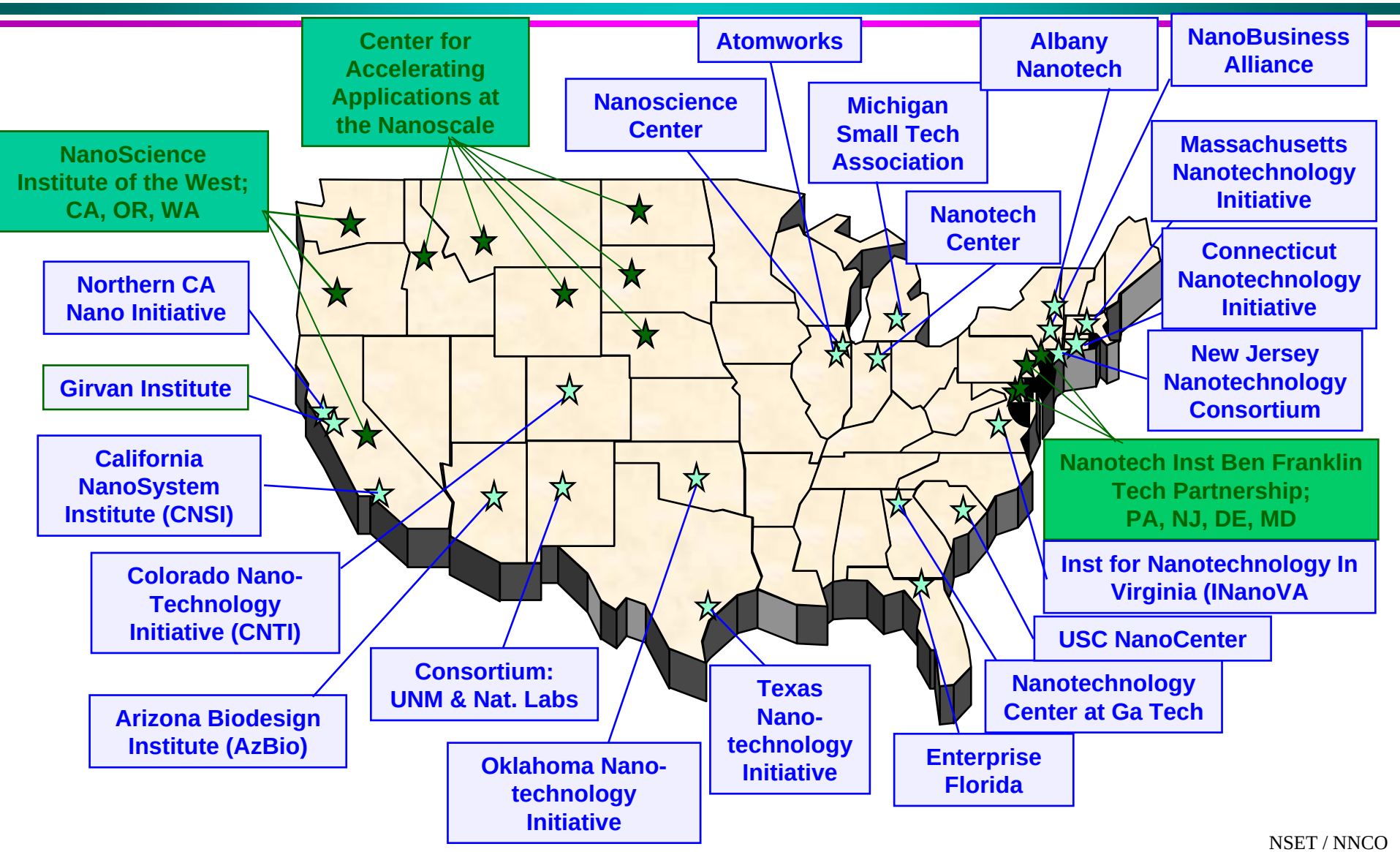
Key for development of nanotechnology, Reciprocal gains

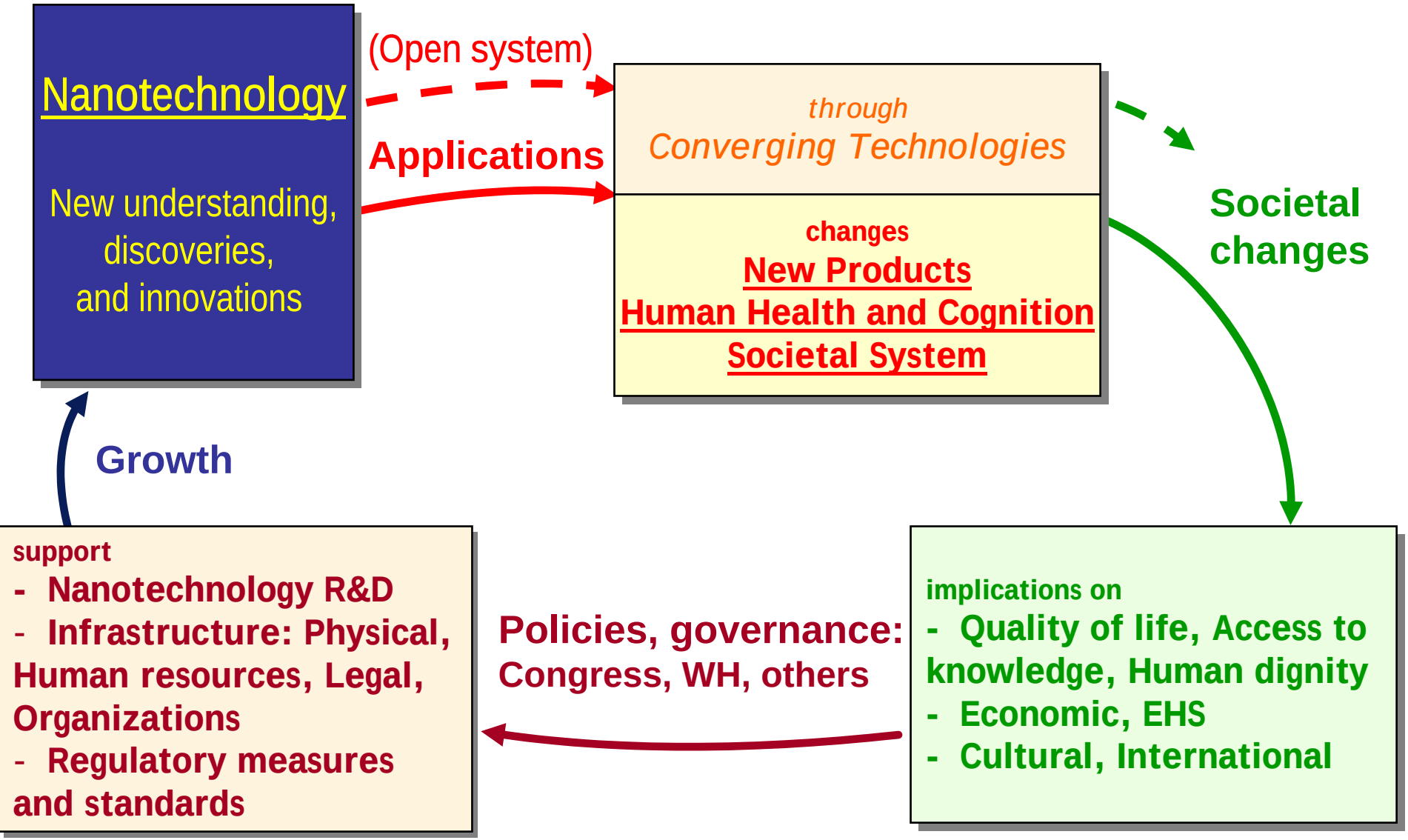
In development

- **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

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



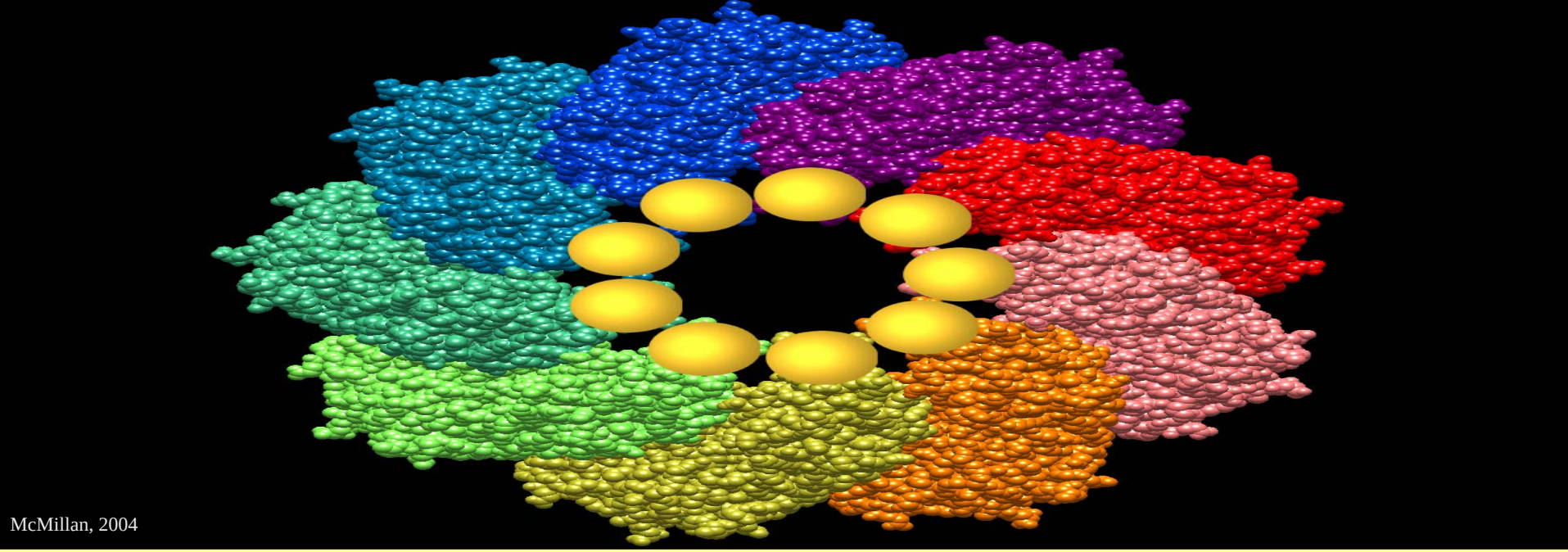


Nanotechnology in Society

J. Nanoparticle Research, 7(2), 2005

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: increasing technological innovation in the 2nd NNI Strategic Plan
- More responsible and effective in including public, industry and states perspectives
- Collaboration and synergism among agencies; Incentives for agency participation and proper reporting
- Need for bold system-oriented programs, particularly in mission-oriented agencies, focused on topics such as: the new catalyst, new transistor, conditioning the cell
- International collaboration and competition



Part D
Societal Dimensions

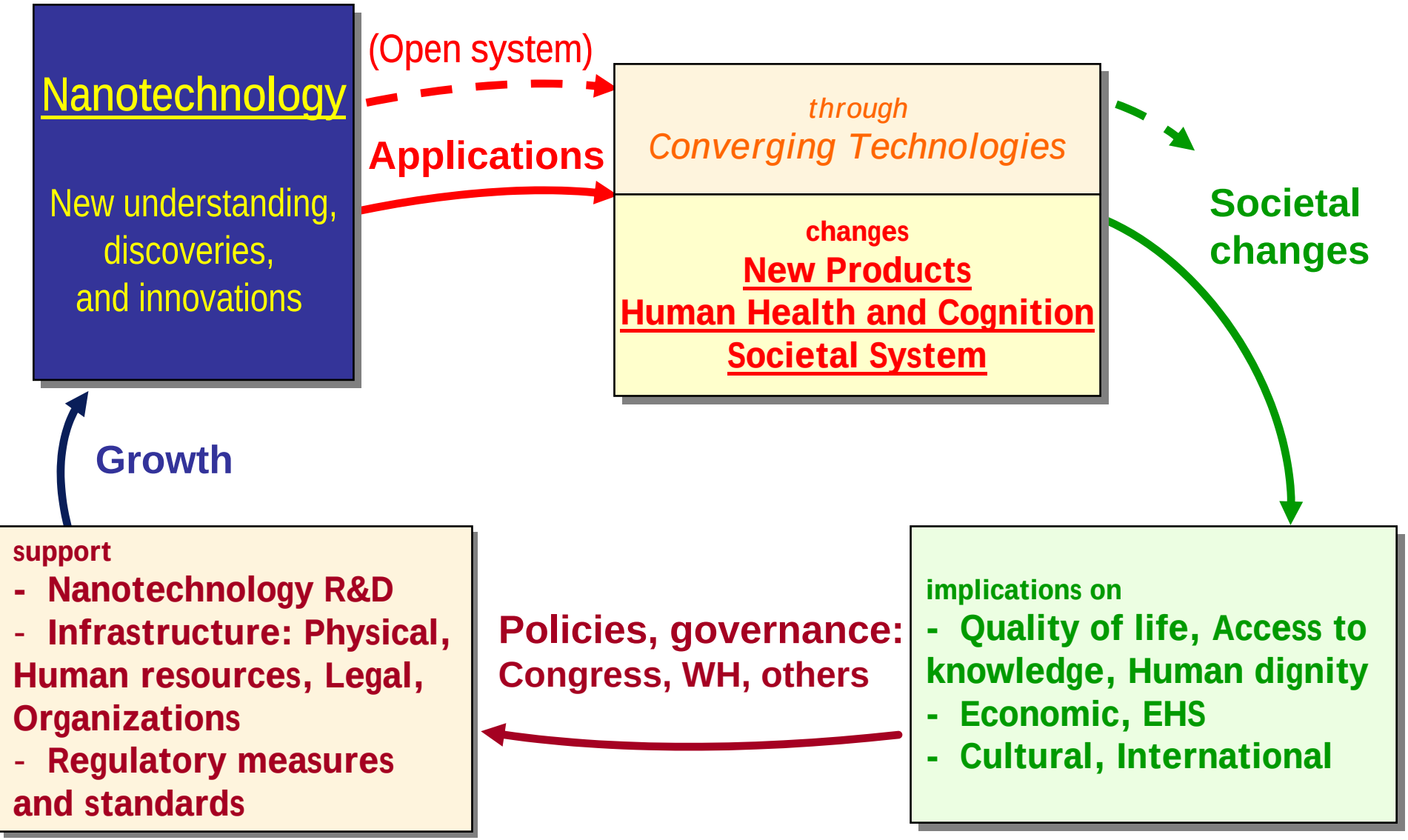
- Environmental, Health and Safety issues
- Education
- Ethical, Legal and other Social Issues

Minneapolis, October 3, 2005

Topics

- **Short and long term issues in societal implications: governance approach**

- **NNI activities in EHS, education and ELSI**



Nanotechnology in Society

J. Nanoparticle Research, 7(2), 2005

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)**

International Risk Governance Council (Geneva) Objective

- **Develop a framework for the governance of certain nanotechnology risks in the general context of emerging technologies**.

  Focus on the second generation of NT (active nanostructures), as well as longer term issues (related to nanosystems and molecular systems).

  Select higher risk applications with global governance aspects (international interactions).

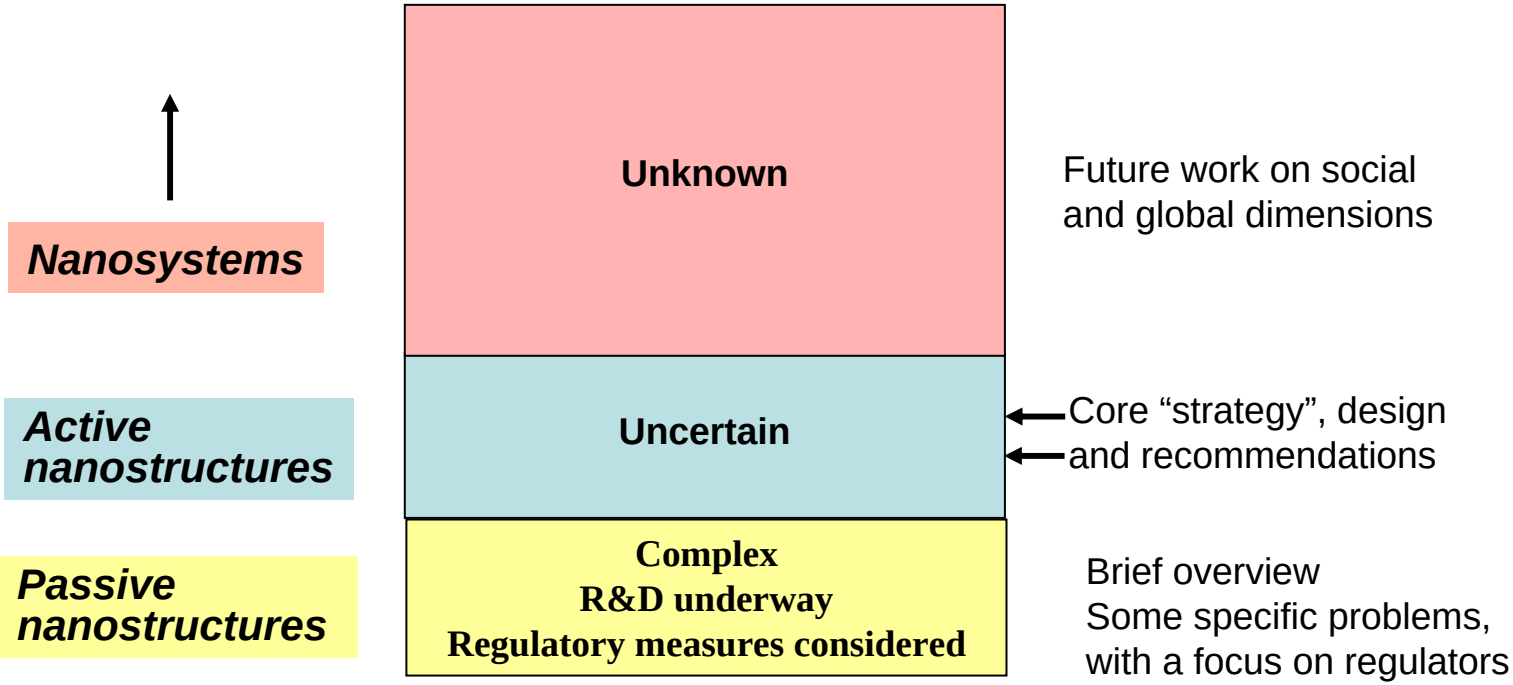
  Address global aspects that cannot be addressed by each country.

  Address longer term and broad societal implications of nanotechnology that are not well covered by national studies.

- **Apply basic principles of the IRGC risk governance framework*.**
- **Agree a common framework of governance recommandations based on consensus.**

* Currently undergoing peer review

Outcomes of the preparatory Workshop on May 19, 2005



Nanotechnology application areas

Timeline for beginning of nanotechnology commercialization:

Perceived higher risks areas

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

~ 2000

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

~ 2005

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

~ 2010

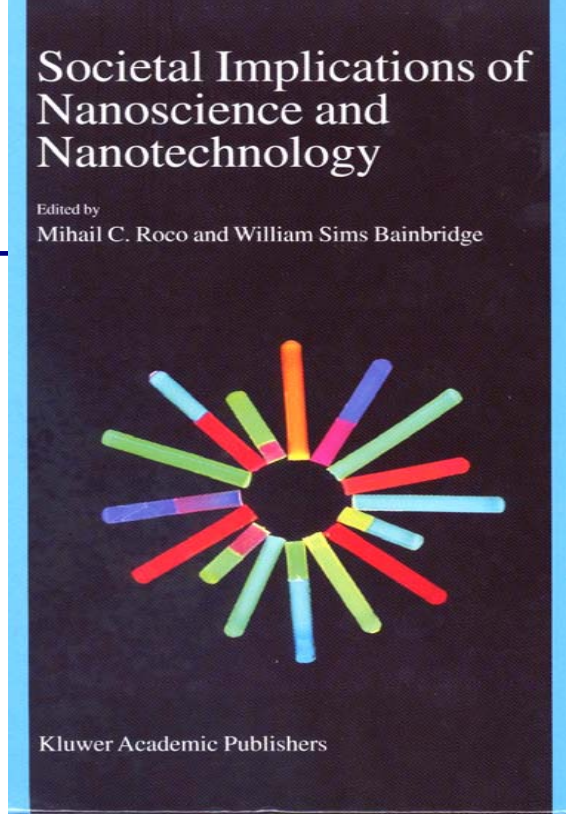
4th: Molecular nanosystems Ex: Neuromorphic eng., Complex systems, Human-machine interface

~ 2015-2020

only R&D

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

Societal Implications: Follow-up of the September 2000 report



http://nano.gov

- Make support for social, ethical, and economic research studies a priority:
  (a) New theme in the NSF program solicitations;
  (b) Centers with societal implications programs;
  (c) Initiative on the impact of technology, NBIC, HSD
- NNCO – communicate with the public and address Environmental, Health and and Safety issues, and unexpected consequences
- NSET's Nanostructures Environmental and Health Issues working group has been established in 8/2003, 12 agencies
- Workshop with EC (2001); Links to Europe, Americas, Asia; International Dialogue (26 countries, NSF-sponsored)

NSET
NEHI WG MEMBERSHIP

- Consumer Product Safety Commission
- Department of Agriculture
- Department of Commerce/National Institute of Standards and Technology
- Department of Defense
- Department of Energy
- Department of Labor/Occupational Safety and Health Administration
- Environmental Protection Agency
- Food and Drug Administration
- National Institute of Environmental Health Sciences
- National Institute for Occupational Safety and Health
- National Nanotechnology Coordination Office
- National Science Foundation
- Office of Management and Budget
- Office of Science and Technology Policy

NEHI ACTIVITIES/IMPACTS

(see www.nano.gov for links to agencies)

- Identify regulatory agency jurisdiction of nano-products
- Toxic Substances Control Act jurisdiction
- Chemical Abstract Service/American Chemical Society approach to nano-particles
- Terminology and nomenclature
- Regulatory agency position on research priorities
- Regulatory agency position statement on regulation of nano-products
- Question & answers for fielding questions from outside interests
- Inter-agency coordination

NNI Publications in 2005 including Societal Implications II (Sept. 2005)

Key issues in long term

- Respect human right to: access to knowledge and welfare; human integrity, dignity, health and safety
- Balanced and equitable R&D nanotechnology investment
- Environment protection and improvement (water, air, soil) Sustainable development, life-cycle of products, global effects (weather), eliminate pollution at the source
- Economic, legal, ethical, moral, regulatory, social and international (developed-developing countries) aspects Interacting with the public and organizations
- Adaptive/corrective approach for a complex system

Immediate and continuing issues:

- *EHS in research laboratories and industrial units*
- *Harmonizing nomenclatures, norms and standards*
- *Primary data and methodology for risk analysis*

NNI activities
for Environmental, Health and other Societal Implications

A. Align R&D investment with societal implications

B. Evaluate and implement regulatory standards

C. Coordinated measures for EHS and ELES

D. Periodical meeting for grantees,
setting research targets, and
interaction with industry and the public

E. International collaboration (International Dialog
for Responsible R&D of Nanotechnology)

(Details in Environmental Science and Technology, ACS, March 2005, Overview)

A. NNI coordination for R&D investments

FY 2001-2005: About 10% budget for EHS/ELSI, incl. env. applications

- NSF research grants on environmental and societal implications
  All basic R&D areas, transport of nanoparticles; Programs since 2000
- NIH research on effects of nanoscale materials in the body
- EPA research grants on environmental implications of manufactured nanomaterials
- National Toxicology Program (NIEHS, NCTR, NIOSH)
  Project to study toxicity of nanotubes, quantum dots, and titanium dioxide
- NIST development of standards and measurements for nanoscale particles
- FDA and USPTO training and specialized activities
- USDA and DOE support fate and transport studies
- DOD supports exposure studies
- Solicitations (SI): NSF (ENV, SI), EPA-NSF-NIOSH, USDA, NIH

NSF environmental centers and interdisciplinary groups with research and education at the nanoscale

Center (details on www.nsf.gov/home/crssprgm/nano/nni01_03_env.htm)	**Institution**
Fundamental Studies of Nanoparticles Formation in Air Pollution	**Worcester Polytechnic Institute ($2.7M)**
Center for Advanced Materials for Water Purification	**University of Illinois at Urbana ($20.1M)**
Center for Environmentally Responsible Solvents and Processes	**University of North Carolina at Chapel Hill ($25.0M)**
Nanoscience in Biological and Environmental Engineering (estimated 50% in environment)	**Rice University ($11.8M)**
Environmental Molecular Science Institute	**Univ. of Notre Dame ($5M)**
NIRT: Investigating Nano-carbon Particles in the Atmosphere: Formation and Transformation	**University of Utah ($1.7M)**
NIRT: Nanoscale Processes in the Environment - Atmospheric Nanoparticles	**Harvard University ($1.6M)**
Center for Advanced Computational Environment	**SUNY Buffalo ($5.5M)**
NIRT: Nanoscale Sensing Device for Measuring the Supply of Iron to Phytoplankton in Marine Systems	**University of Maine ($0.9M)**

NNI projects supporting toxicity research (examples)

Project	Agency, Institution
National Toxicology Program ($0.5M in FY 2004 to $5M in FY 2008)	NIH/NIEHS, FDA/NCTR, NIOSH
Particle characterization for health and safety ($1.7M in FY 2004 rto $2.3M in FY 2005)	NIOSH
Nanotechnology Characterization Laboratory ($5M/yr, part of $144M/yr NCI for FYs 2004-2008)	National Cancer Institute
Multidisciplinary University Research on Nanoparticle Toxicity	Department of Defense supported center
Molecular function at the Nano-Bio Interface (component on nanostructures and cell behavior)	NSF/NSEC U. Pennsylvania
Nanomanufacturing Center for Enabling Tools (component on safe manufacturing)	NSF/NSEC Northeastern University
Size Dependent Neural Translocation of Nanoparticles	NSF/SGER, Rochester University
Reverse Engineering Cellular Pathways from Human Cells Exposed to Nanomaterials	NSF/SGER

National Toxicology Program organization

NTP Director
Dr. K. Olden,
Dir NIEHS

Policy Oversight

Executive Committee

ATSDR	NCI/NIH
CPSC	NIEHS/NIH
EPA	OD/NIH
FDA	NIOSH/CDC
NCEH/CDC	OSHA

Environmental Toxicology Program

External Science Oversight and Peer Review

Board of Scientific Counselors

Scientific Advisory Committee On Alternative Toxicological Methods

NIEHS

NCTR
National Center for Toxicological Research
U.S. Food and Drug Administration

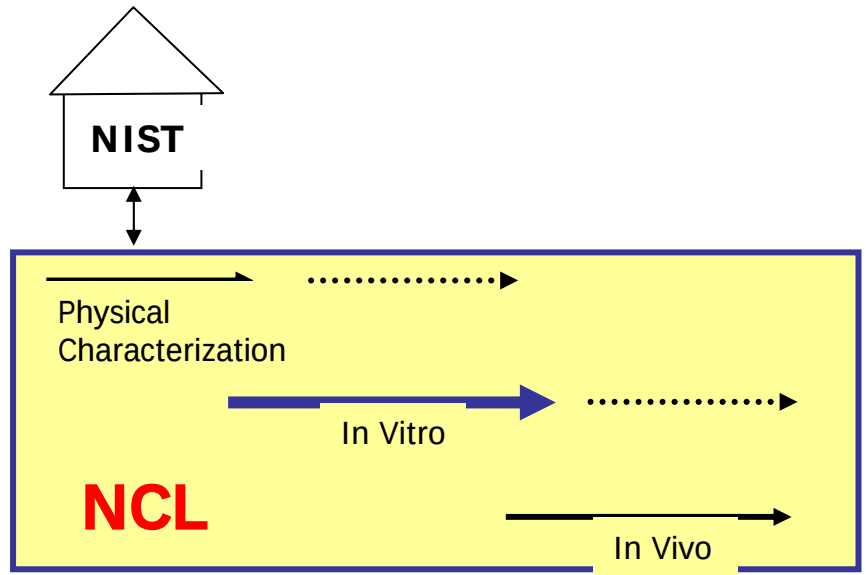
NIOSH

Nanotechnology Characterization Laboratory (NCI) Concept of Operations

For comparison and characterization of nanomaterials intended for cancer detection, diagnostics, and therapeutics in humans.

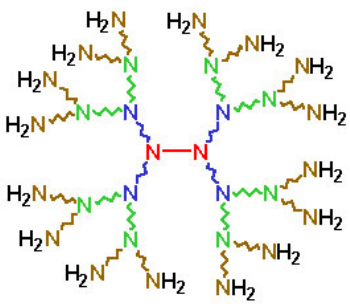
Sources of Nanomaterials

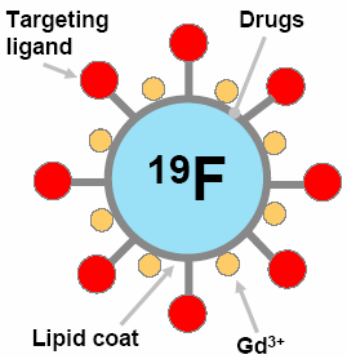
- Cancer Centers of Nanotech Excellence (CCNEs)
- Academia
- NNI
- Small Business
- NCI, NIH, NSF
- DoD, DoE
- Unconventional Innovative Program (UIP)

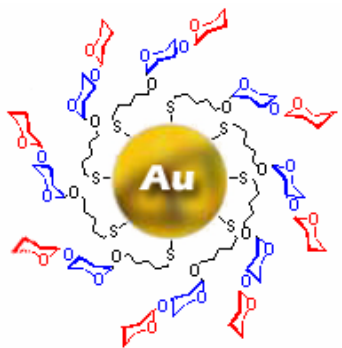


- Detection
- Diagnostics
- Therapeutics

Candidate Nanoparticles







MC. Roco, 10/03/05

NNI projects supporting social implications (examples (1))

Project	Agency, Institution
Nanotechnology and its Publics	**NSF,** **Pennsylvania St. U.**
Public Information, and Deliberation in Nanoscience and Nanotechnology Policy (SGER)	**Interagency,** **North Carolina St. U.**
Social and Ethical Research and Education in Agrifood Nanotechnology (NIRT)	**NSF,** **Michigan St. U.**
From Laboratory to Society: Developing an Informed Approach to NSE (NIRT)	**NSF,** **U. of South Carolina**
Social and ethical dimensions of nanotechnology	**NSF,** **U. Of Virginia**
Ethics and belief inside the development of nanotechnology (CAREER)	**NSF,** **U. Of Virginia**
All centers, NNIN and NCN have a societal implications components	**NSF, DOE, DOD and NIH** **All nano centers and networks**

NNI projects supporting social implications (examples (2))

Project	Agency, Institution
Citizen Learning, Deliberation, and Reasoning in Internet-Mediated Technology Policy Forums	**NSF, North Carolina State University**
Public Information, and Deliberation in Nanoscience and Nanotechnology Policy (SGER)	**Interagency, North Carolina State University**
An Integrated Approach to Teaching Nanotechnology and Society (NUE)	**University of Wisconsin**
Nanotechnology: Content and Context (NUE)	**Rice University**
Undergraduate Exploration of Nanoscience, Applications and Societal Implications (NUE)	**NSF, Michigan Technological U.**
Assessing the Implications of Emerging Technologies (IGERT)	**NSF, MIT**
Nanoparticle Science and Engineering (IGERT)	**NSF, University of Minnesota**

Four NSF centers with national outreach fully or partially dedicated to societal dimensions

- **Center for Nanotechnology in Society**
  (ASU, UCSB, other small groups, 2005 -)
- **Nanotechnology Center Learning and Teaching**
  (Northwestern University, 2004 -)
- **Center for Nanotechnology Informal Science Education**
  (Boston Museum of Science, 2005 -)
- **Center for Hierarchical Nanomanufacturing**
  (U. Mass, 2005 -)

US NSF - Nanoscale Science and Engineering - NSF ACTIVITIES, Solicitations and Their Outcomes - Microsoft I...

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National Science Foundation
WHERE DISCOVERIES BEGIN

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

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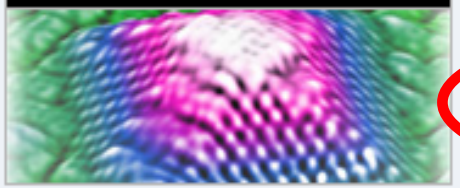
NNI



Solicitations & Outcomes

New Items

Activities

Program Reviews

NSF & NNI Symposia

NSF & NNI Reports

NSF & NNI Reports

Links to Related Reports

NNI Endorsements

NNI Presentations

NSF National Nanotechnology Initiative (NNI)

Search for NSF awards by keywords
(go to the "Full text search", and complete the box with your keywords; Examples of keywords are nano*, selfassembl* and nanoparticle)

NSF press releases on Nanotechnology Research since January 2004

NSF press releases on Nanotechnology Research from 2003 to 2001

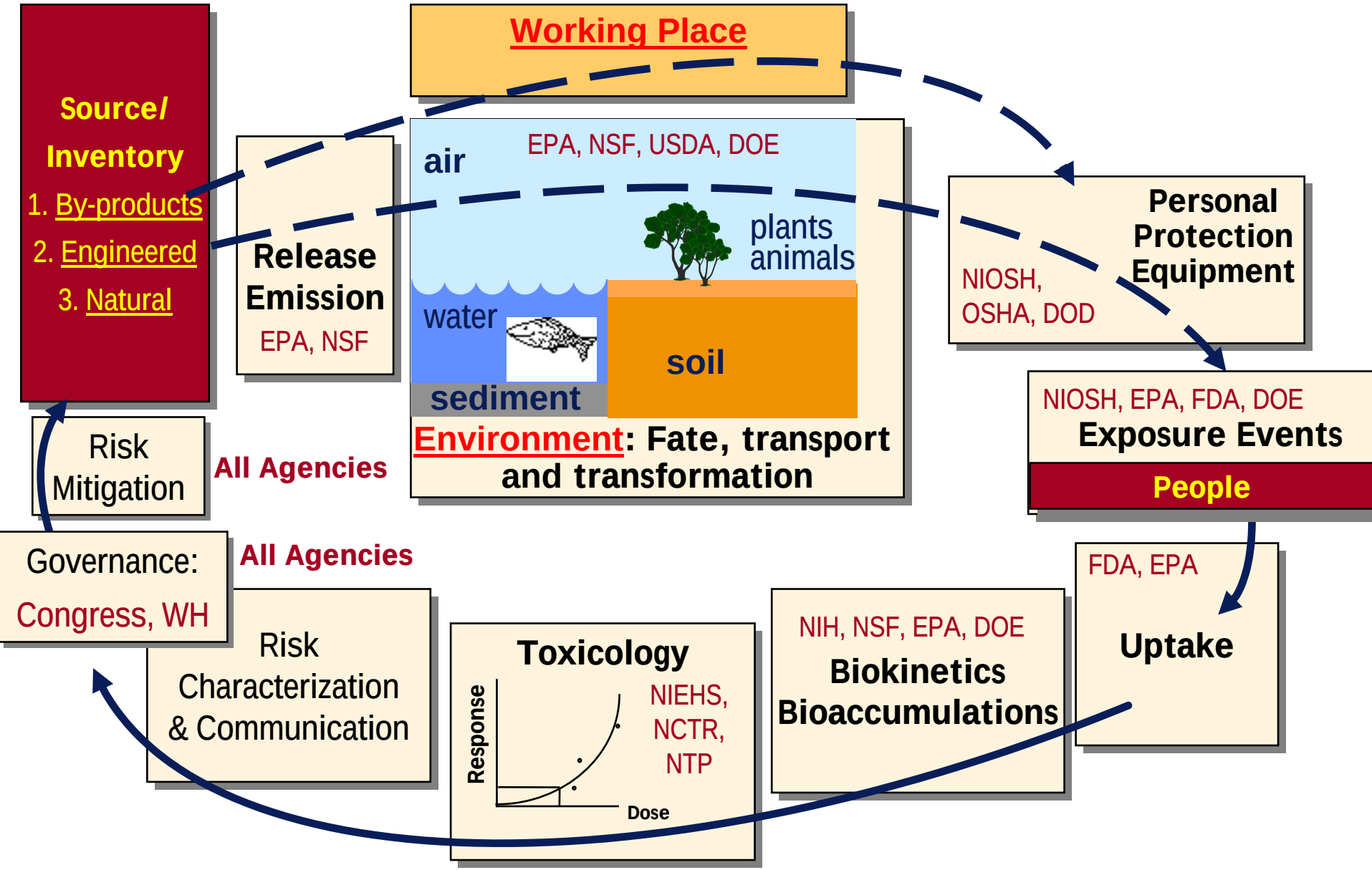
SOLICITATIONS AND OUTCOMES IN FY 2005

NSF Announcement 05-543: Nanoscale Science and Engineering Education (NSEE)
"Preparation workshop: Public Engagement in Nanoscale Science and Engineering"(PDF, 776KB)

NSF Announcement 04-043: Nanoscale Science and Engineering (NSE)
NSEC on "Nanotechnology in Society" workshop

Joint EPA-NSF-NIOSH solicitation for research in Environmental and Human Health Effects of Manufactured Nanomaterials

B. EHS research and regulatory topics for nanomaterials



Modified from a schematic by M. Alper
J. Nanoparticle Research, Vol. 7, 2005 (M. Roco)

C. Current NNI coordinated measures for EHS

- Develop statement on "Best practices" for research laboratories and industry units (NIOSH, NSF, DOE, NASA, DOD), and identify gaps
- Map of EHS responsibilities and contacts in each NNI agency
- Establish response approach to an unexpected event or an emergency

- Identify protective equipment suitable for nanoparticles and other nanostructured materials (OSHA, NIOSH, other agencies)
- Support development of instrumentation and metrology (NSF, NIST)
- Develop a unified, explicit nomenclature (agencies, ANSI)
- Develop standards for nanotechnology (NIST, ANSI, IEEE, ASME)

- Collaborative activities with industry (SRC, CCR, Phrma, IRI)
- Identify research and educational needs (Fundamental, GCs)

NSET Group: "Nanomaterials Environmental and Health Implications"

OSTP Group: "Risk Assessment of Nanotechnology" task force

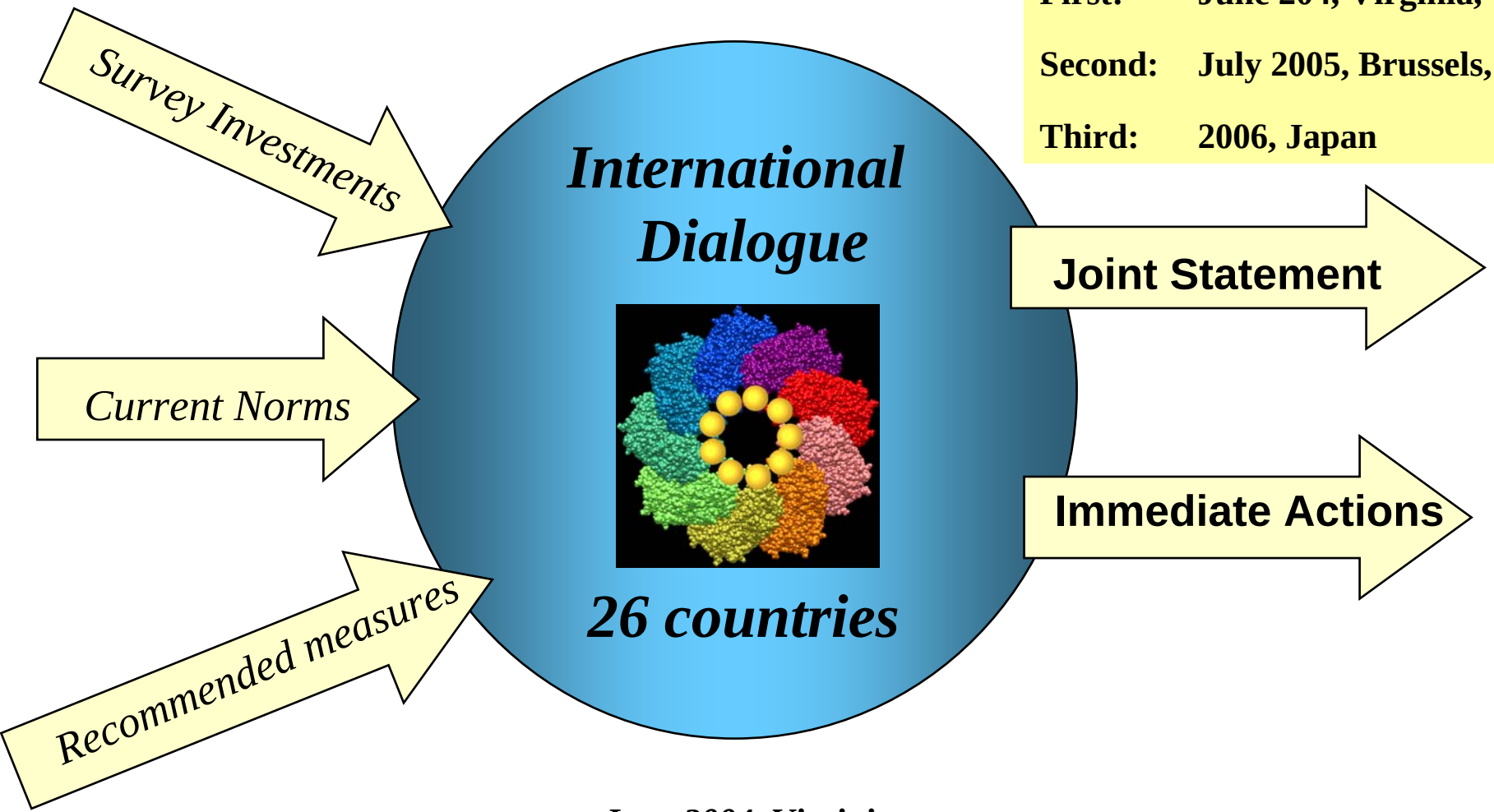
D. NNI workshops on nano-environmental research

examples

- NSF, 9/2000: "Societal Implications of Nanoscience and Nanotechnology"
- NSF, 6/2002: "Nanoparticles and the environment" (grantees meeting, book)
- EPA, 11/2003: "Nanotechnology and the environment applications and implications" (grantees meeting, brochure)
- ACS, 3/2003: "Symposium on nanotechnology implications in the environment", New Orleans
- NNI, 5/2003: "Vision for environmental implications and improvement" *(interagency, report)*
- NSET/NNCO, 8/2003: Review of Federal Regulations (report)
- NNI, 9/2003: Interagency : grantees meeting (report);
- Wilson Center, 10/2003: EPA and FDA regulatory functions (report)
- NSET, 12/03 "Societal Implications of Nanoscience and Nanotechnology (II)"

E. International Dialogue on Responsible Nanotechnology R&D

First:	**June 204, Virginia, USA**
Second:	**July 2005, Brussels, EC**
Third:	**2006, Japan**



June 2004, Virginia

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

International Dialogue on Responsible Nanotechnology R&D

Activities after the June 2004 International Dialogue on Responsible Nanotechnology (Virginia, U.S.)

- **October 2004/October 2005 - Occupational Safety Group**
- **November 2004 – OECD group on nanotechnology begins**
- **December 2004 – Meridian study for developing countries begins (next meeting in March 2005)**
- **December 2004 - International collaboration for nomenclature and standards has been initiated (ISO, ANSI)**
- **February 2005 – N-S Dialogue on Nanotechnology (UNIDO)**
- **May 2005 – Nano-world, MRS (Materials, Education)**
- **July 2005 – 2nd International Dialogue (host: EC)**
- **May 2005- - International Risk Governance Council initiate study on nanotechnology**

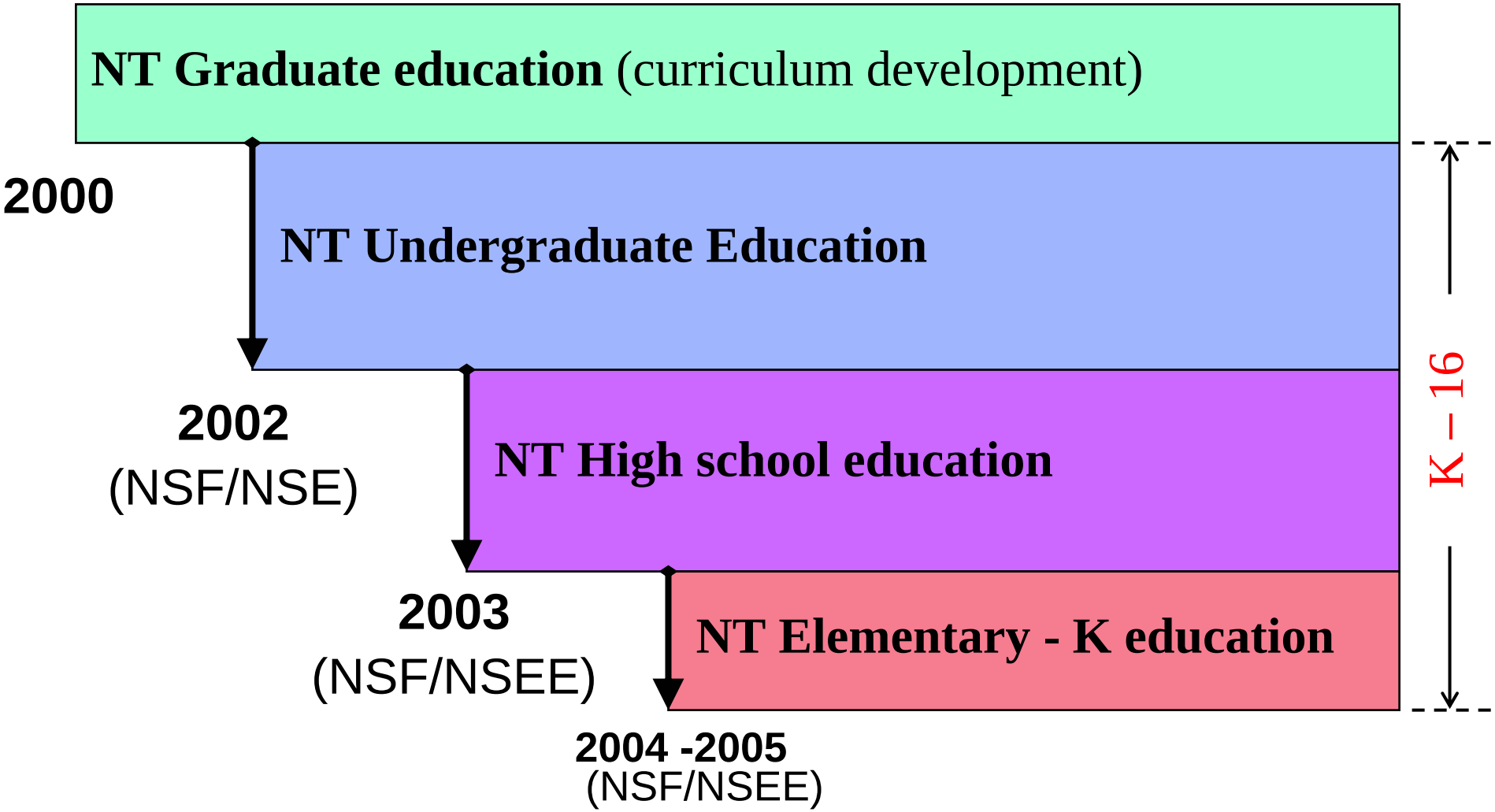
NNI Activities in Education and Training

- **Integrated Research and Education - Make Every Lab a Place of Learning** (about 10,000 trained per year)
- **Curriculum development**
  New courses, 10 IGERT, Nanotech Undergrad Education
- **Education and outreach programs**
  from K-12 to G; includes NSEE; science museums
- **International education opportunities**
  young researchers to Japan and Europe; REU sites; attend courses abroad; PASI - Latin America, NSF-E.C.; bi-lateral workshops and exchanges

Objectives for nanotechnology education

- Fundamental understanding from the nanoscale:
  moving the foundation of learning from "microscale" to "nanoscale"
- Sharing similar concepts in various disciplines and relevance areas:
  unifying concepts earlier in education
- **"Reversing the pyramid of learning"**: learning first unifying concepts of matter/ biology/ information systems, and then averaging techniques specific to each discipline
- **Combine "depth" with "breadth"**
- **Broader accessibility and motivation to S&T**
- **Engineering has an increased role** because of its interdisciplinary, integrative, system approach and transforming characteristics. Nanotechnology deals with systems.

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



Nanotechnology university education
- examples of activities -

- Nanotechnology curriculum development (G, UG)
- Integration of research and education
  (ex: IGERT, CRCD, REU, RET)
- Local and long-distance outreach education (G, UG, K-12)
- Technological education
- Education and training in centers and networks
- Modules for individual training
- Public education (non-technical audiences)
- Courses and tutorials offered by professional societies
- International dimension

Examples : IGERT projects

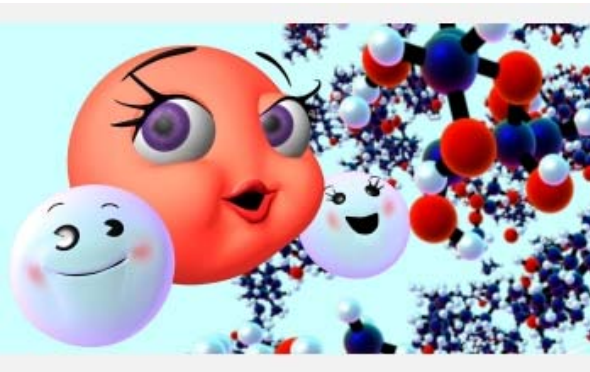
Focus on interdisciplinary fellowships, research and education
Each IGERT (Integrative Graduate Education, Research and Training) provide support for > 12 interdisciplinary graduate fellowships / site.

- **NEAT (Nanophases in the Environment, Agriculture and Technology)**
  University of California -Davis (A. Novrotski)
- **Nanostructural Materials and Devices**
  City University of New York (D.L. Akins)
- **Nanobiotechnology**
  University of Washington (A. Vogel)
- **Nanoparticle Science and Engineering**
  University of Minnesota (U. Kortshagen)
- **11 sites in FY 2002 (4 since 2001, and 4 since 2002)**

K-12 NANOTECHNOLOGY Education Modules

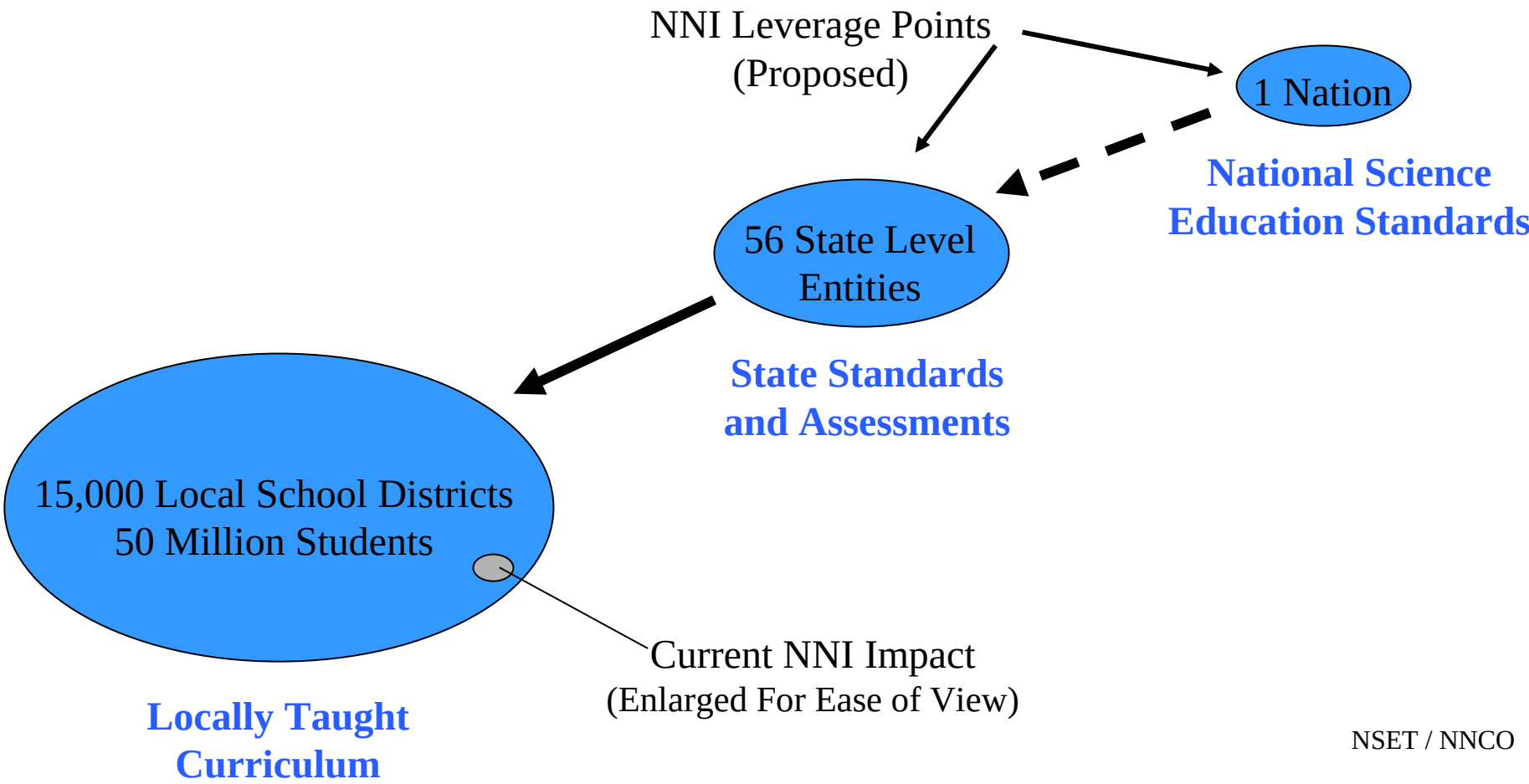
Illustrations

- **University of Wisconsin - Art Ellis: Nanoworld for kids**
- **Rice University – James Tour: NanoKids**
- **Cornell University: for nano-biotechnology, and -electronics**
- **Northwestern University, Chicago: manuals, public museum**
- **Harvard University: manuals, museum**
- **UNC Nanomanipulator**
- **Purdue NanoHub**
- **Molecularium, RPI**



- NSF plans to have 10 K-12 education modules in 2005

State K-12 Curriculum Standards and NNI



Transforming and Responsible development of nanotechnology

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

Besides the immediate and continuing societal implication issues, a long-term concern is a possible instability in human development, because perturbations created at the foundation of life and of the new transforming tools

There is a need for an anticipatory and corrective approach in

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