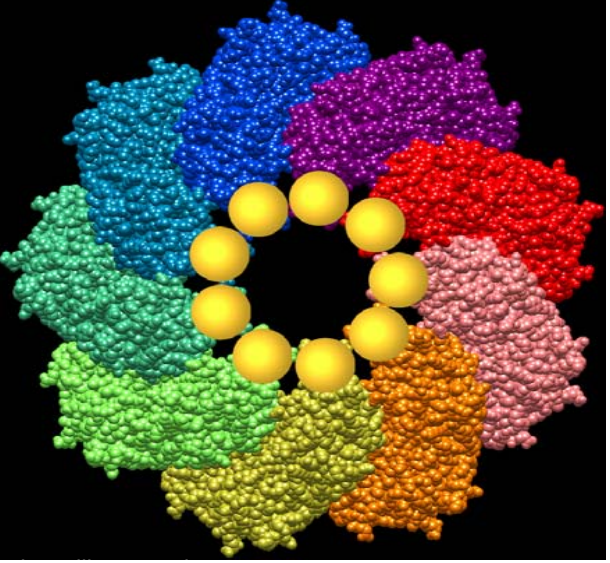


Four generations of nanoparticle products -

from passive dispersions to molecular nanosystems

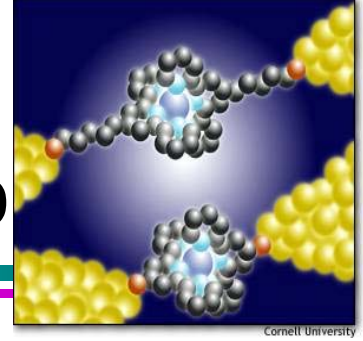
Dr. M.C. Roco
National Nanotechnology Initiative (NNI),
National Science Foundation (NSF), www.nano.gov and www.nsf.gov/nano

- **Functional nanoparticles and devices**
- **Four generations of products**
- **The U.S. National Nanotechnology Initiative**

Tokyo, August 22, 2005

Nanotechnology

Definition on www.nano.gov/omb_nifty50.htm (2000)



- **Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure**

- **NNI definition encourages new contributions that were not possible before**

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

TRANSFORMING 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

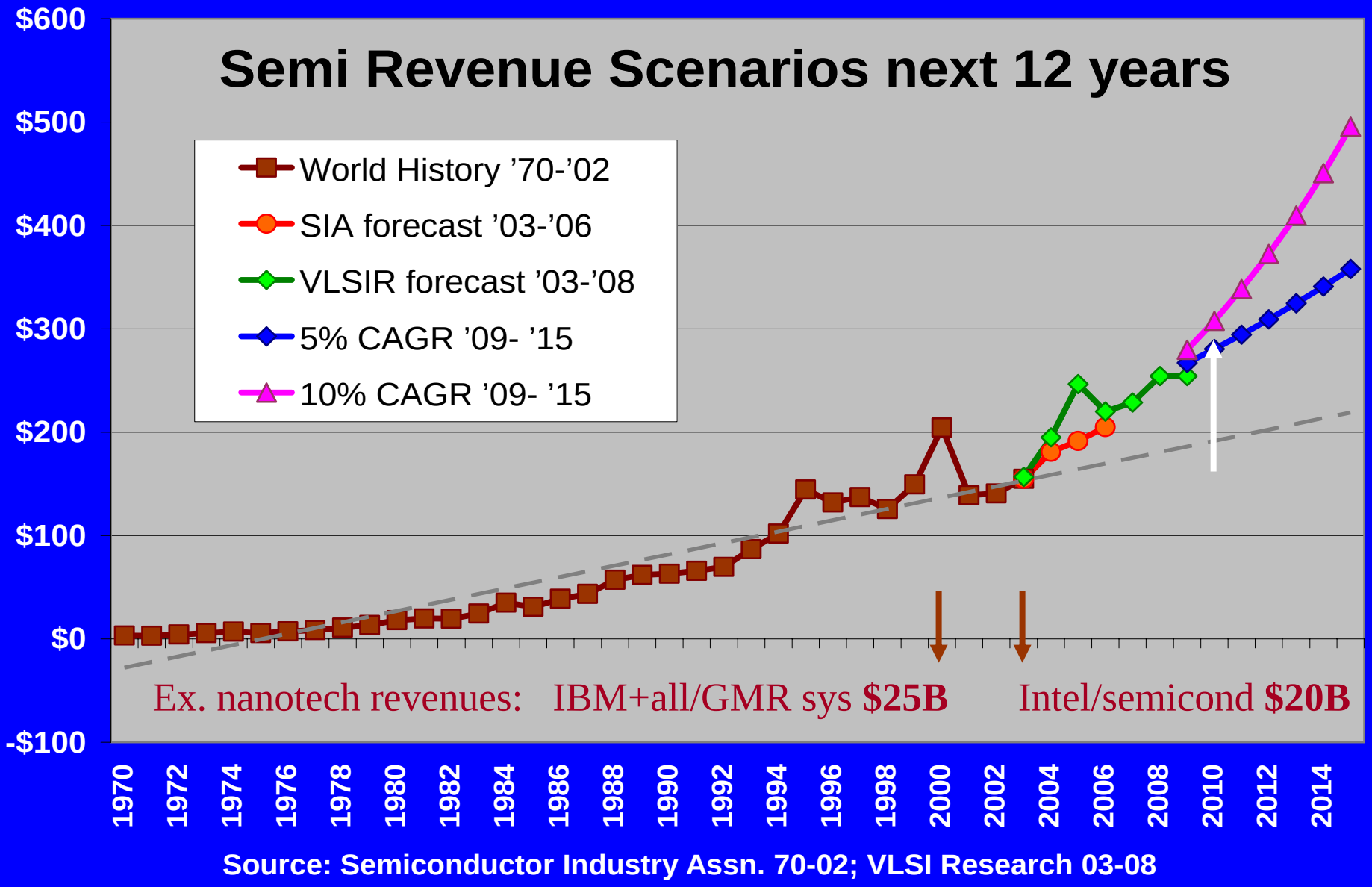
  Est. in 2000 (NSF) : about $40B for catalysts, GMR, materials, etc.; + 25%/yr
  Est. in 2002 (DB) : about $116B for materials, pharmaceuticals and chemicals

  Would require worldwide ~ 2 million nanotech workers

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

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

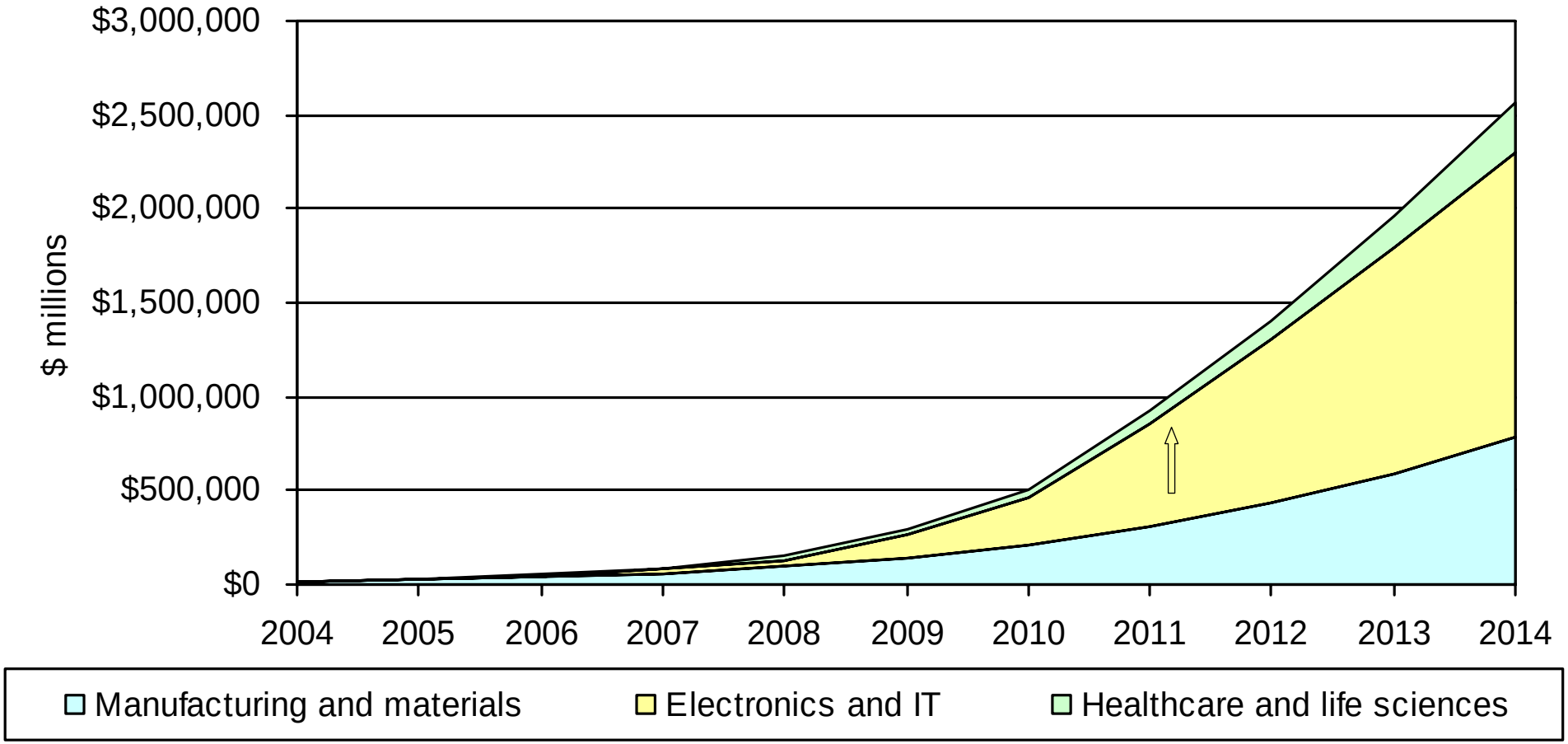
Semiconductors Extrapolated to 2015 ($B)



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

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

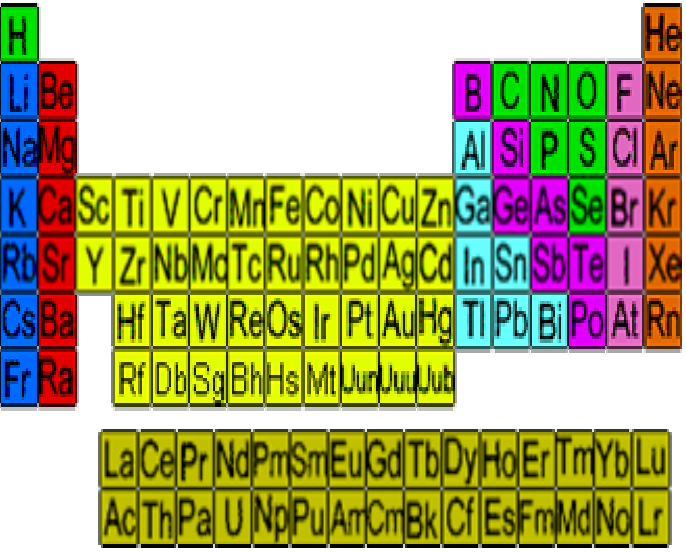
Global forecast, products sold incorporating emerging nanotechnology, 2004 to 2014, 3 sectors



Source: October 2004 Lux Research Report “Sizing Nanotechnology’s Value Chain”

Manufacturing at the Nanoscale

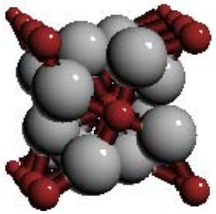
Transforming raw materials into products with desired properties and performance – generally in large quantities



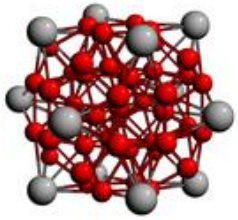
(NRL Center for Computational Materials Science)

Examples of structures and devices

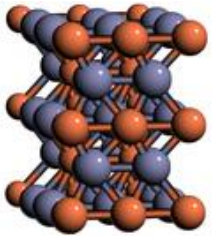
Al_2Cu



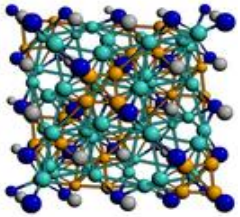
$BaHg_{11}$



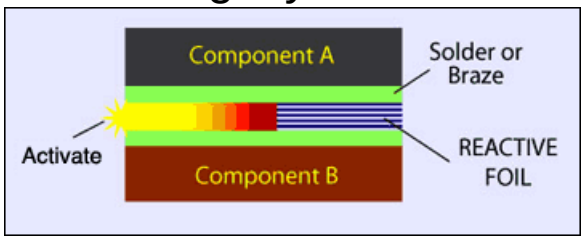
$MoPt_2$



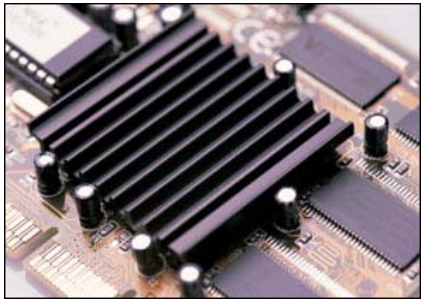
Fe_3W_3C



~ 5,000, 10 –20 nm alternating layers of Ni - Al



Reactive Nanotechnologies



Highly localized, low-energy, high-T, heat source

Atoms, molecules → nanoparticles → materials, devices, systems

Utilization of Nanoparticles

- *Introduction* -

- **NP may play two roles**
  - precursors for functional structures, devices and systems
  - agents of change (enhancing or changing) of physical phenomena, chemical and biological processes
- **NP take advantage of**
  - new physical/chemical/biological properties because of the size
  - new molecular structures and architectures by nanofabrication, chemistry and biotechnology routes
- Currently, a variety of NPs are commercially available
  Few NP synthesis processes were developed decades ago: particle polymerization started during the second WW; self-assembly of micelles; synthesis of colorants), and one-dimensional nanostructures are used for GMR, supperlatices, coatings as optical and thermal barriers, coatings
- Present challenge: control, use various materials, system processing, 3D structures, bottom-up methods, scale-up

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

Manufacturing at Nanoscale
- typical bottom-up processes -

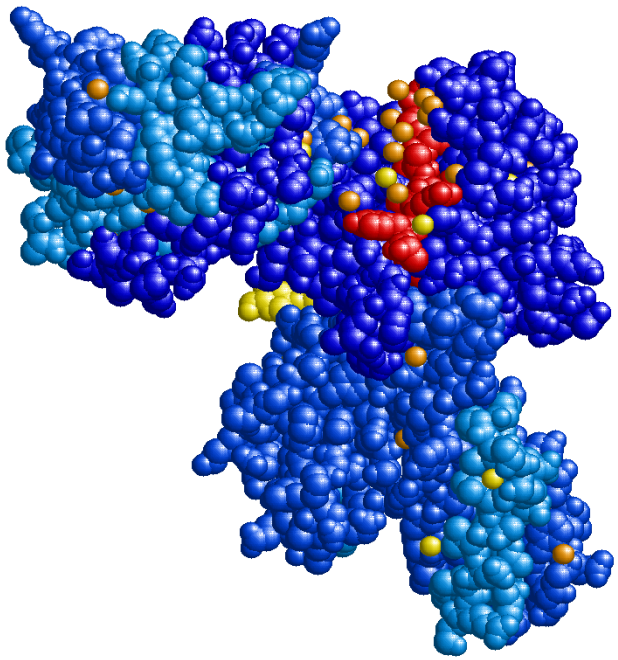
- Nucleation and growth
  - Aerosol and colloidal dispersions; deposition on surfaces
- Selfassembling
  - Natural process in living systems and biomimetics
  - Chemistry/chemical manufacturing
  - Guided by electric, magnetic, optical fields, DNA controlled ..
- Templating
  - Al and carbon nanotubes; 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, ..

Selfassembling: The model of molecular biology

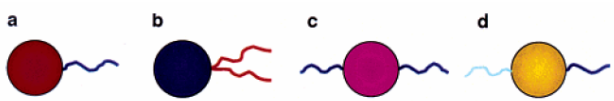
DNA	$\xrightarrow{\text{Transcription}}$	RNA	$\xrightarrow{\text{Translation}}$	polypeptide	$\xrightarrow{\text{Folding}}$	functional protein
Linear nucleic acid		Linear nucleic acid		Linear amino acid sequence		Three-dimensional structure

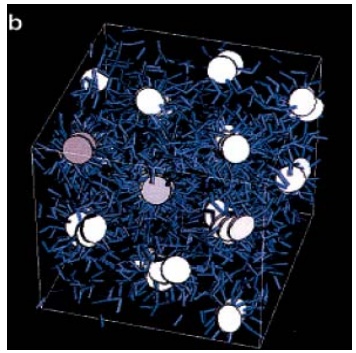


- All information leading to final folded structure is contained with the gene sequence
- Protein polymers spontaneously fold to final 3-D structure (U. Penn.)

Directed selfassembling

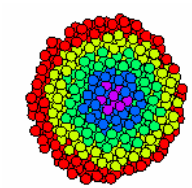
Ex: Approach based on surface recognition (Harvard)



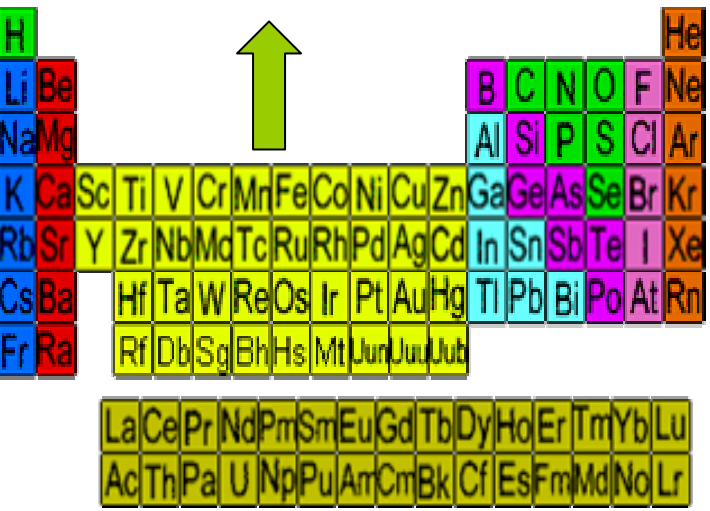


Directed self-assembly of building blocks

Attach oligomeric, polymeric, or biomolecular tethers

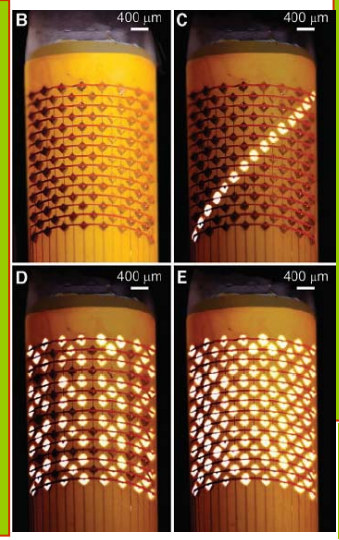


Form nanospheres, nanorods, …



Scaffolds and structures for:

- Catalysis
- Hydrogen storage
- Fuel cells
- Tissue engineering
- Drug delivery
- Electronics



Increasing scale of self-assembly of building blocks directed by:

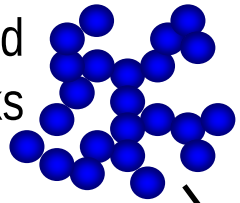
- Electric fields
- Structured light
- Patterned substrates
- Free-energy minimization

H.O. Jacobs, A. R. Tao, A.Schwartz, D. H. Gracias, G. M. Whitesides

Directed selfassembling

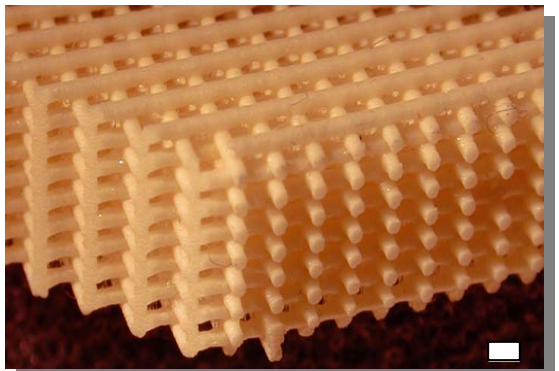
Ex: Robotic deposition of nanoparticle/polymer gels

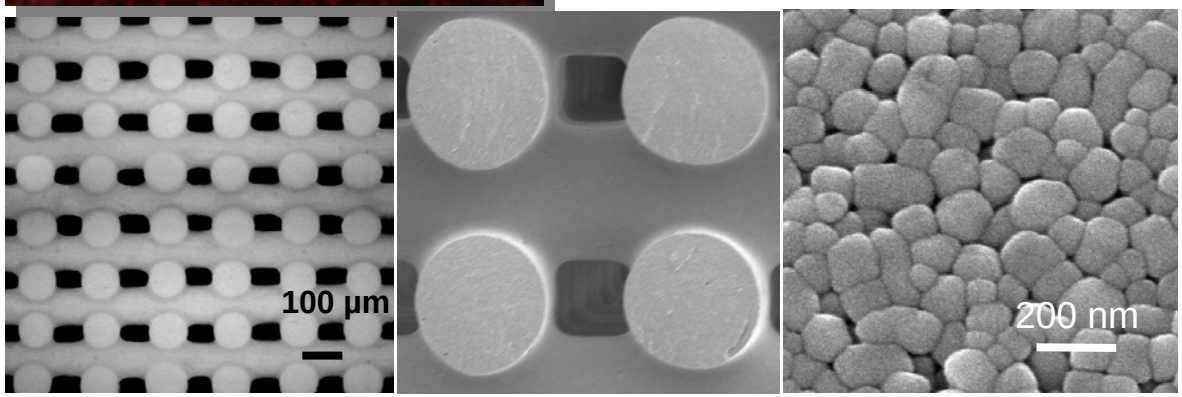
nanostructured inks

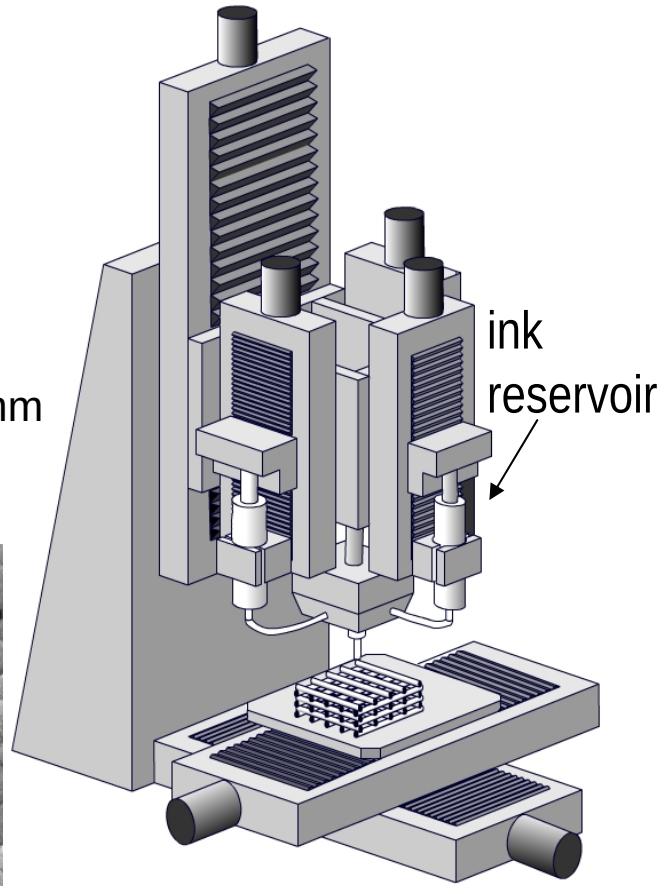


direct-write assembly
of 3-D structures with
build rates: ca 1mm/s
nozzle diameters: 1µm -1mm

Lewis et al. (2003)







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

Templating nanomaterials

Nearly any synthetic method used to prepare bulk materials can be adapted: the template used as a mechano-chemical reactor

- Electrochemical metal deposition.
- Electroless metal deposition.
- Electrochemical polymerization.
- Chemical polymerization.
- Chemical vapor deposition.
- Sol-gel methods.
- Hydro-thermal methods

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 asssembling),
- engineering of molecules and supramolecular systems (molecules as devices "by design", nanoscale machines, etc.),
- hierarchical integration with larger scale systems.

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

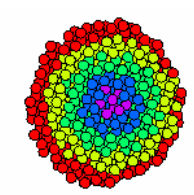
Defining Nanomanufacturing (2)

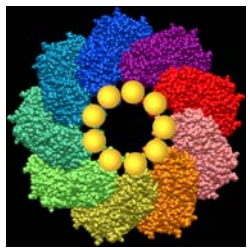
- Fragmentation
- Patterning
- Restructuring of bulk
- Lithographie, ..

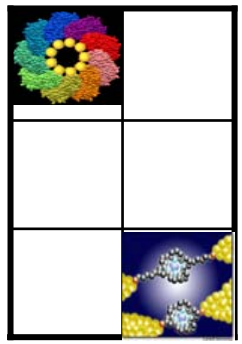
- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

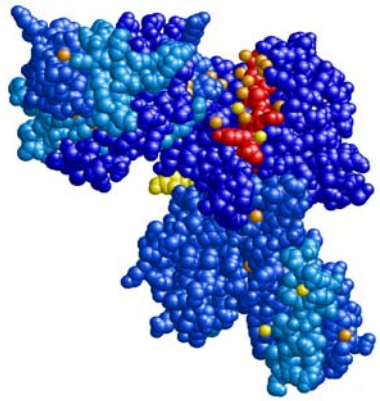
- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration..









Assembling

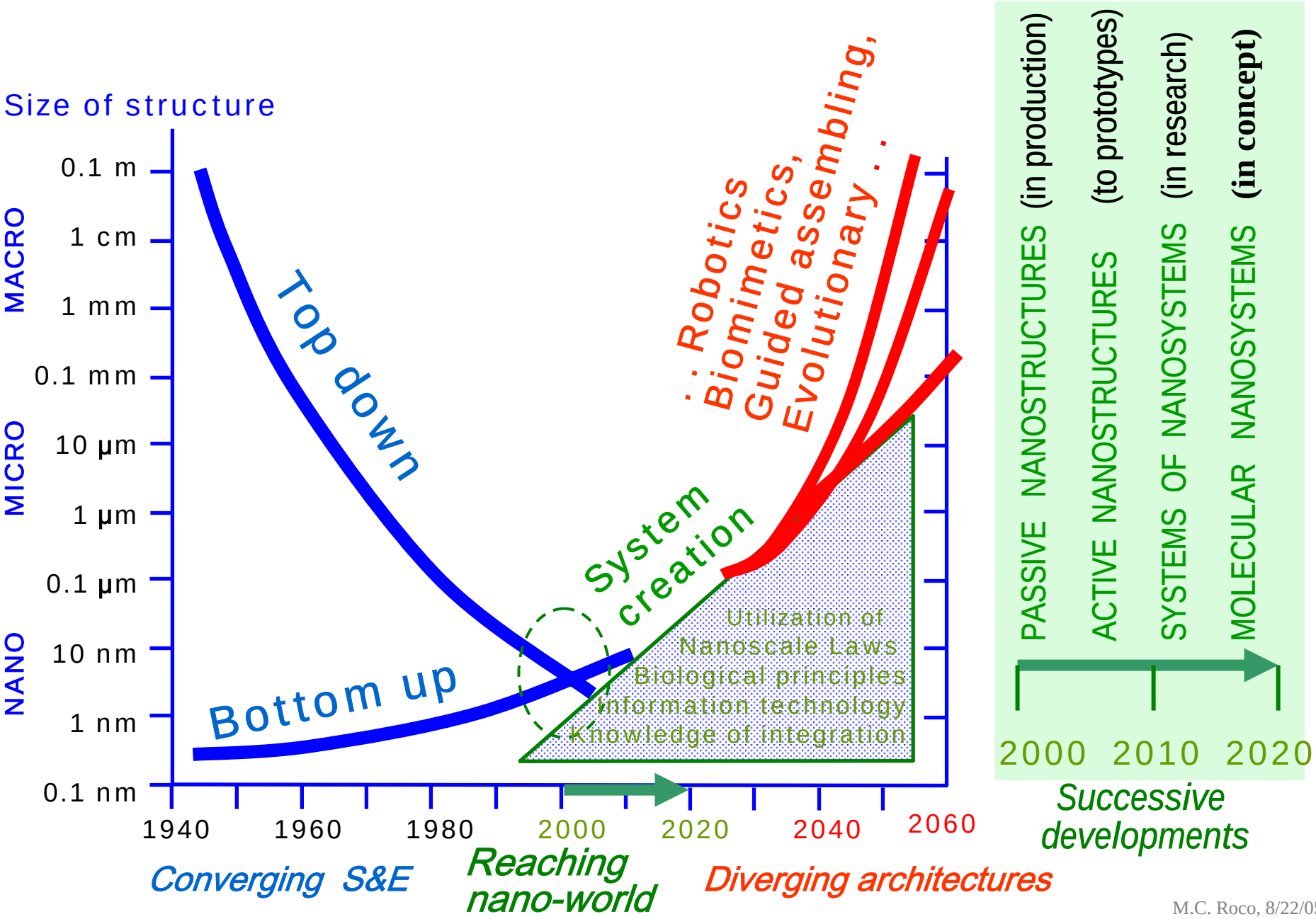
- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

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

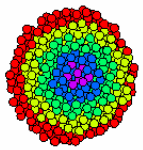
PASSIVE NANOSTR. - ACTIVE NANOSTR. - SYSTEMS OF NANOSYSTEMS - MOLECULAR NANOSYSTEMS

Reaching nano-world and system creation



M.C. Roco, 8/22/05

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



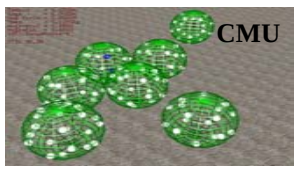
1st: Passive nanostructures (1st generation products)

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

~ 2000

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

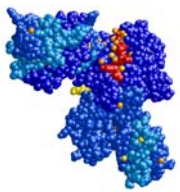
~ 2005



3rd: Systems of nanosystems

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

~ 2010



4th: Molecular nanosystems

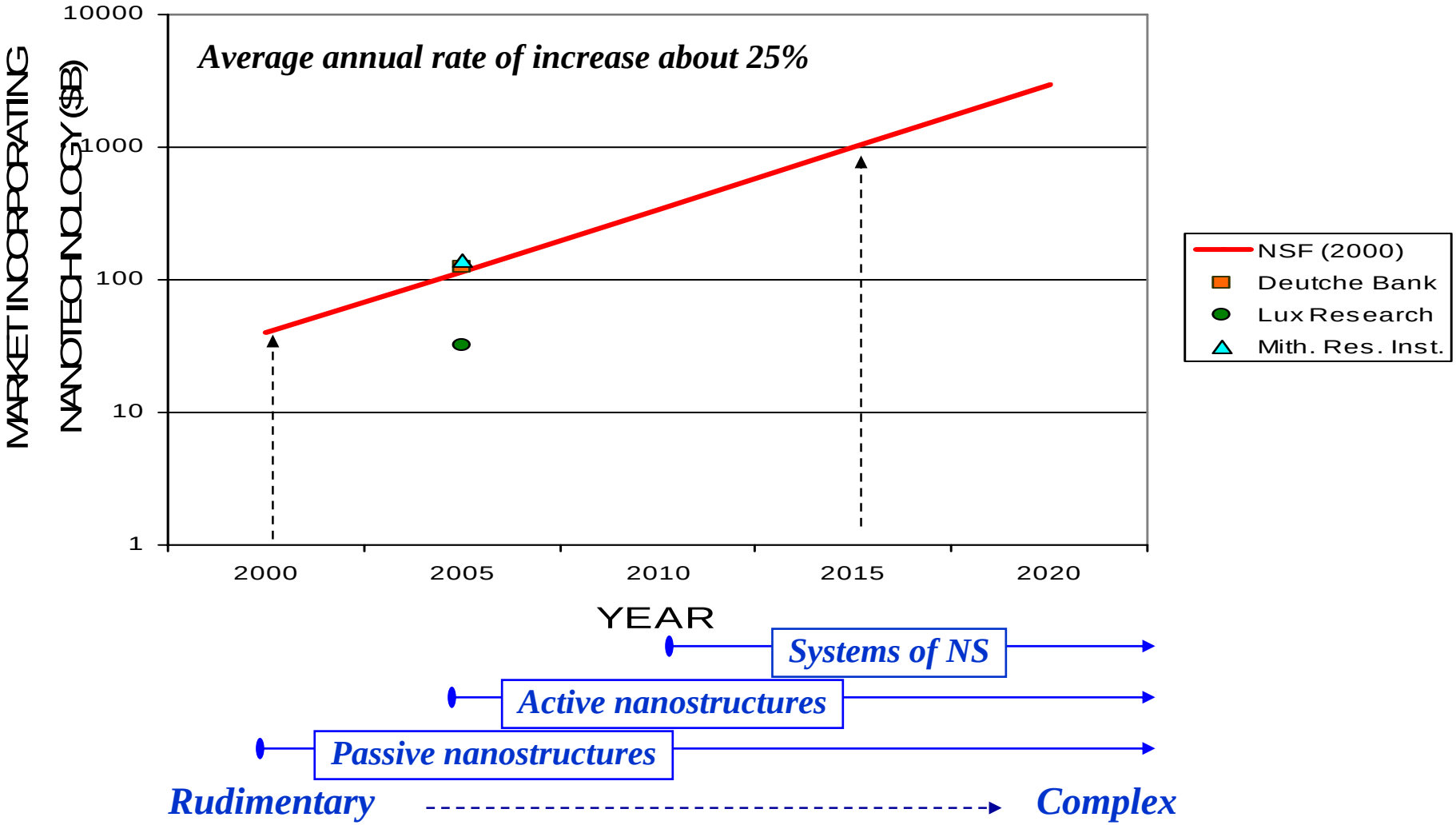
Ex: molecular devices 'by design', atomic design, emerging functions

~ 2015-2020

New R&D challenges

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

Worldwide market affected by nanotechnology. Estimation made in 2000



Nanoelectronics:
Example of Enablers for Successive Product Generations

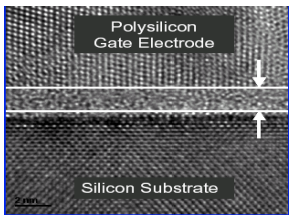
- First generation: Scaling down "masked-lithography of thin-films" approach (the cost-per-function trend is threatened); Nanoscale comp. (ex: layers) w/ new physics
- Second generation:
  - Manufacturing technique to lower the cost of: capital equipment, pattern generation, and "atomic-level" process 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

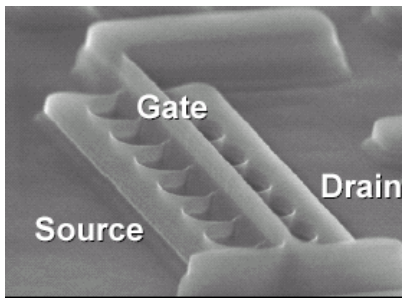
- In the 70s, 80s and 90s; after 2000 in the nano domain
  Geometrical scaling was the major driver

- 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

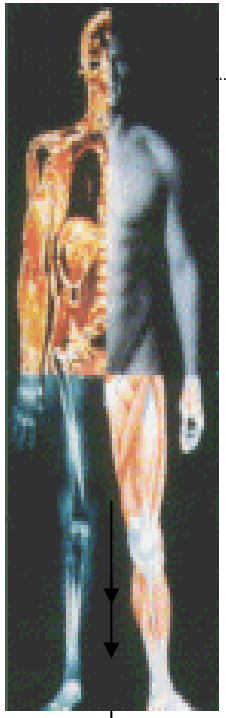
In addition, to explore beyond CMOS:

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

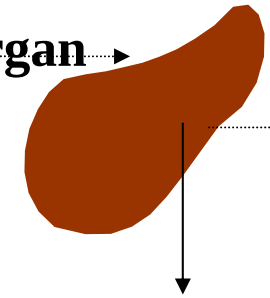
Examples of levels for intervention of nanobiotechnology

in human life extension: 4 generations of products

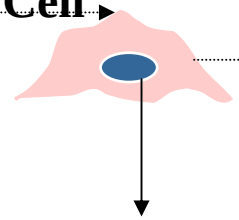
Human



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)

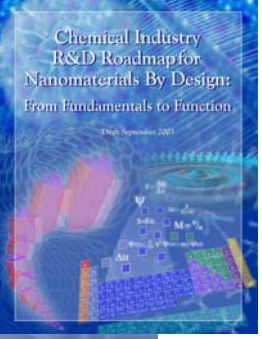
First generation of products: passive nanostructures (~ 2000 –)

- 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

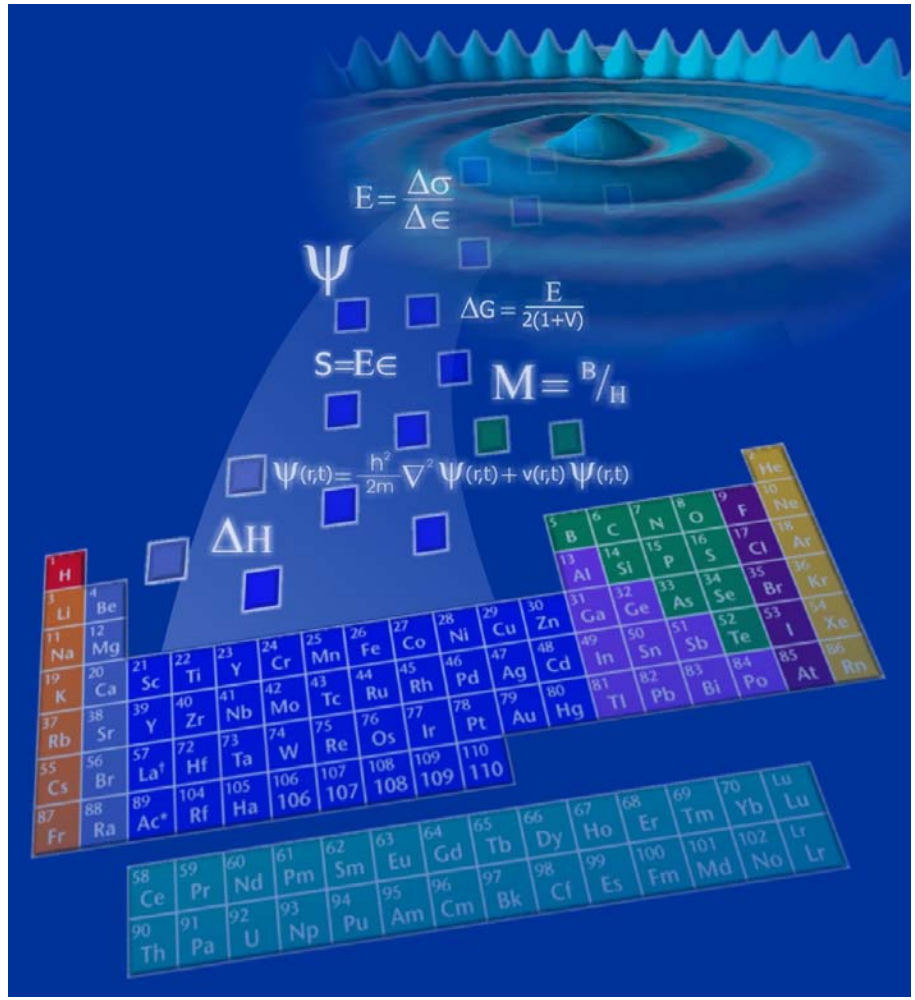
- **R&D focus:** on new properties of materials and new tools
  Ex.: grain boundary simulation, nanomechanics



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



Nanomaterial Development: Future

Application-based Problem Solving

Start with existing needs, problems, or challenges in end-uses

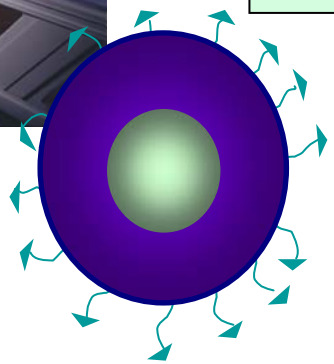
Design, produce, and scale up nano-based materials with the exact properties needed*

Large numbers of diverse products based on nanomaterials "By Design" rapidly enter and succeed in multiple markets

* Based on established understanding and methods

Aircraft Engines

Healthcare



Nanotechnology Platform

NanoTubes and NanoRods

NanoParticles

NanoCeramics

NanoStructured Metal Systems

Hybrid Materials

Water

Energy

Nanotechnology at General Electric

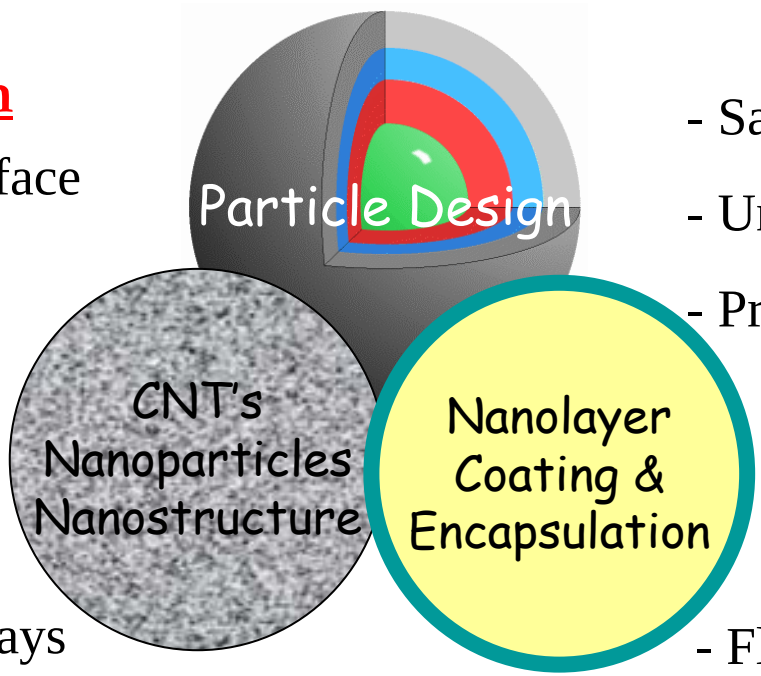
DuPont: Process Engineering & Manufacturing

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)

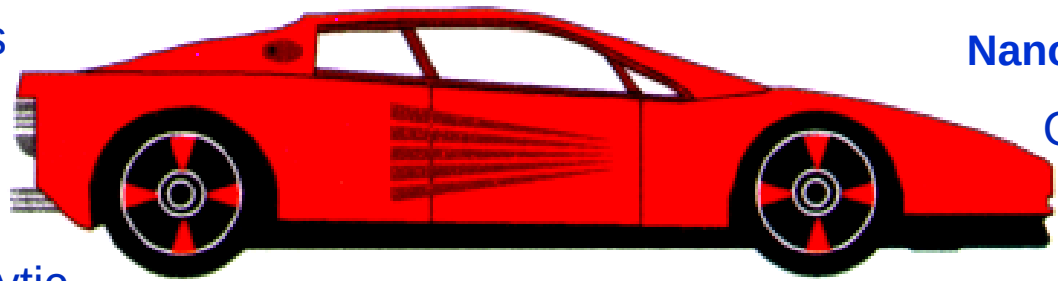
Ex: "Nano in Cars" consortium in Germany - 6 car manufacturers, 10 suppliers, and 26 R&D university and laboratories

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

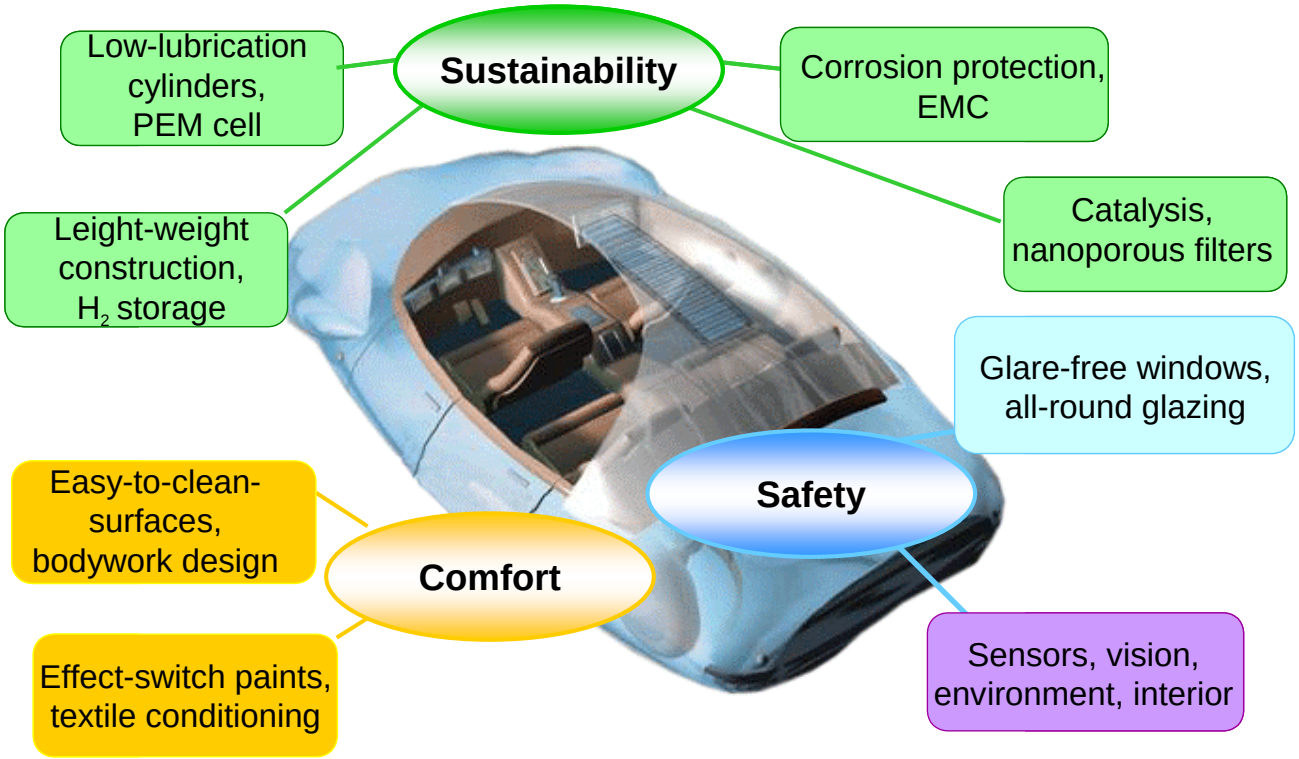
Catalytic converter

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 –)

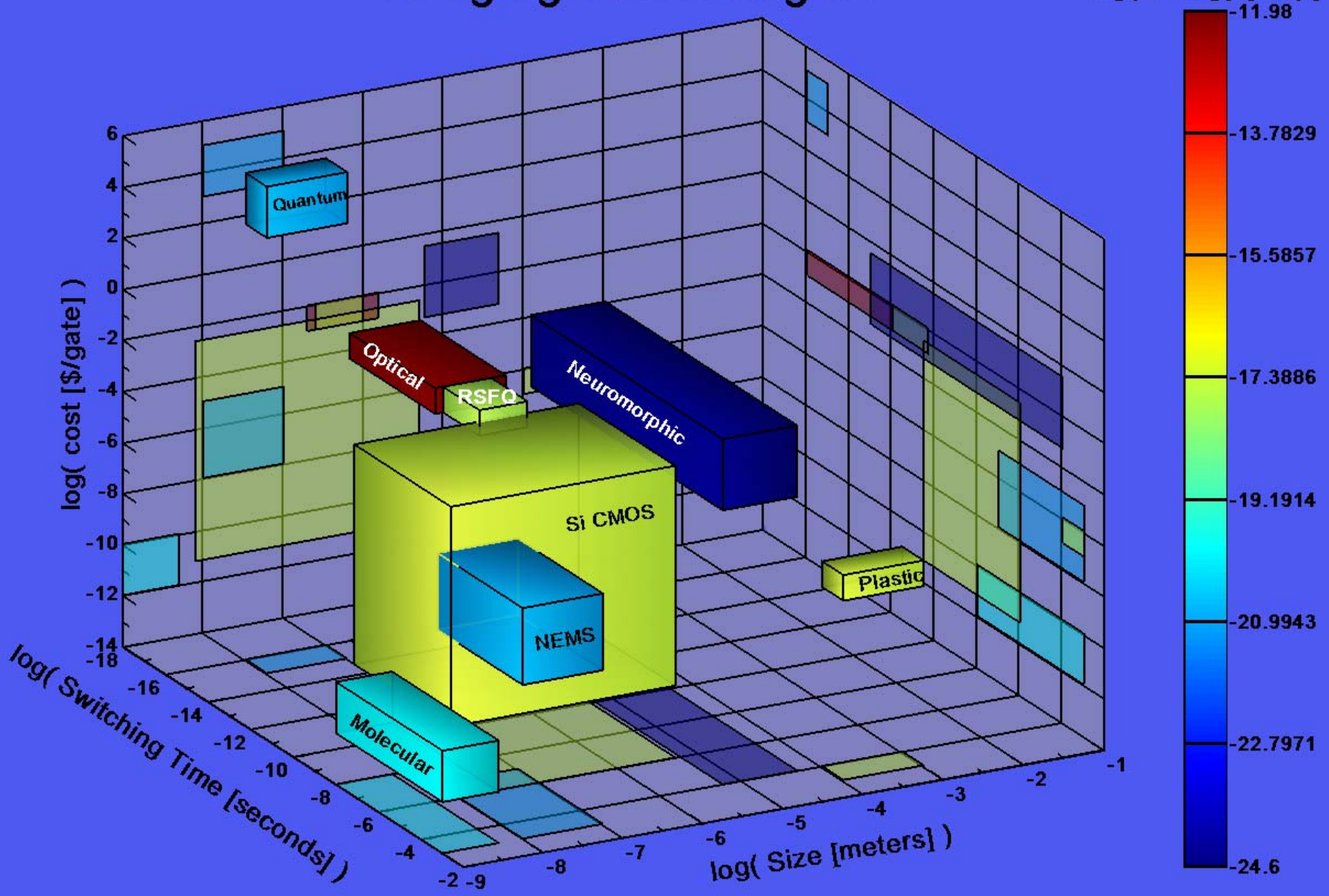
- IN DESIGN -

- **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

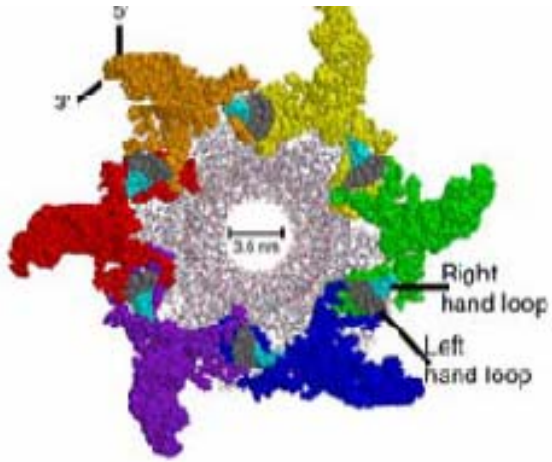


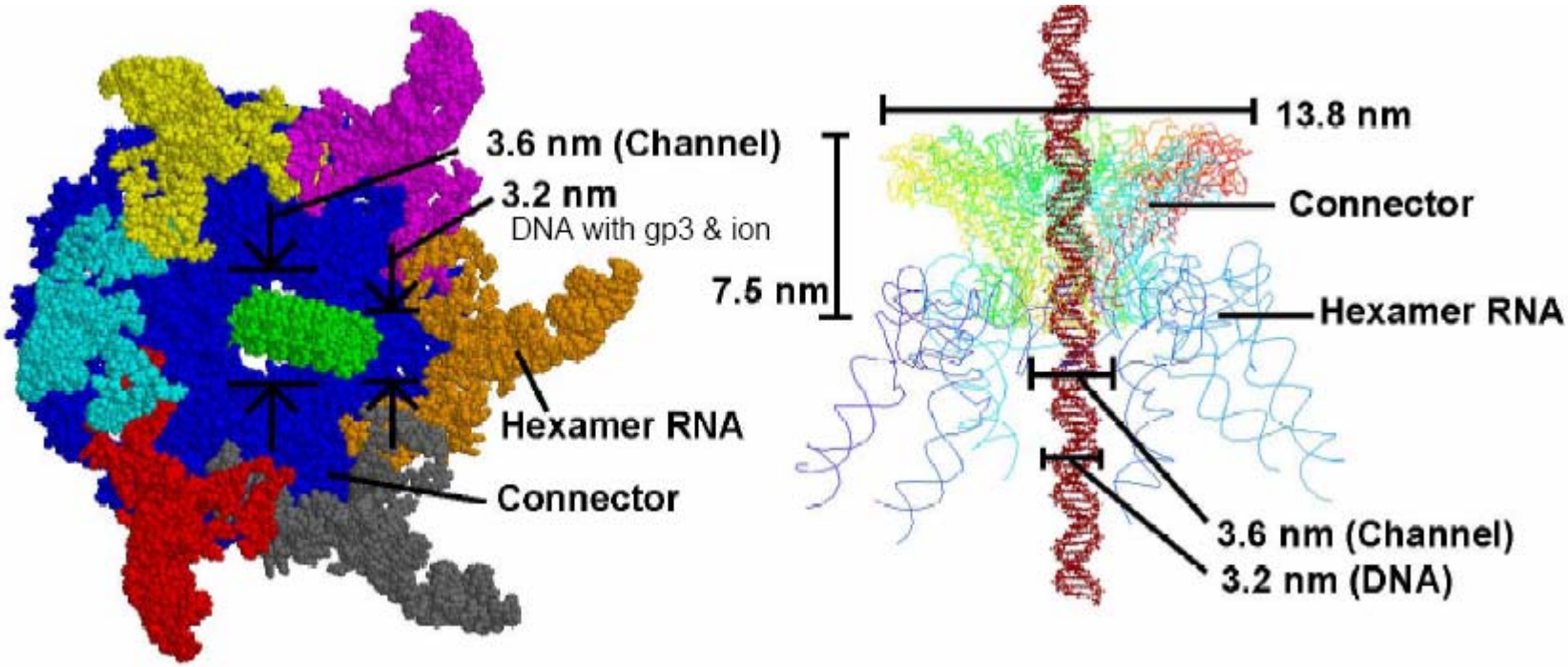
Motivation for hybridizing other devices with CMOS

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 -

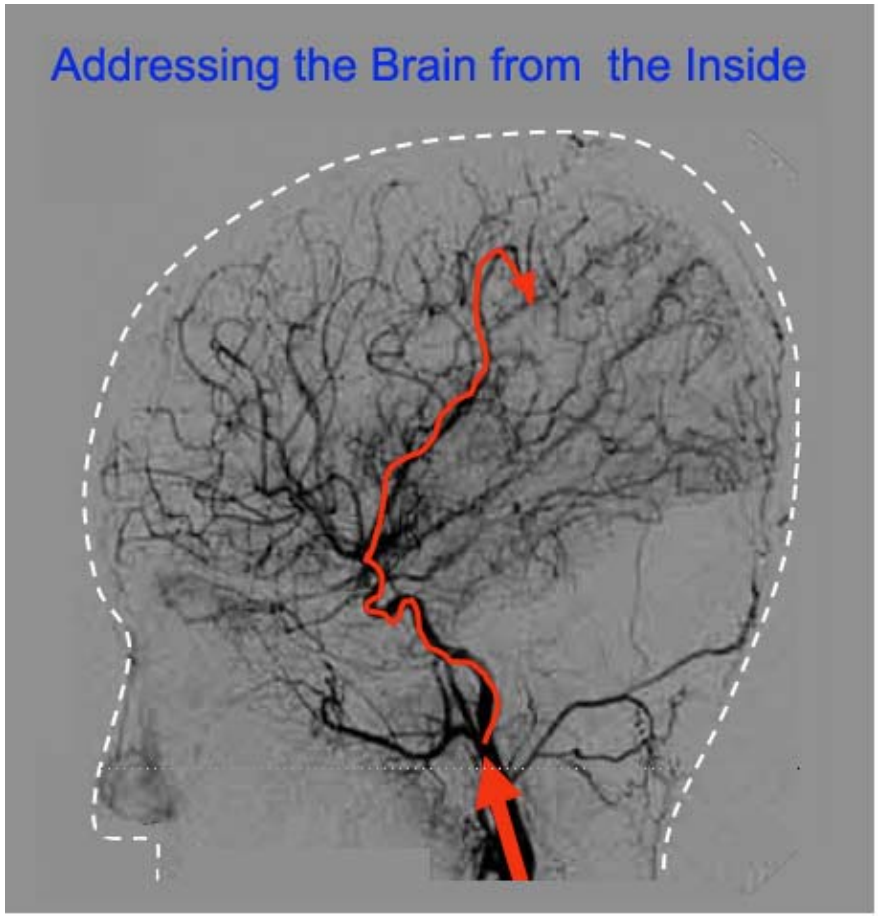
- **Goal:** engineer and manufacture 3D nanosystems with heterogeneous components, systems of nanosystems; typically for nanoscale assemblies and systems

- **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

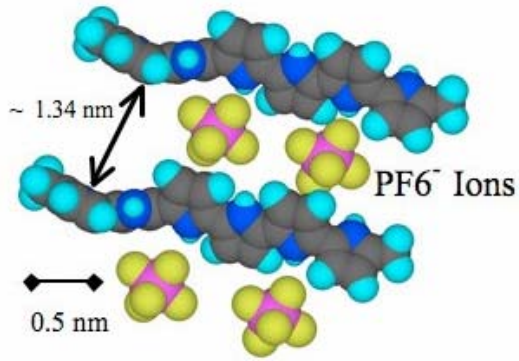
Example: Neuro-vascular Central Nervous Recording/ Stimulating System: Using Nanotechnology Probes

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

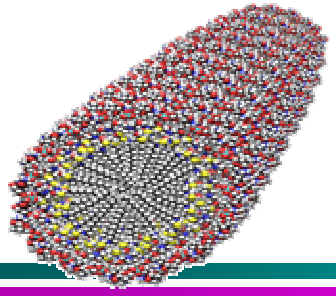
Fourth generation of products: molecular nanosystems (~2020?)

- 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

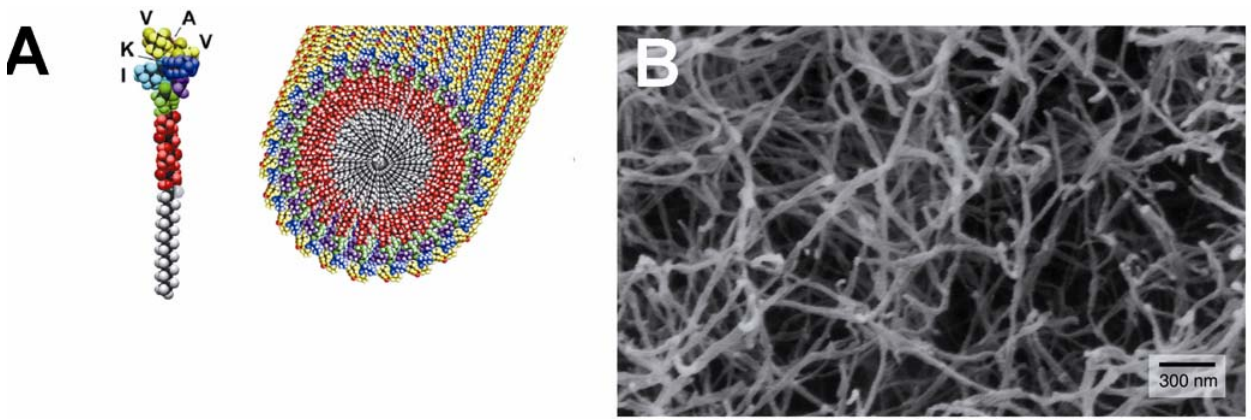
- **R&D focus:** atomic/molecular design, collective behavior and chemical-mechanical interaction of molecules, tissue nanoengineering, nano-bio-info-cognitive convergence, neuromorphic engineering

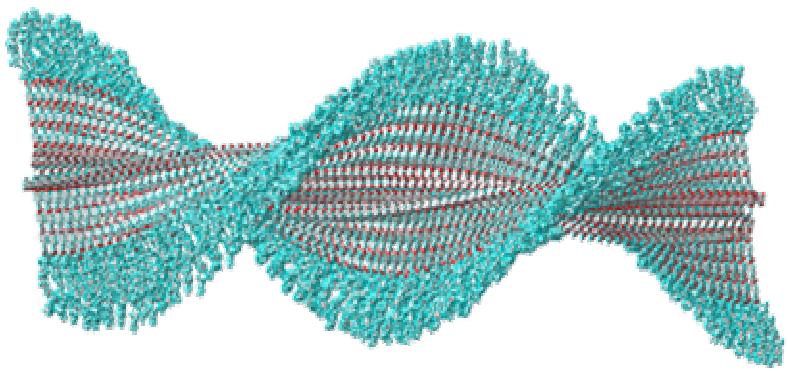


Designing molecules for hierarchical selfassembling

EX: SAMUEL I. STUPP, *Northwestern University*

Application: biomaterials for human repair, reactive filters, others



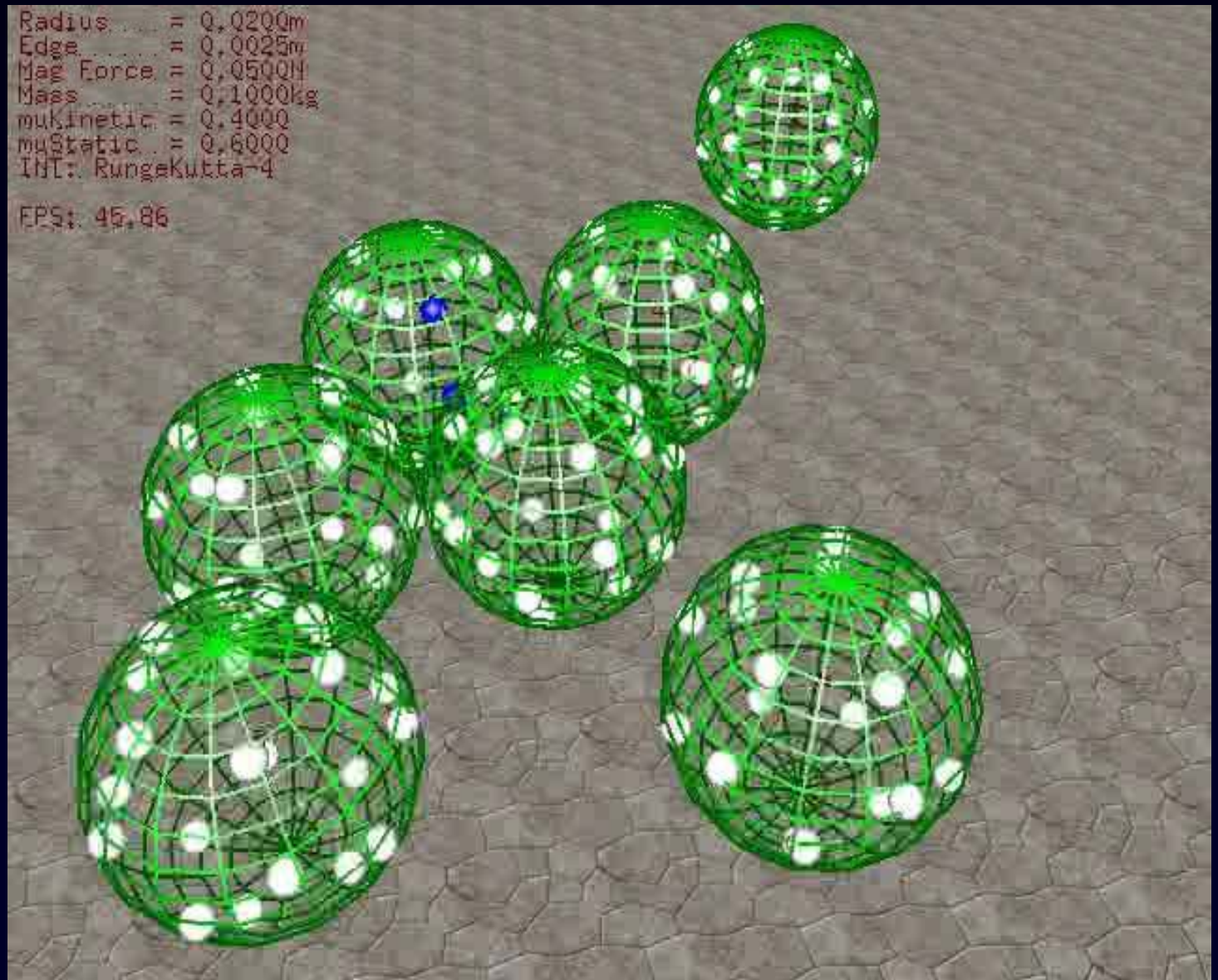


Characteristics of Micro/Nano-Robots
(NNI workshop Dec. 2004)

- New physics and mechanisms
- Smaller, faster, light weight, and cheaper
- Direct *accessibility* to smaller spaces and scales
- Massively parallel, in large numbers, and distributed (robust, flexible, and versatile)
- Multi length scale system integrati (macro/micro/nano/molecular)
- Bio-inspiration
- Interdisciplinary

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

(Seth Goldstein, CMU)

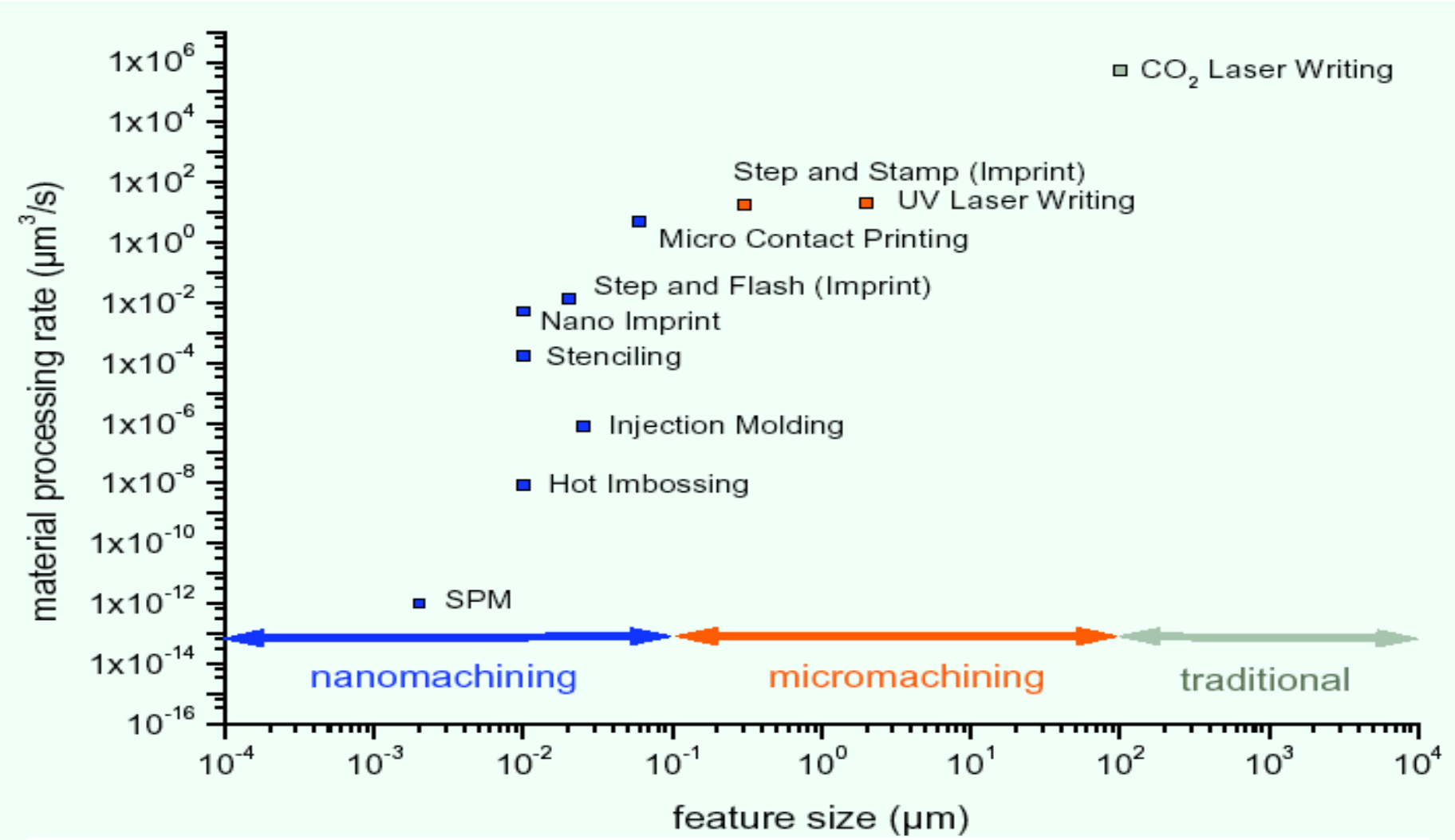


Nanomanufacturing: Several key issues

- 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.

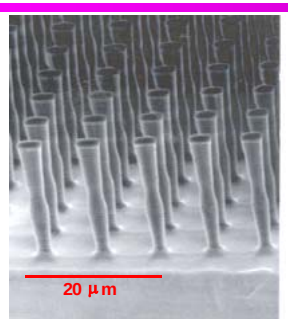
Scaling length and time scales of manufacturing processes from macro to micro to nano

(Courtesy: A. Menon, Technical University of Denmark)

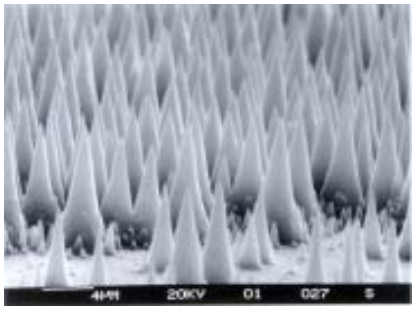


Nanomanufacturing: scaling up

- Focus on manufacturing **SCALE-UP** issues for industrial production: *producibility*, *predictability*, *productivity*



Micropost pattern



Nanopost pattern

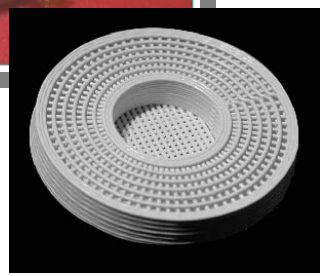
- Emphasis on 3-D systems **UP-SCALING**
  - integration across dimensional scales: *nano-structures → functional devices → system architectures → products & services*
  - integration of materials, geometries
  - integration of functionality *(mechanical, electromagnetic, thermal, biological, chemical)*

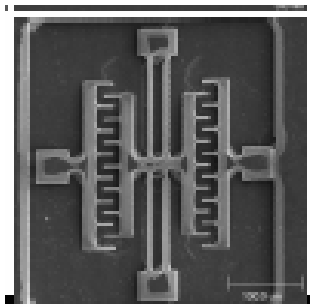
NANO

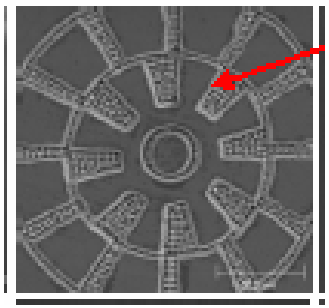
to

MICRO and MACRO

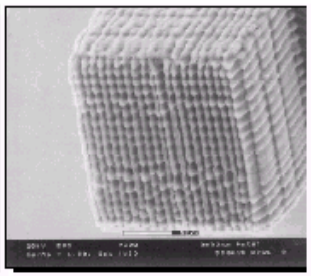
Manufacturing and Materials Processing and Integration Across Scales (UCLA)

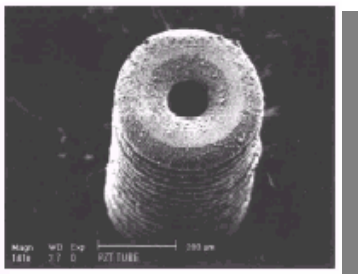


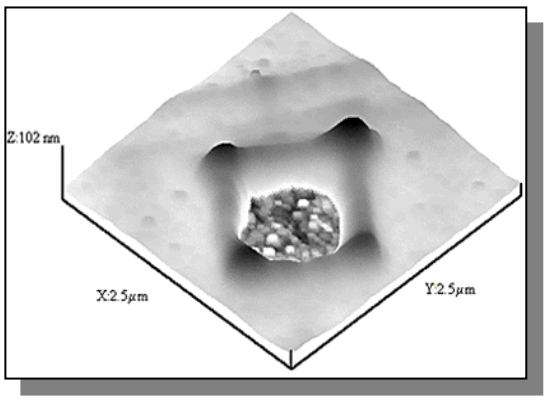




Macro→ Meso→ Micro→ Nano







C. Nanotech EHS Questions and R/D Needs

- Toxicology of new chemicals and materials considered for use in microelectronics and nanotechnology areas
- Interaction of nano-particles with biological systems
- Validation of the current standard methods for EHS assessment of materials
- Development of new methods for rapid and reliable assessment of the EHS impact of process chemicals and product materials.

Nanotech EHS Evaluation

For: Raw materials/ Manufacturing tools (metrology)/ New process byproducts / Product contents

For: Particles, surfaces

NATIONAL NANOTECHNOLOGY INITIATIVE

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

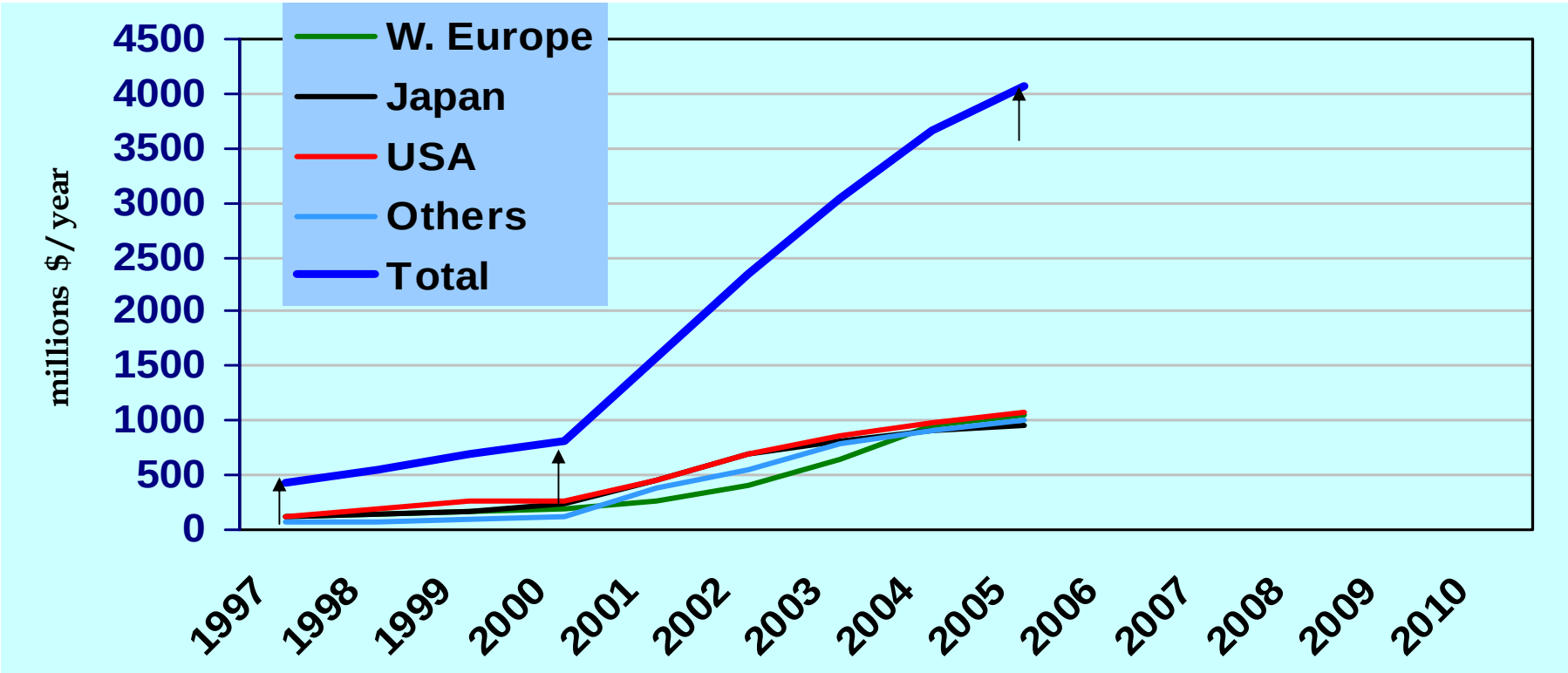
Fiscal year (all in million $)	*2000* Actual	*2001* Enact/Actual	*2002* Enact/Actual	*2003* Enact/Actual	2004 Req./Actual	2005 Req/Est.
National Science Foundation	97	150 /150	199 /204	221 /221	249 /256	305/338
Department of Defense	70	110 /125	180 /224	243 /322	222 /291	276/257
Department of Energy	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 /108	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
Congressional ads-ons at DOD		/25	/40	/80	/103	/150
TOTAL	270	422 /490	600 /737	770 /942	849 /1092	982/1231
		+82%	+50%	+28%	+16%	+ 13%

- Industry, state and local organizations: about 1.5 times NNI budget in 2003
- 22 NSET departments / agencies, including: OSTP, NSTC, OMB, DOC, DOS, DOT, DOTreas, FDA, NRC, DHS, IC, NIOSH, USPTO; partnerships with others
- 2004 NNI budget: 65% to academia; 25% - R&D labs; 10% - industry (7% SBIR)

MC Roco

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 nanostruct. & systems)

Total government expenditure in FY 2005 – about $4.1 billion

MC. Roco, 8/22/05

NSET: Support Transition of Fundamental Discoveries into Innovative Technology

- **Grand challenges (2001-2005) for technology base**

  Ex: nanomanufacturing – new NSF program $22M in FY 02-, 2 centers established in FY 03, 1 in FY04, 1 in FY 05

- **Infrastructure for instrumentation, tools, laboratories**

  Ex.: 33 centers and networks by 5 agencies; NSF/DMR instrumentation program, NNIN, NIST metrology and standards

- **Prepare the workforce at all levels**

  Ex: Technological, Community Colleges and UE in PA (PFI award)

- **Various mechanisms for interaction with industry**

  Ex.: Fund collaborations with industrial partners (GOALI, centers); Provide the NNI results to industry; Provide user facilities; Assistance for instrumentation, standards, manufacturing; Direct technology transfer and funding industrial projects: SBIR/STTR all agencies

"Nanoparticle Synthesis and Processing" program
NSF, 1990 -

GOAL: **SYNTHESIS & PROCESSING OF NANOPARTICLES**

NICHE: PRODUCTION AT HIGH RATES; SPECIAL PROPERTIES

A PROJECT HAS CO-P.I. FROM DIFFERENT DISCIPLINES. Ex.:

- *Nanoparticle Formation Using a Plasma Expansion Process, U. MN*
- *Nanocrystalline Materials Prepared by Spark Erosion, UCSB*
- *Controlled Production of Nanoparticles Using Microemulsions, MIT*
- *Combustion Process for Nanosized Reinforced Composites, U. WA-SL*
- *High Volume Production Using Laser Ablation of Microparticles, UT*
- *Particle-particle and Particle-substrate Interactions, Purdue U.*
- Others: *Submicron Aerosol Agglomeration, UCLA*
- *Nanophase Composite Materials for Magnetic Refrigeration, SUNY-B*
- *Effect of Electric Fields in Nanoparticle Flame Reactors, U. Cincinnati*

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

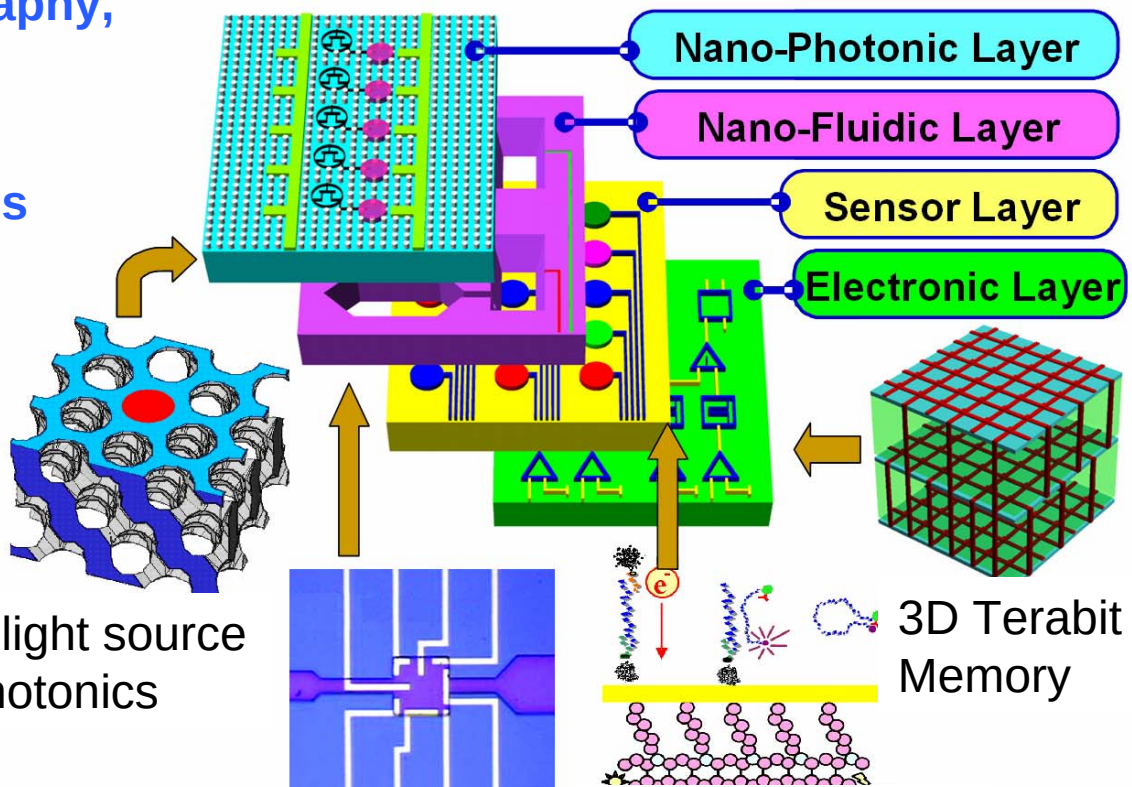
Center of Scalable and Integrated Nanomanufacturing

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

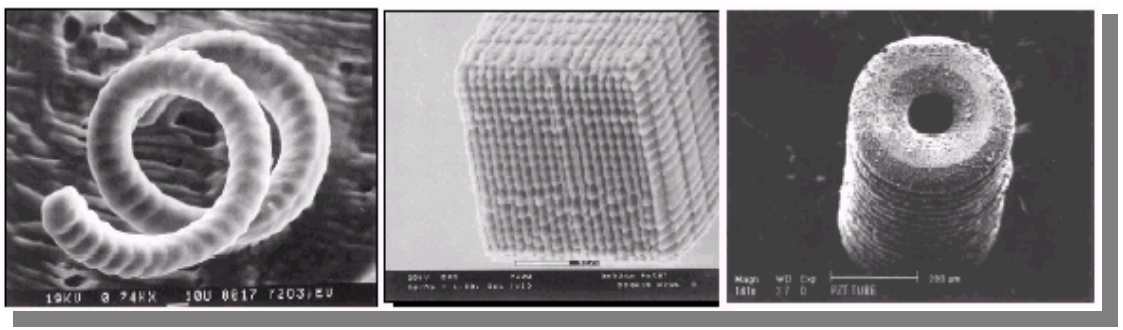
Ultra Sensitive Bio-sensor

3D Terabit Memory

Center for Scalable and Integrated Nano-Manufacturing

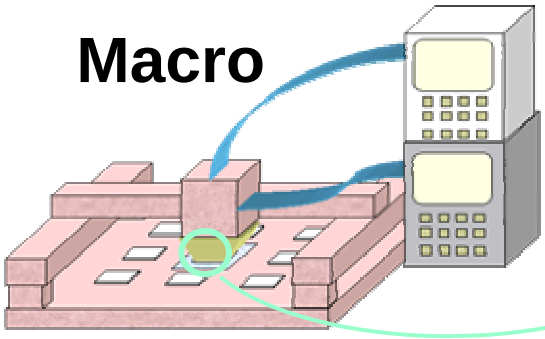
UCLA, UC-Berkeley, Stanford, UC-San Diego, UNC-Charlotte *(~$18M, 5 years)*

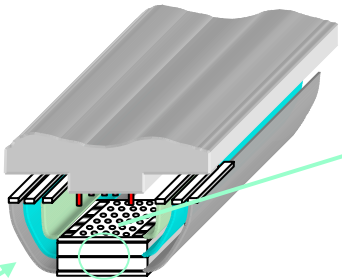
- **plasmonic imaging lithography, nano-imprinting, ultra-molding and imprinting lithography (sub-20nm 3D nano-manufacturing)**
- **field-assisted parallel nano-assembly (massively parallel integration)**
- **nano-scale precision engineering/tooling/metrology, nano-CAD platform, cluster tool**
- **nanoelectronics/nanophotonics/biosensor testbeds**
- **workforce development – LA school district, CA science center**



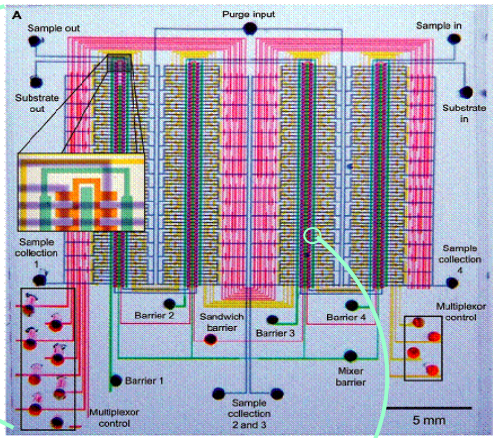
Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, UIUC, NCSU, Caltech

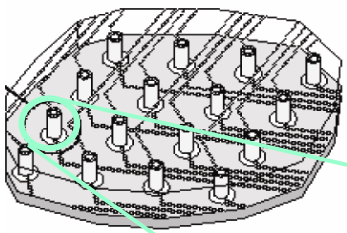
Macro

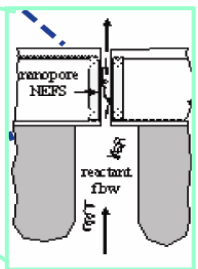




Micro







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

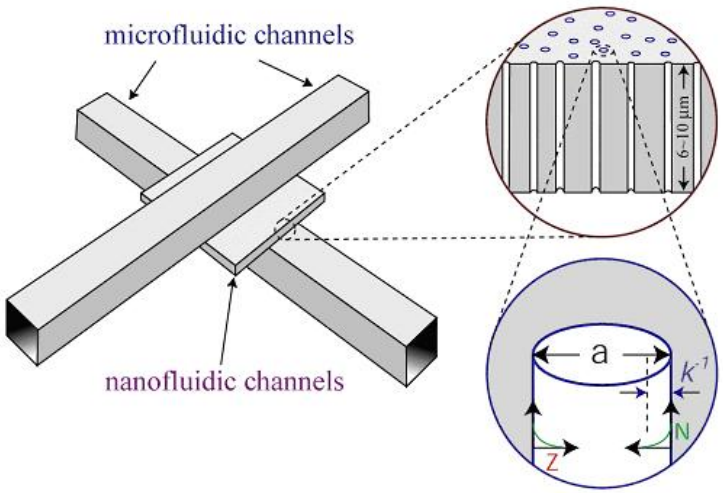
Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems Center

U.Illinois (UIUC), North Carolina A&T, Caltech (~$13M over 5 years)

- molecular gate array tool, electronically controlled nanopores
- efficient electrokinetic flows, micro- and nano-fluidic networks
- nanoscale positioning and sensing
- nanoscale organic optoelectronic/combinatorial chemistry and biology array testbeds
- workforce development

  collaboratory,

  community colleges,…



The Center for High-rate Nanomanufacturing
www.nano.neu.edu

CHN

Northeastern UNIVERSITY

UMASS LOWELL

Director: Ahmed Busnaina, NEU, Deputy Director: Joey Mead, UML
Associate Directors: Carol Barry, UML; Nick McGruer, NEU; Glen Miller, UNH
Task Leader: David Tomanek, MSU

Outreach Universities: Michigan State University
Collaboration and Outreach: Museum of Science-Boston, City College of New York, Hampton University, Rice University, ETH, University of Aachen, Hanyang University, Inje University, The Korean Center for Nanoscale Mechatronics and Manufacturing (CNMM), Taipei University, University of Hyogo

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

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 NSF in 2005: 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

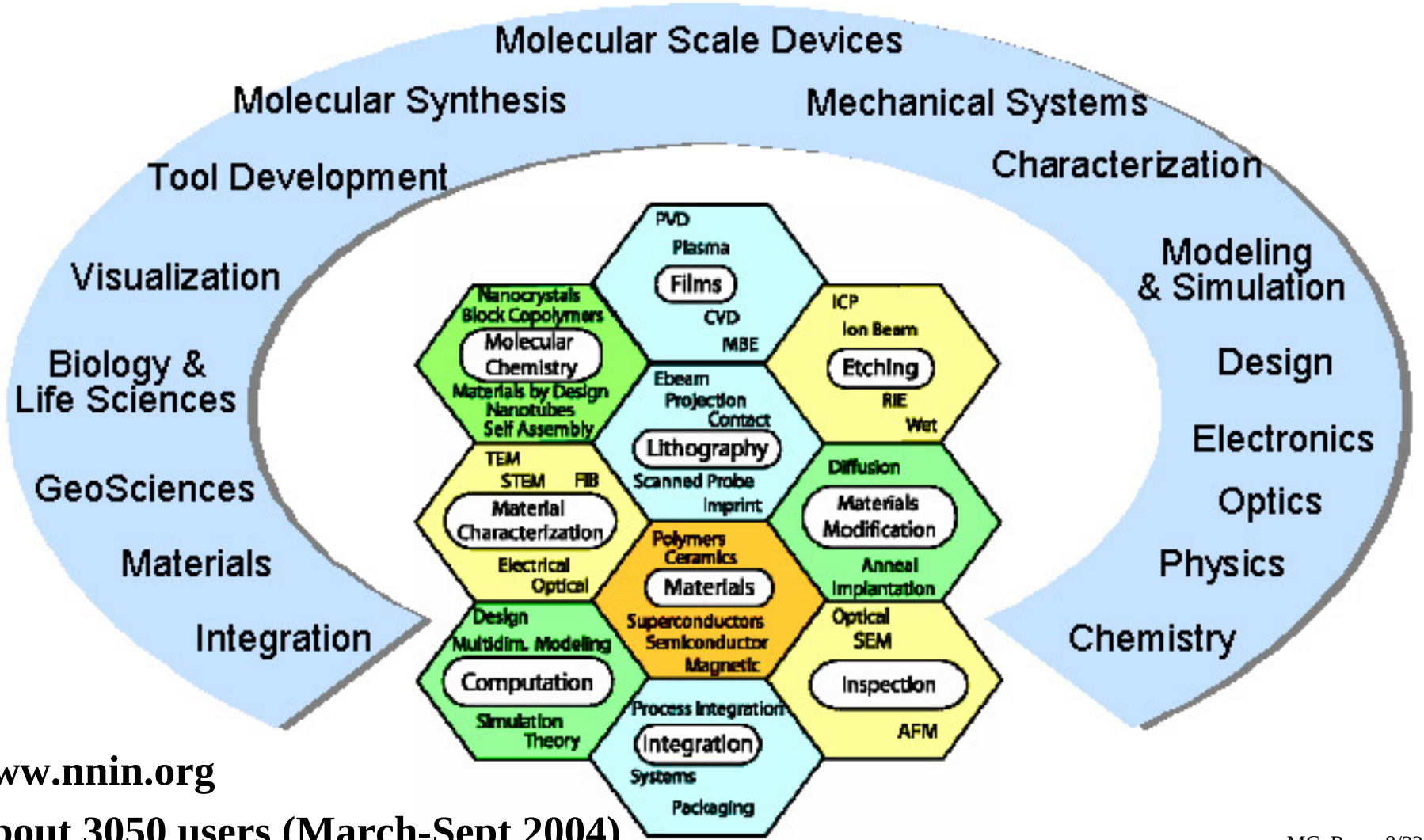
Nanotechnology Labs, NIST at MA and CO

Nanotechnology Characterization Lab, NCI

NIOSH

MC Roco, 8/22/05

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

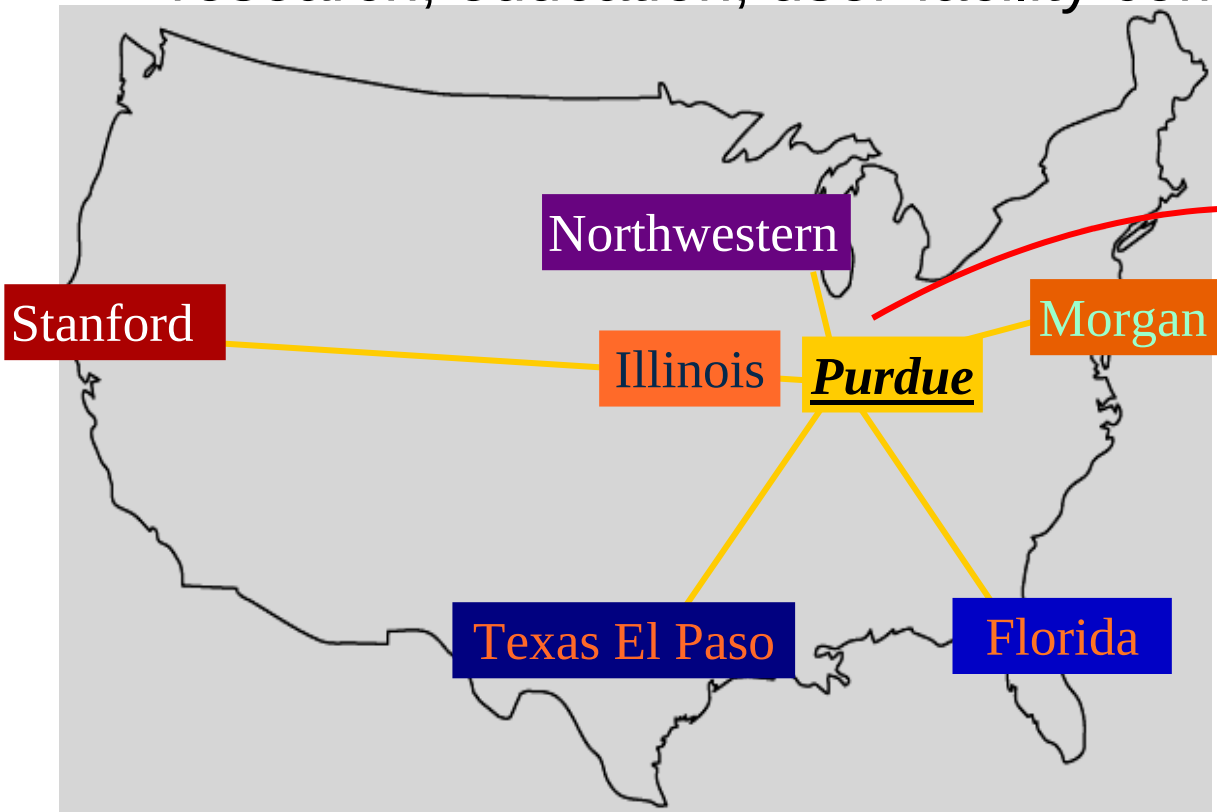


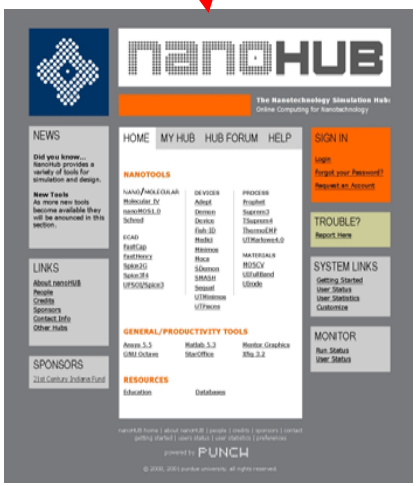
www.nnin.org

About 3050 users (March-Sept 2004)

Network for Computational Nanotechnology (7 nodes, lead Purdue University)

Multi-scale, multi-disciplinary from “atoms to systems” research, education, user-facility components





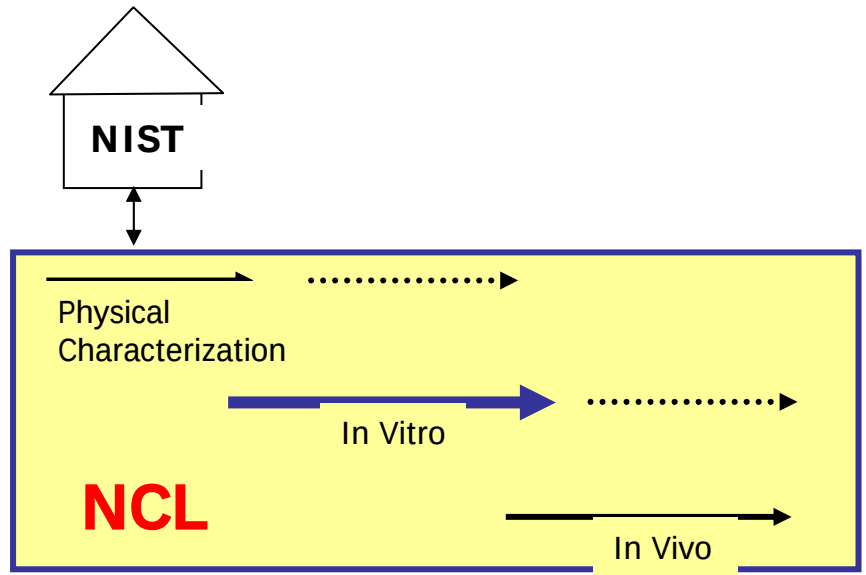
www.nanohub.purdue.edu ; About 3,200 users in FY 2004

Nanotechnology Characterization Laboratory (NCI) Concept of Operations

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

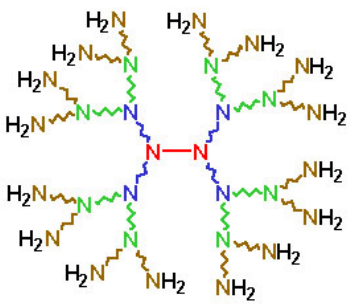
Sources of Nanomaterials

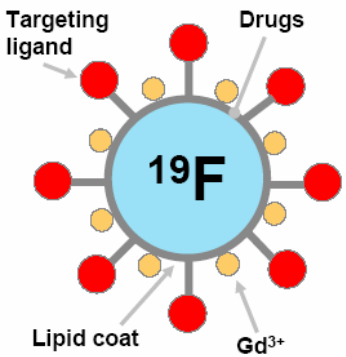
- Cancer Centers of Nanotech Excellence (CCNEs)
- Academia
- NNI
- Small Business
- NCI, NIH, NSF
- DoD, DoE
- Unconventional Innovative Program (UIP)

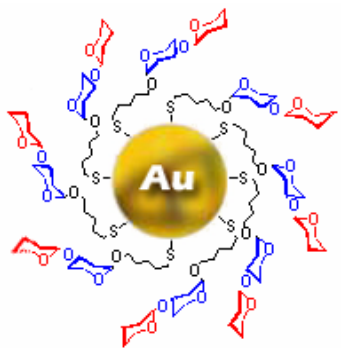


- Detection
- Diagnostics
- Therapeutics

Candidate Nanoparticles







MC Roco, 8/22/05

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

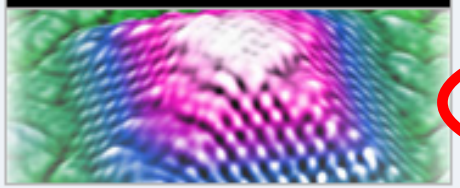
File Edit View Favorites Tools Help Address Links

National Science Foundation
WHERE DISCOVERIES BEGIN

SEARCH
NSF Web Site

HOME | FUNDING | AWARDS | DISCOVERIES | NEWS | PUBLICATIONS | STATISTICS | ABOUT | FastLane

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)

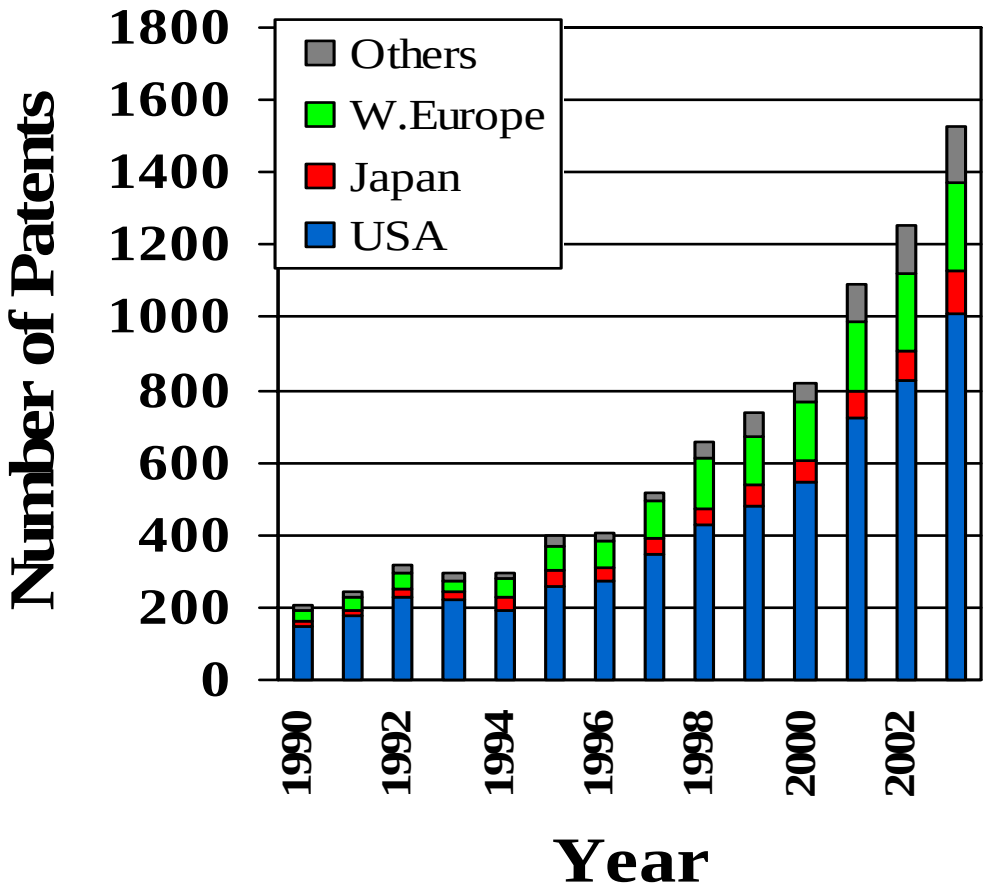
NSF Announcement 04-043: Nanoscale Science and Engineering (NSE)
NSEC on "Nanotechnology in Society" workshop

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

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)

"Title-claims" search:
nanotechnology claims



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
  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**
  - **Joint activities in R&D technology management**
  - **2 working groups (nanotech in industry, EHS)**
  - **Exchange information, use NNI results, support new topics**
- **NNI-Automotive Industry, 3/2005-**

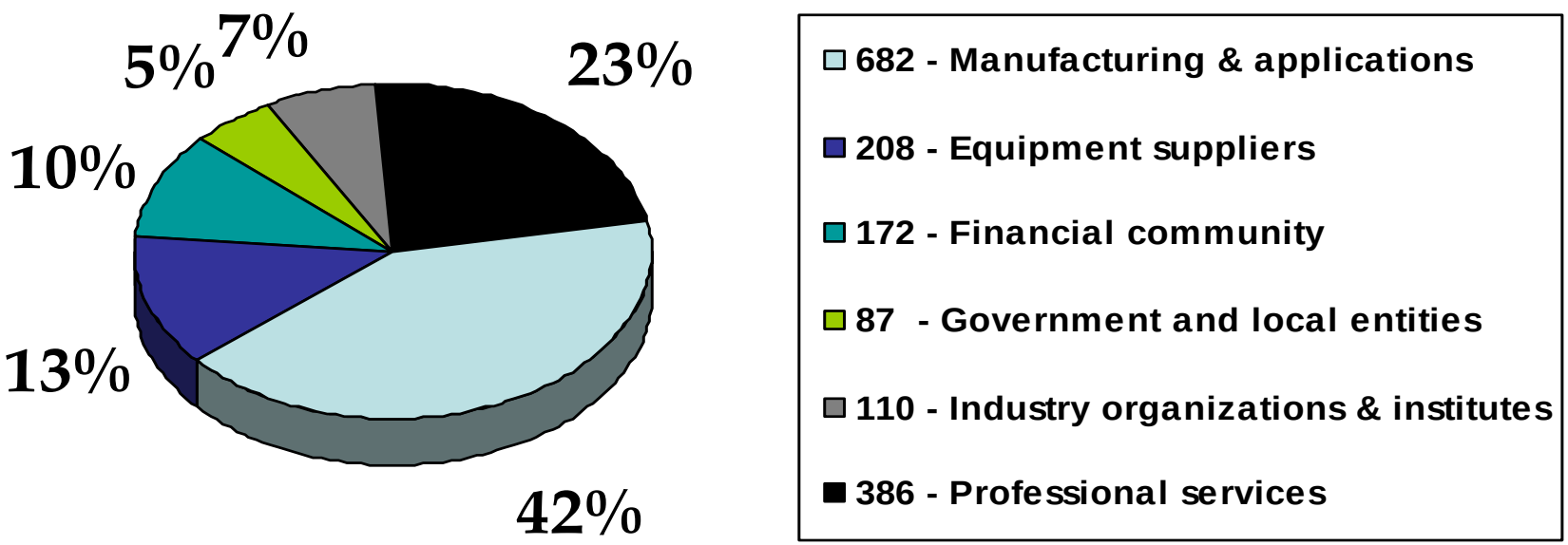
Other contacts: industry sectors such as aeronautics, plastics, food products, energy-related

General interest on nanotech EHS and business issues

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



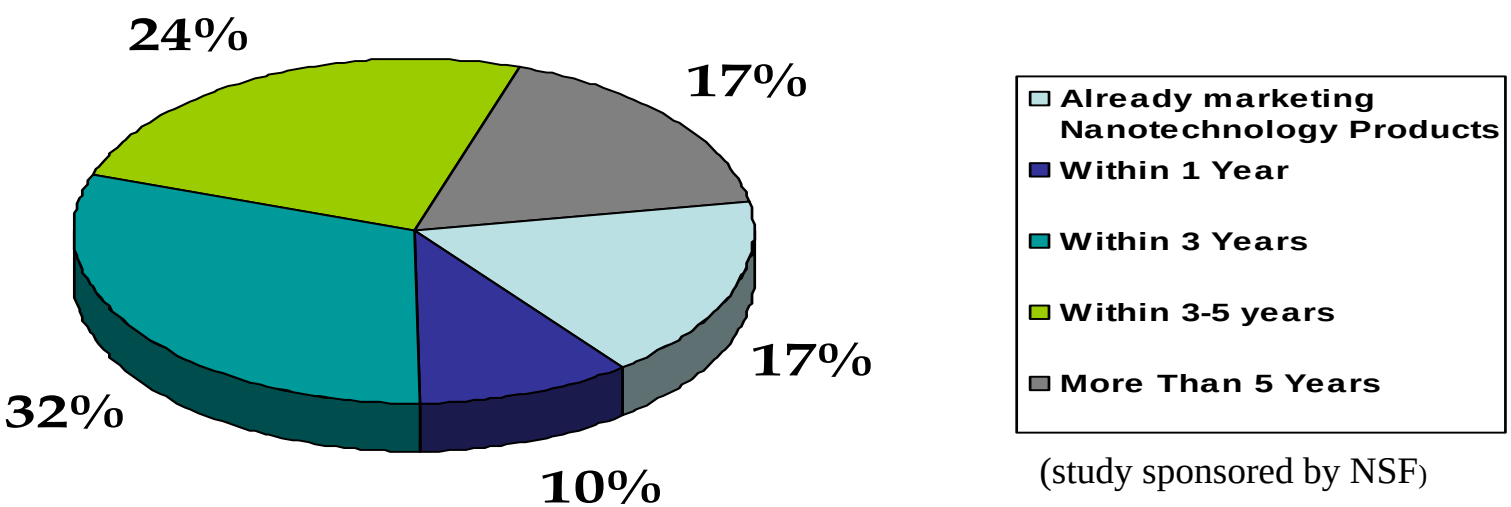
Industry surveys (2)

- 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



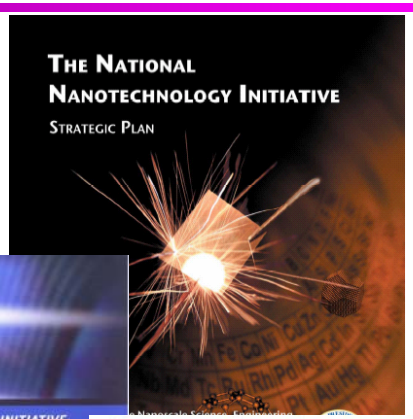
(study sponsored by NSF)

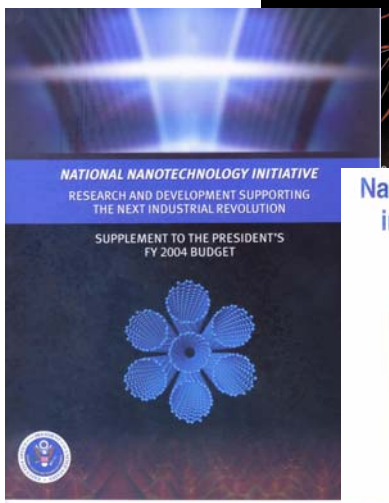
Defining the vision for the second strategic plan (II)

National Nanotechnology Initiative

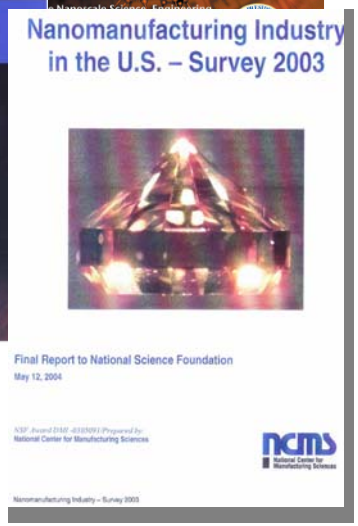
2004

2004:
10-year
vision/plan



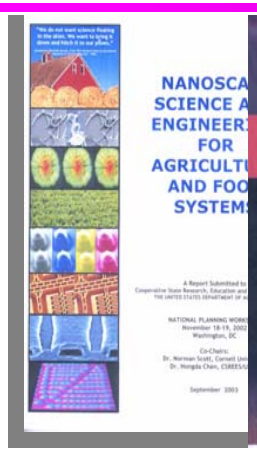


Government
Plan (annual)

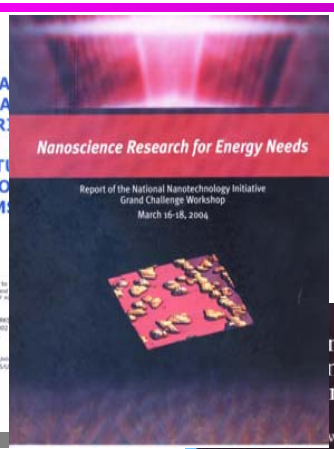


Survey
manufacturing

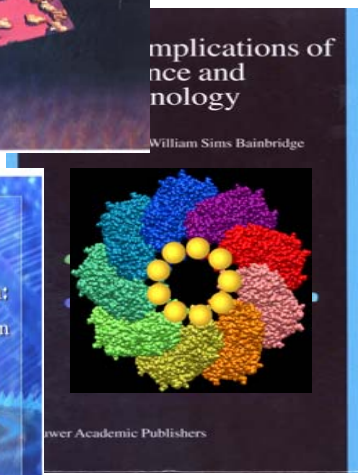
Agriculture
and Food



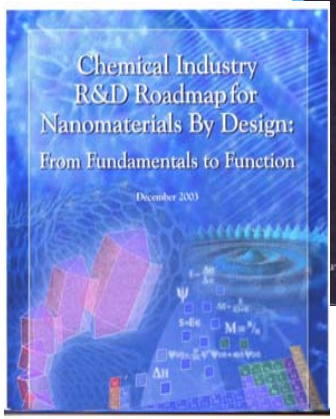
Energy



Societal
Implications
2004



Reports



Other topical reports
on www.nano.gov

2004: Update 10 year vision, and develop strategic plan

Requested FY 2006 NNI Investment by Program Component Areas - each with specific research targets

2006 Planned Agency Investments by Program Component Area (In $ millions)								
	Fundamental Nanoscale Phenomena and Processes	Nano-materials	Nanoscale Devices and Systems	Instrumentation Research, Metrology, and Standards for Nanotechnology	•	Major Research Facilities and Instrumentation Acquisition	Societal Dimensions	NNI Total**
NSF	95	75	54	12		24	60	344
DOD	35	83	99	3		6	2	230
DOE	48	33	5	11		109	1	207
HHS (NIH)	46	17	67	6		1	8	144
DOC (NIST)	5	1	2	39		8	1	75
NASA	4	17	10	0		0	0	32
USDA	1	2	3	0		0	1	11
EPA	> 0.5	0	> 0.5	0		0	4	5
HHS (NIOSH)	0	0	0	0		0	3	3
DOJ	0	0	0	0		0	2	2
DHS	0	0	1	0		0	0	1
TOTAL	234	228	241	71		148	82	1054

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 (CBANs)
- Collaboration with the NSTC Working Group on Manufacturing R&D

After 4 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 4 years of NNI:

New R&D potential targets for 2015 (2)

2004 **2015**

Nano-materials/devices/systems: ½ from molecular level

Pharmaceuticals synthesis and delivery: ½ based on nano

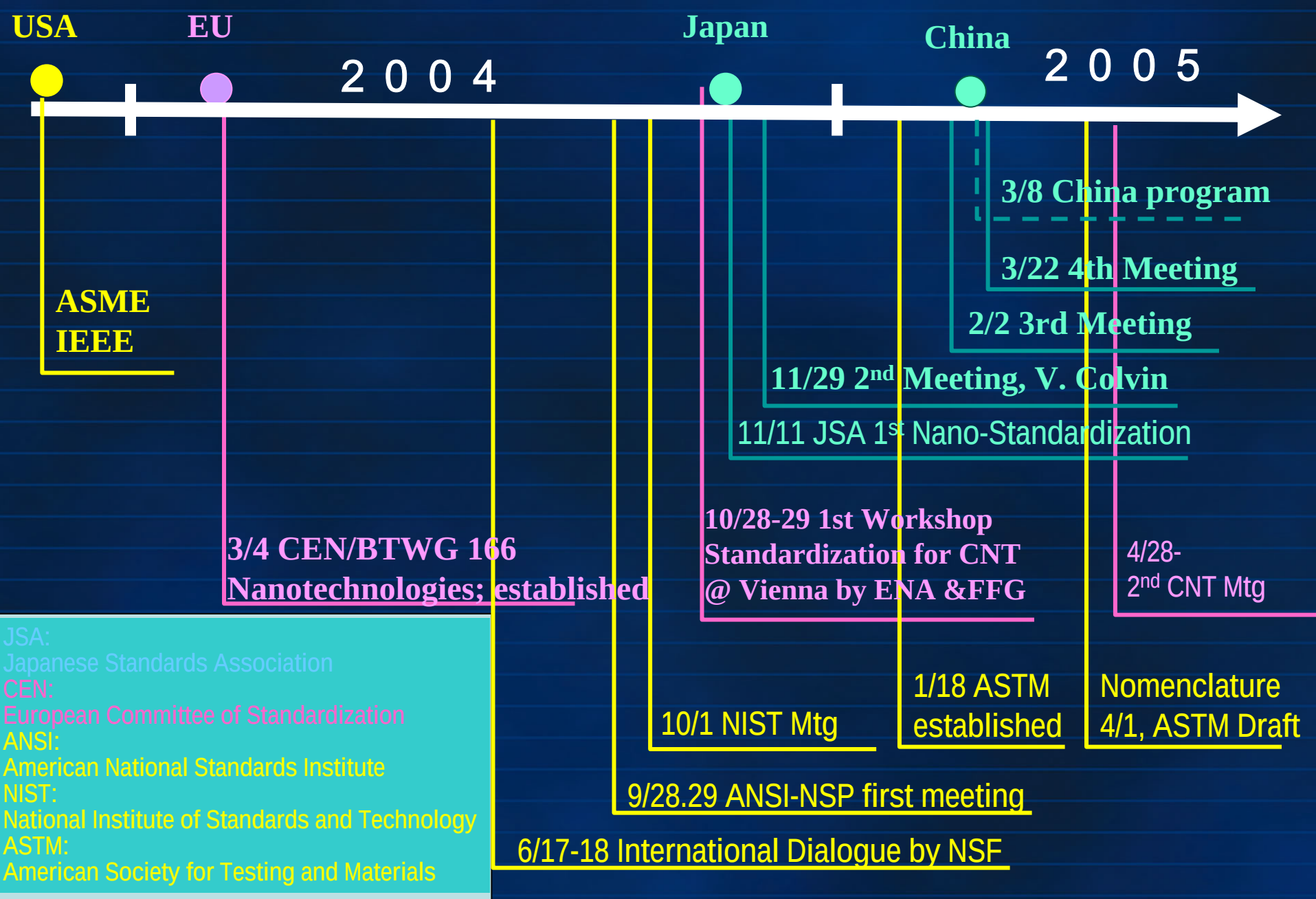
Converging technologies from the nanoscale

Including: artificial organs, manufacturing multidisciplinary platforms, etc.

Life-cycle biocompatible/sustainable development

Education: nanoscale instead of microscale-based

Global nanotechnology standardization



Timeline for beginning of nanotechnology commercialization:

Perceived higher risks areas

1st: Passive nanostructures Ex: Cosmetics (pre-market tests), Pharmaceuticals (incomplete tests for inflamatory 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

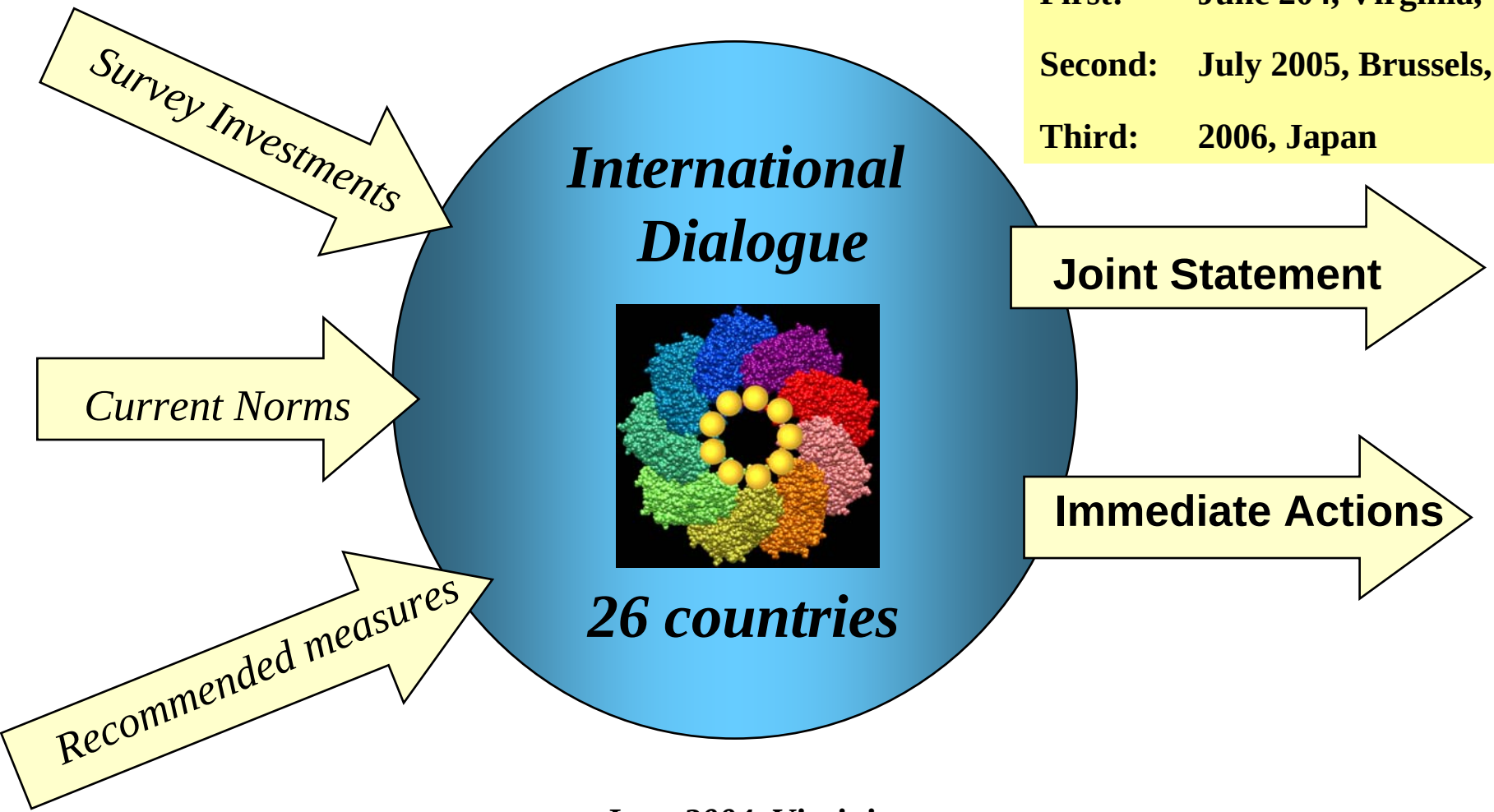
~ 2015-2020

R&D

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

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

MC. Roco, 8/22/05

Transforming and Responsible development of nanotechnology

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

There is a need for an anticipatory and corrective approach in

- **planning: be transforming, responsible, visionary**
- **supporting: infrastructure, tools, education, innovation**
- **addressing societal implications for each major R&D program or project from the beginning**
- **global risk governance of converging technologies**

Appendix (1): Reports from NNI Conferences/workshops

Regional workshops of NNI

"Nanotechnology: Opportunities and Challenges"
South-west region; host UCLS, September 2001, wtec.org/nanoreports/FinalUCLAnanoRpt0302.pdf

"From the Laboratory to New Commercial Frontiers"
South-east regional; host Rice University, May 2002, wtec.org/nanoreports/ACF64.pdf

Grand Challenge (topical) workshops

"Nanotechnology Innovation for Chemical, Biological, Radiological, and Explosive Detection and Protection"
May 2002, www.wtec.org/nanoreports/cbre/

"Chemical Industry R&D Roadmap for Nanomaterials By Design: From Fundamentals to Function"
October 2002 Vision 2020/NNI Grand Challenge Workshop, www.chemicalvision2020.org/nanomaterialsroadmap.html

Buildings for Advanced Technology Workshop, at NIST, Jan 14-16, 2003; www.nanobuildings.com/bat/overview/default.htm

Appendix (2): Other Grand Challenge (topical) workshops

NNI Grand Challenge (GC) Workshop on Nanomaterials, at NSF, June 11-13, 2003

NNI GC Workshop: Nanoscale Processes for Environmental Improvement, at NSF, May 8-10, 2003.

Interagency Grantees Meeting on Nanotechnology and the Environment: Applications and Implications, at NSF, September 15-16, 2003. es.epa.gov/ncer/publications/nano/index.html

NNI Workshop on NanoBiotechnology, Arlington, VA, Oct. 9-11, 2003

NNI Workshop on Societal Implications of Nanoscience and Nanotechnology, at NSF, Dec. 3-5, 2003

NNI GC Workshop on Instrumentation and Metrology for Nanotechnology, at NIST, Jan. 27-29, 2004

NNI GC Workshop on Nano-electronics, -photonics, and -magnetics, Arlington, VA, Feb. 11-13, 2004

NNI GC Workshop on Nanoscience Research for Energy Needs, Alexandria, VA, March 16-18, 2004

Appendix (3): Other Reports on Nanotechnology Sponsored by NNI Agencies, 2000 to Present

Nanoscience and Nanotechnology: Shaping Biomedical Research, Bioengineering Consortium, BECON, report from the June 2000 BECON workshop. www.becon.nih.gov/nanotechsympreport.pdf

***NNI: The Initiative and its Implementation Plan*.** National Science and Technology Council (NSTC), Committee on Technology, Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), July 2000. www.nsf.gov/home/crssprgm/nano/nni2.pdf

Societal Implications of Nanoscience and Nanotechnology. NSF Report, March 2001. www.wtec.org/loyola/nano/societalimpact/; also available in hardcover from Kluwer Academic Publishers, 2001

***WTEC Panel Report on Tissue Engineering,* WTEC, Inc., January 2002. Sponsored by NSF, NIH, DARPA, NIST, and FDA; www.wtec.org/loyola/te/final/; also Academic Press**

***Theory and Modeling in Nanoscience*.** Report of the May 10–11, 2002, Workshop BES/DOE www.sc.doe.gov/bes/Theory_and_Modeling_in_Nanoscience.pdf

Appendix (4): Other Reports on Nanotechnology Sponsored by NNI Agencies, 2000 to Present

Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science. June 2002, NSF/DOC-sponsored report. www.wtec.org/ConvergingTechnologies/; also Kluwer, 2003

***Report of the Nanogeoscience Workshop*, Berkeley, CA, June 14-16, 2002,** Sponsored by NSF. http://www.nsf.gov/home/crssprgm/nano/geo_workshop.pdf

***Nanotechnology and the Environment: Applications and Implications*. EPA Nanotechnology Grantees Workshop,** August 29, 2002. www.nsf.gov/home/crssprgm/nano/GC_ENV_EPA2002_Proc_03-0204.pdf

***Research Directions and Nanoscale Science Research Centers*, DOE/BES, February 2003,** www.sc.doe.gov/bes/NSET_NSRC_brochure_FEB03.pdf

***Nanoscale Science and Engineering for Agriculture and Food Systems*. Report from the National Planning Workshop, Washington, DC, Nov. 18-19, 2002.** www.nseafs.cornell.edu/web.roadmap.pdf

***Emerging Issues in Nanoparticle Aerosol Science and Technology*, National Science Foundation Report, January 2004.** www.nano.gov/html/res/NSFAerosolParteport.pdf

Appendix (5): Other Reports on Nanotechnology Sponsored by NNI Agencies, 2000 to Present

- ***National Nanotechnology Initiative; R&D Supporting the Next Industrial Revolution:*** *Supplement to the President's FY 2004 Budget*, National Science and Technology Council (NSTC), Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology (NSET), Oct. 2003. www.nano.gov/html/res/nni04_budget_supplement.pdf
- ***Small Wonders, Endless Frontiers: Review of the National Nanotechnology Initiative*. NRC, June 2002.** www.nano.gov/html/res/smallwonder.html

Updates information on :

www.nano.gov

www.nsf.gov/nano