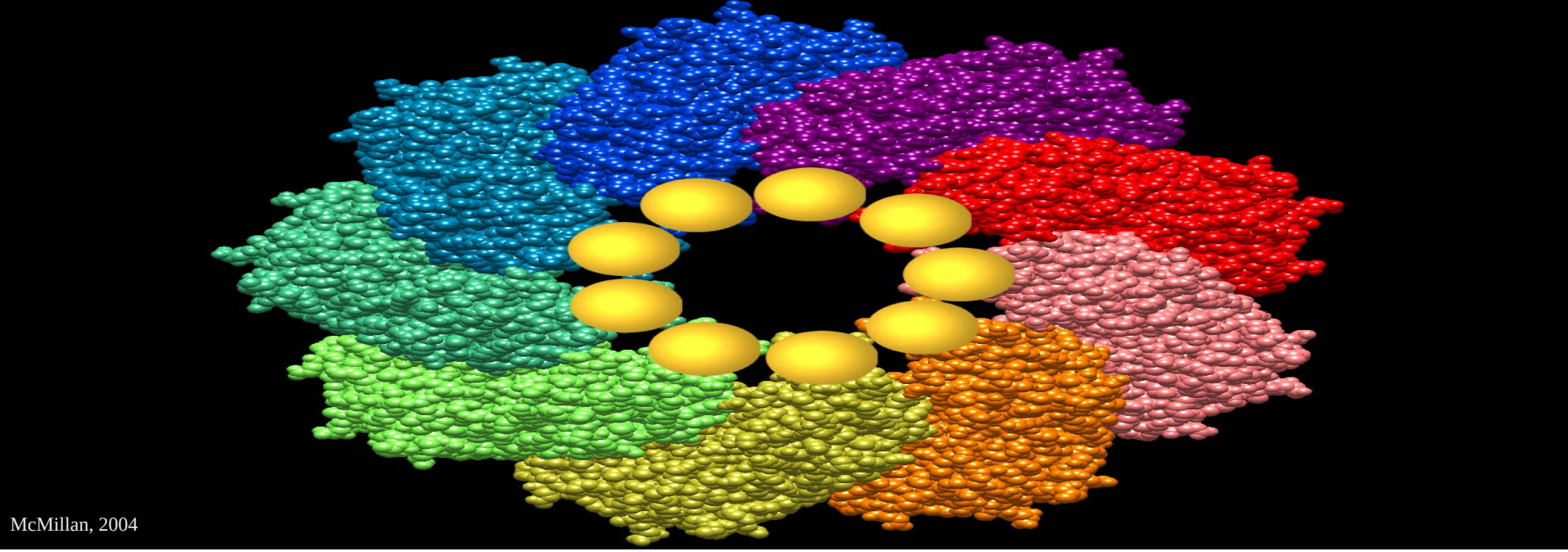


The Challenge of Transforming and Responsible Nanotechnology

Dr. M.C. Roco

U.S. Nanoscale Science, Engineering and Technology (NSET), NSTC
Senior Advisor for Nanotechnology, National Science Foundation
Presentation posted on **www.nsf.gov/nano**

iNEMI, Herndon, September 16, 2005

Topics

- **Nanotechnology - transforming outcomes for economy, quality of life, education (first NNI strategic plan: 2001-2005)**

- **New frontiers for nanotechnology in 2005 (second NNI strategic plan)**

- **Societal implications: responsive to people needs and aspirations**

Nanotechnology

Definition on www.nano.gov/omb_nifty50.htm

- 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

- **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

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**

R&D towards the Next Industrial Revolution

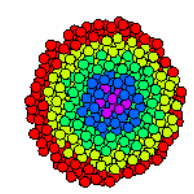
1999 metrics, 2004 check the progress, 2015 to satisfy first criteria

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)**

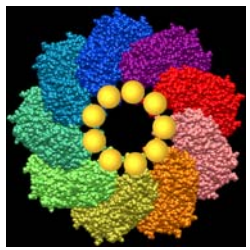
Defining Nanomanufacturing

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



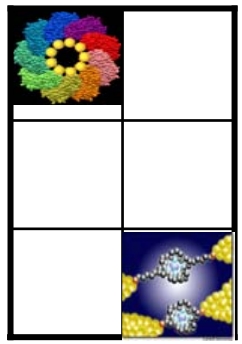
Assembling

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



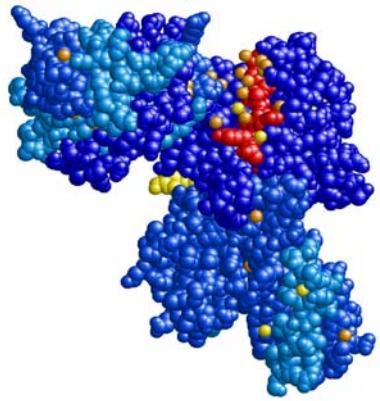
- Directed selfassembling,
- Templating, ..

- System engineering,
- Device architecture,
- Integration, ..



- Multiscale selfassembling,
- In situ processing, ..

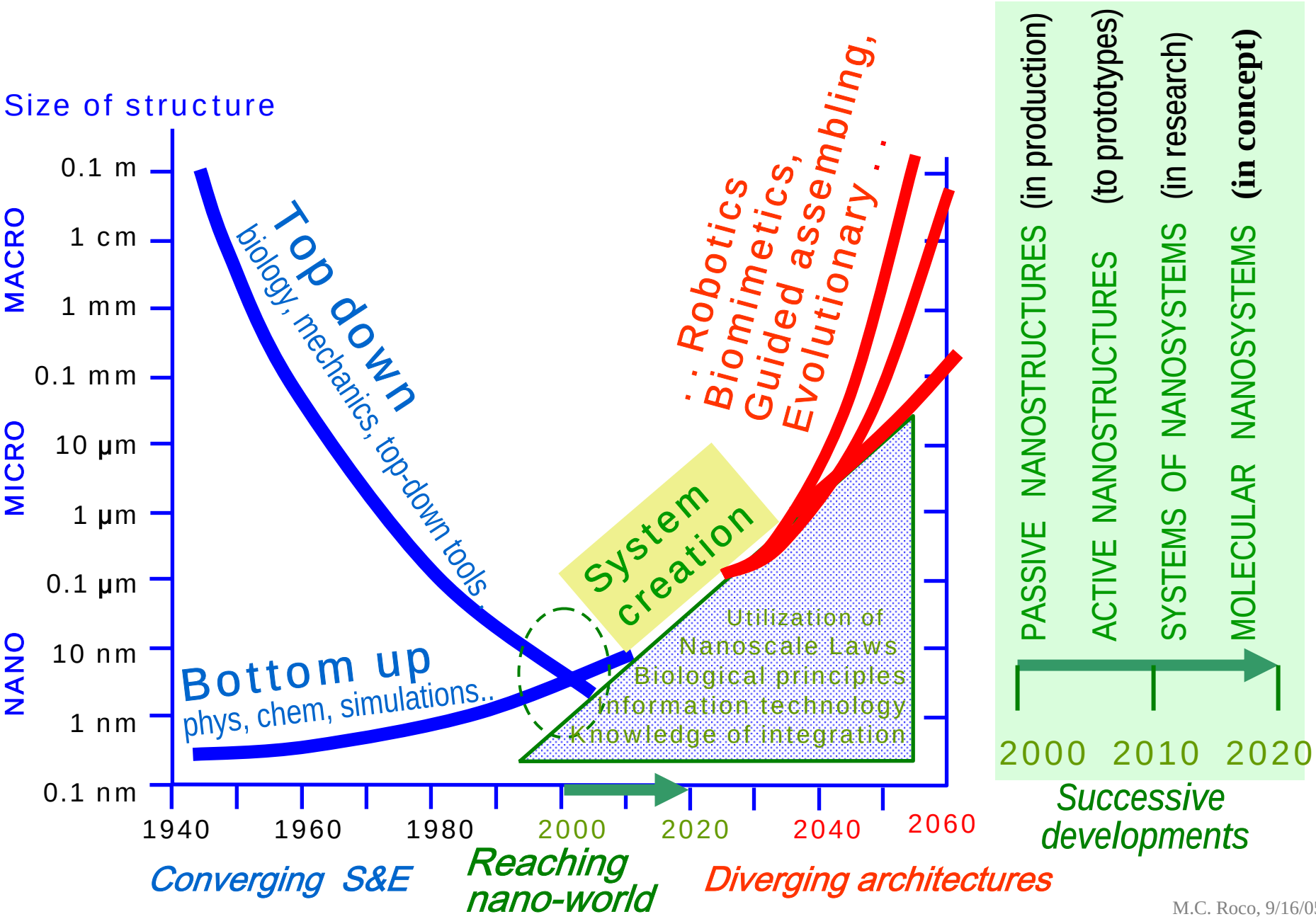
- Nanosystem biology,
- Emerging systems, ..



- Molecules as devices,
- Quantum control, ..

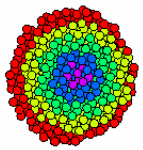
PASSIVE - ACTIVE - HETEROGENEOUS - MOLECULAR
NANOSTRUCTURES NANOSYSTEMS

Reaching nano-world and system creation



M.C. Roco, 9/16/05

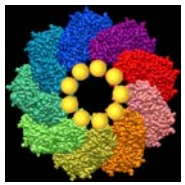
Timeline for beginning of industrial prototyping and nanotechnology commercialization: Four Generations



1st: Passive nanostructures (1st generation products)

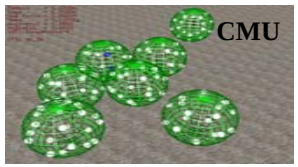
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2000



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

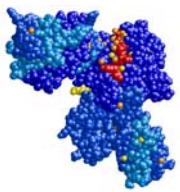
~ 2005



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

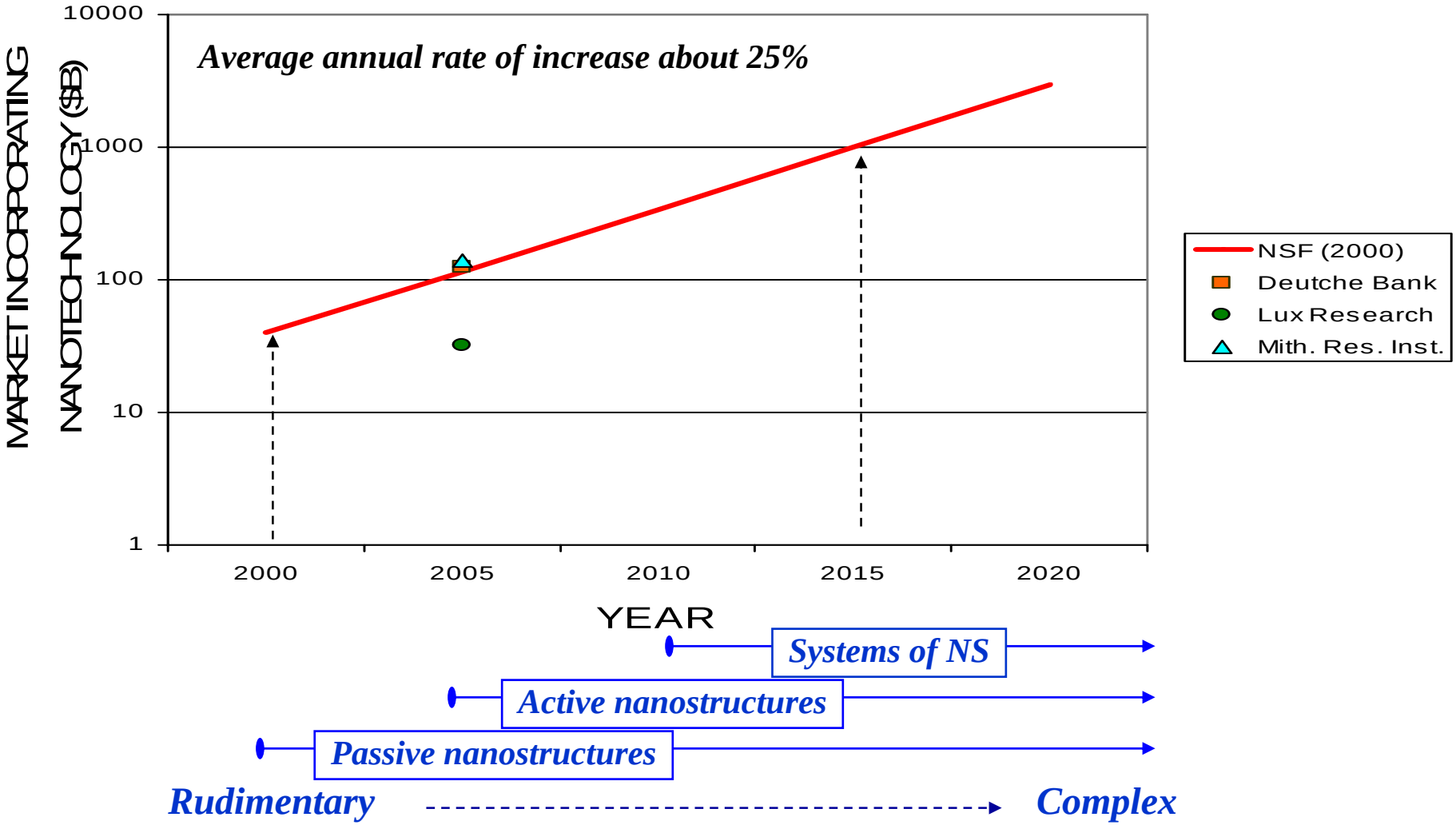
~ 2015-2020

New R&D challenges

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

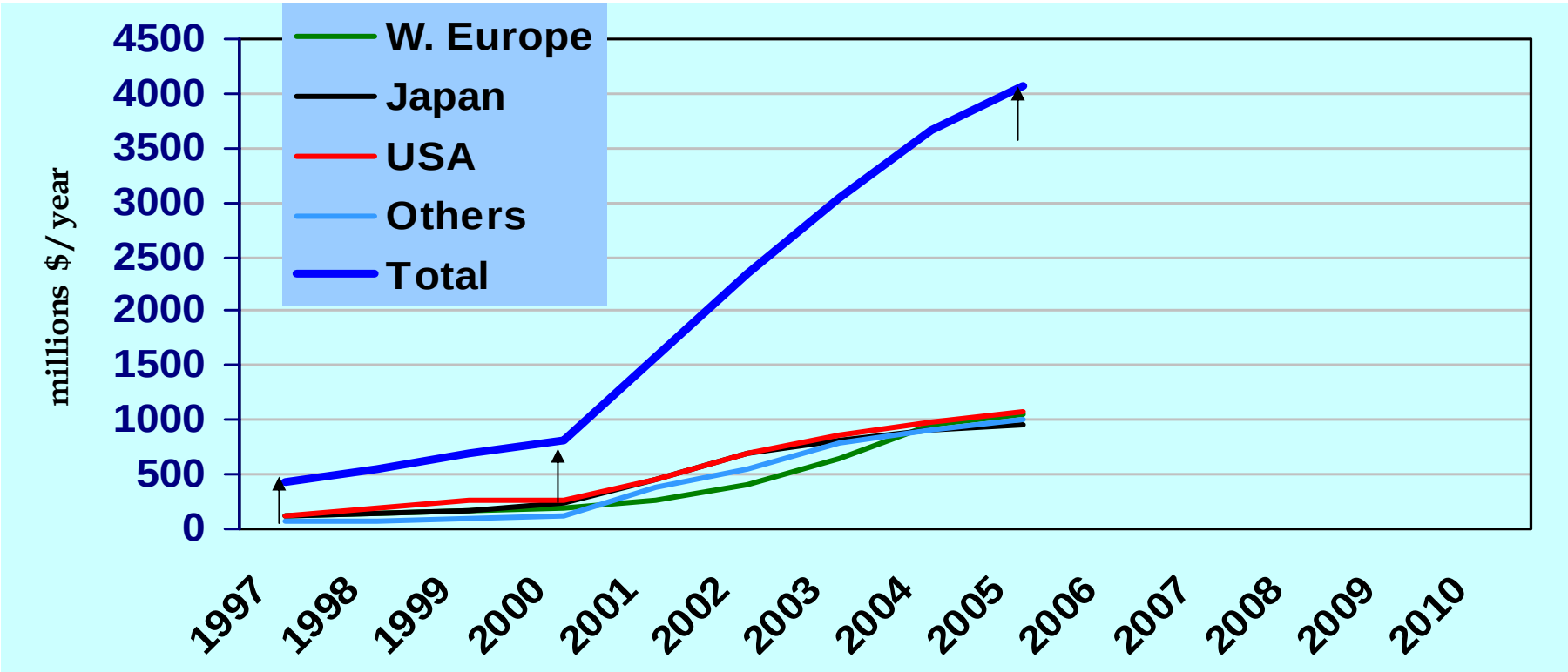
AIChE Journal, 2004, Vol. 50 (5), M. Roco

Worldwide market affected by nanotechnology. Estimation made in 2000



Context – Nanotechnology in the World

Past government investments 1997-2005 (est. NSF)



Seed funding (1991 -)

NNI Preparation (vision / benchmark)

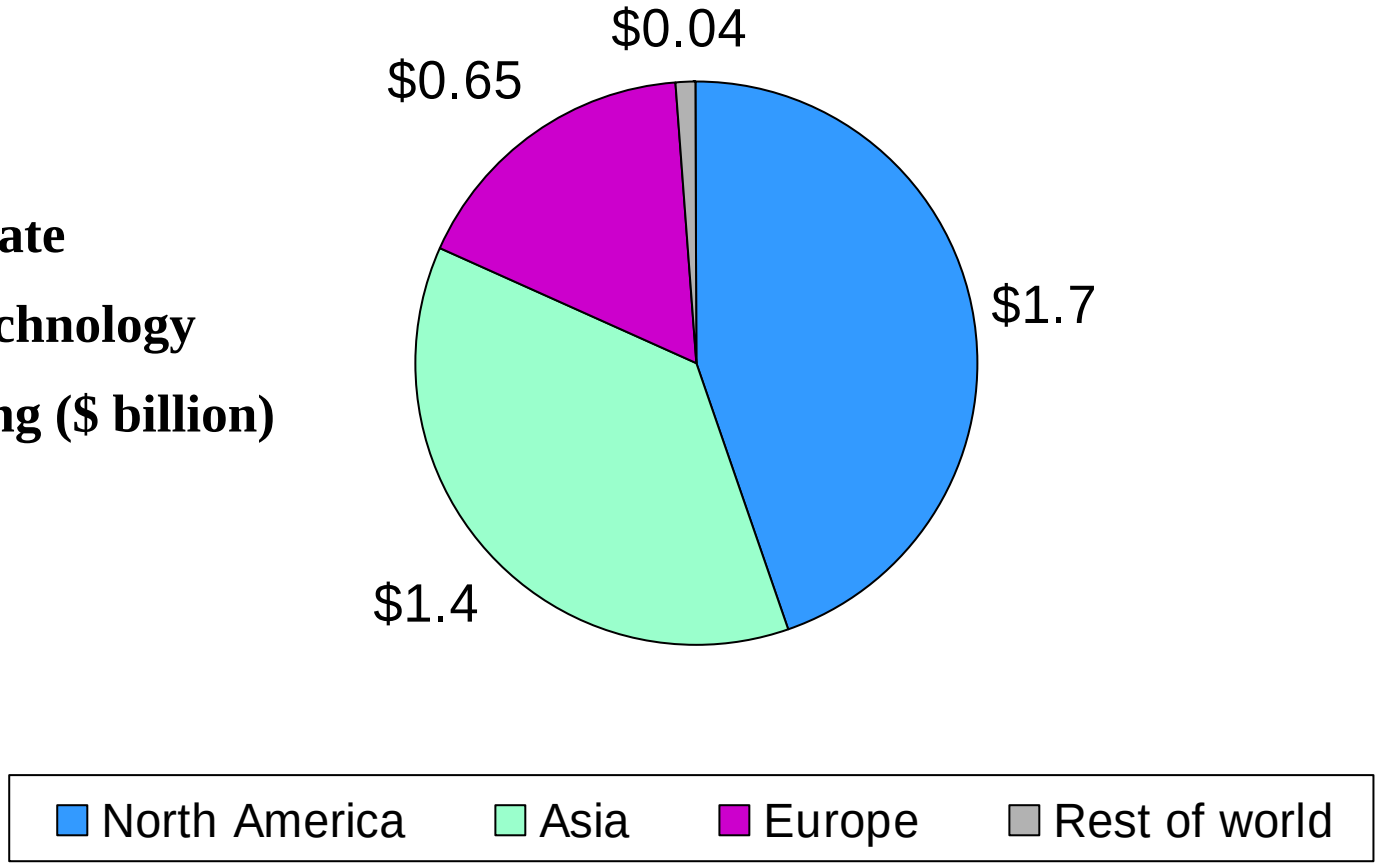
1st Strategic Plan (passive nanostructures)

2nd Strategic Plan (active nanostruct. & systems)

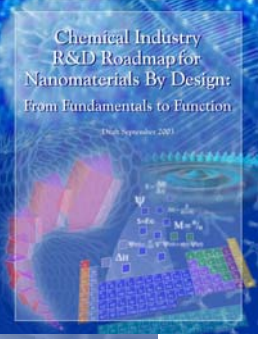
Total government expenditure in FY 2005 – about $4.1 billion

Established corporations will spend more than $3.8 billion globally on nanotechnology R&D in 2004

Corporate Nanotechnology Spending ($ billion)



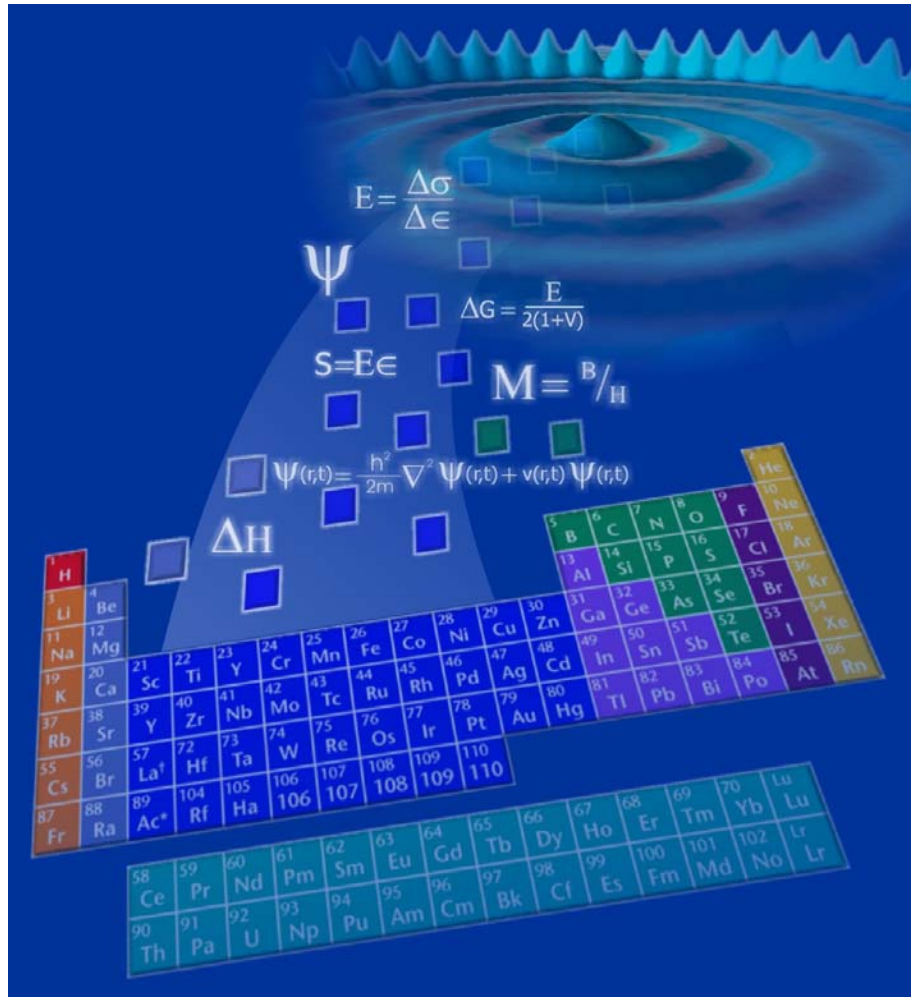
Source: Lux Research reference study “The Nanotech Report 2004;” based on published spending figures, national statistics, Lux Research analysis



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

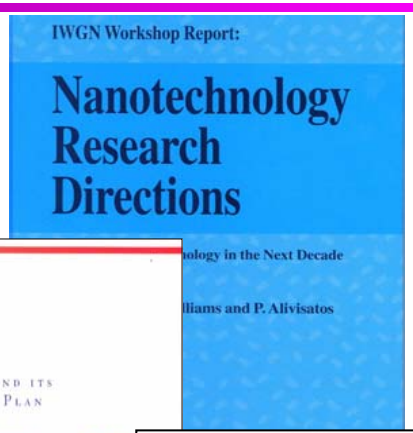


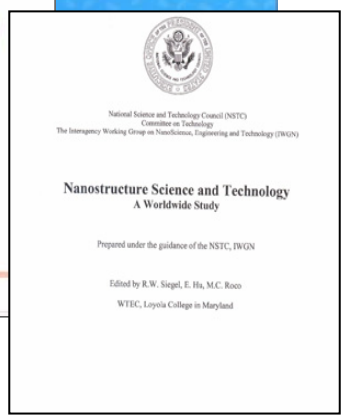
Defining the vision for the *first strategic plan (I)*

National Nanotechnology Initiative

1999-2000

1999:
10-year
vision

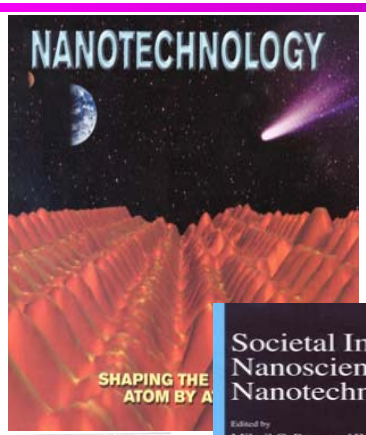




Government
plan

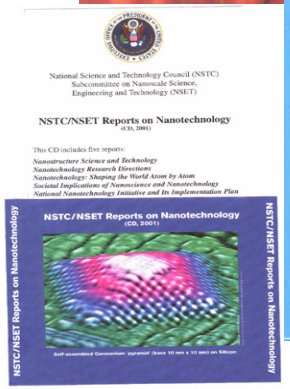
Reports

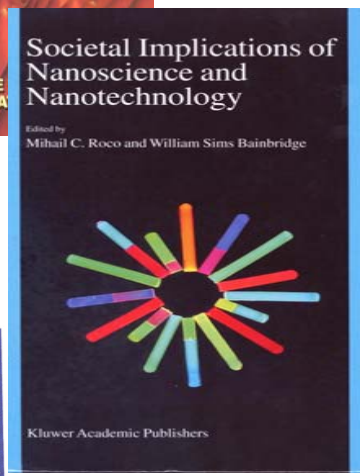
Worldwide
benchmark



Brochure for
public

Societal
implications





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

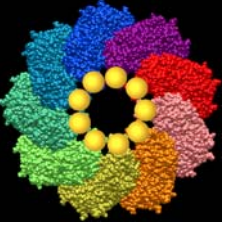
NATIONAL NANOTECHNOLOGY INITIATIVE

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 /1094	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



Accomplishments (1)

- Developed foundational knowledge for control of matter at the nanoscale: over 3000 active projects in > 500 universities, private sector institutions and gov. labs in all 50 states
- "Created an interdisciplinary nanotechnology community" [1]
- R&D / Innovation Results: With ~25% of global gov. investments, the U.S. accounts for
  - ~ 50% of highly cited papers,
  - ~ 60% of USPTO patents[2], and
  - ~ 60-70% of startups[3] in nanotechnology worldwide.
- Infrastructure:
  - 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), regional alliances in U.S. (22), international (over 25 countries), professional societies
- Societal implications and applications - from the beginning, about 10% of 2004 NNI
- Nanotechnology education and outreach - impacting 10,000 graduate students and teachers (2004); expanded to undergraduate and high schools, and outreach; from 5 universities (2000) to about 300 (2004); create national networks for formal and informal education.
- The U.S. NNI has catalyzed global activities in nanotechnology and served as a model for other programs.

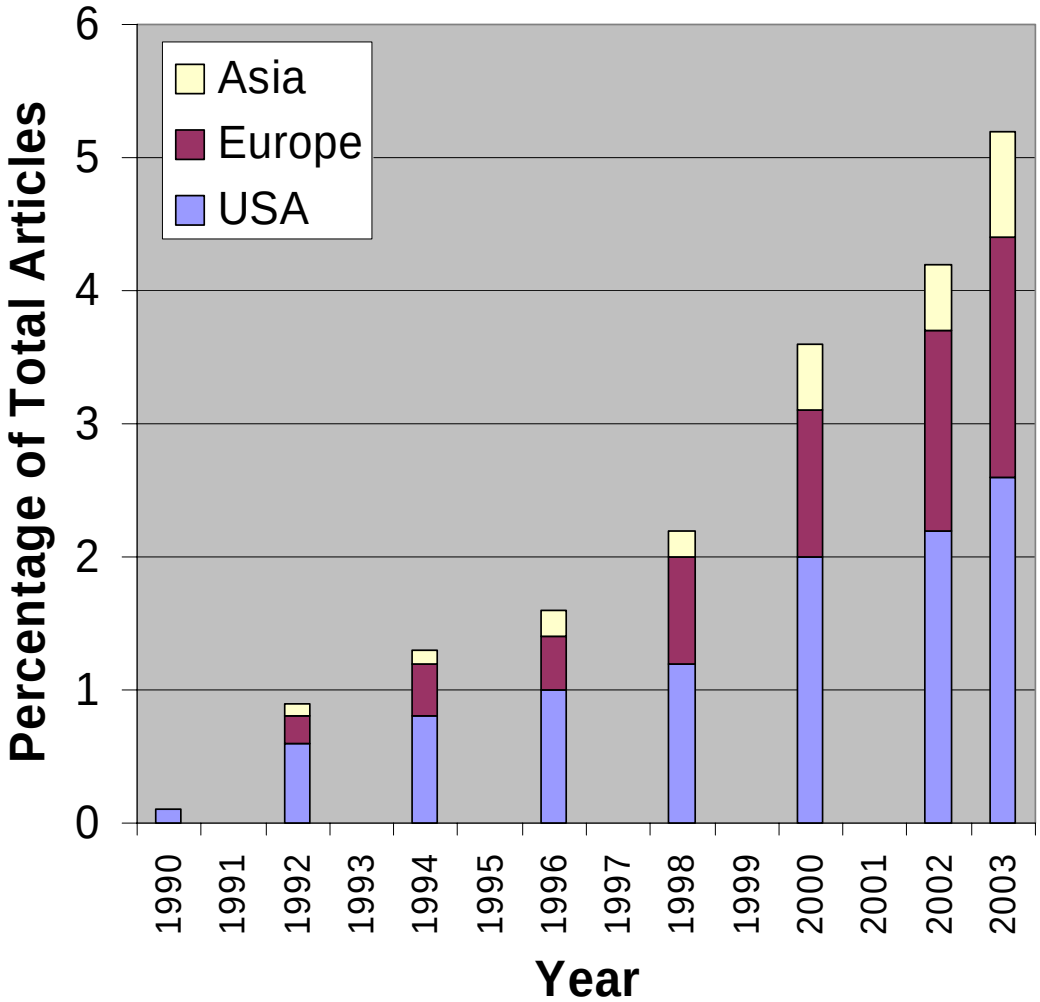
Exponential growth; About half of the highly cited papers in key journals originate in U.S.

("nano*" keyword search, after NNI Report, 2005)

Journal ISI with high Impact Factors (2001):

Nature	27.9
Science	23.3
Physics Review Letters	6.6

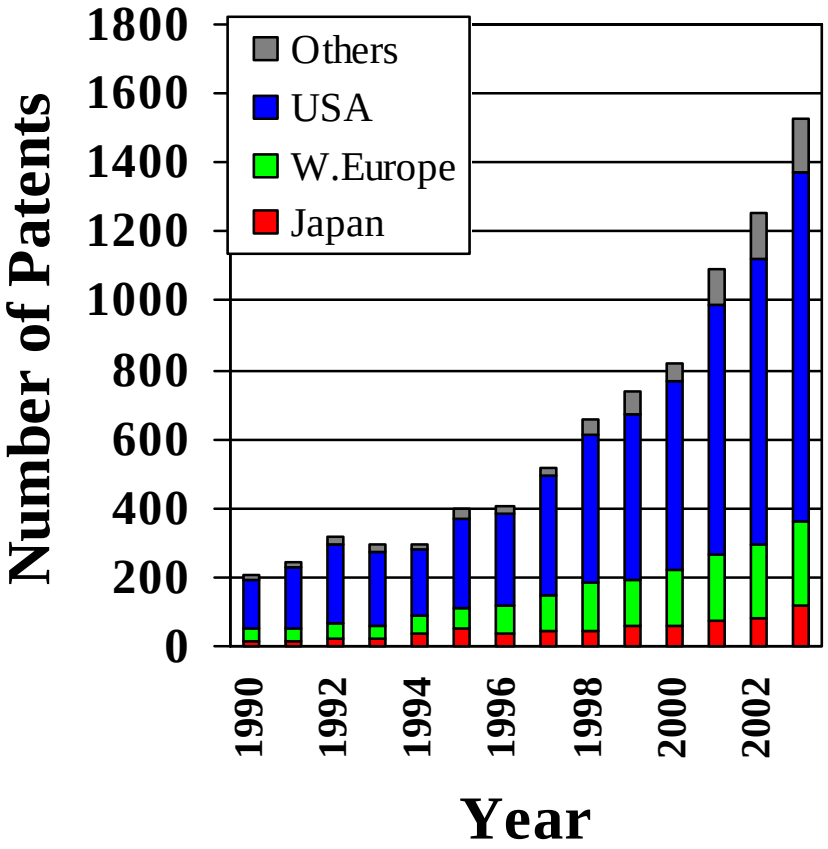
Correlates well with the overall papers with ISI high impact (UCLA study)



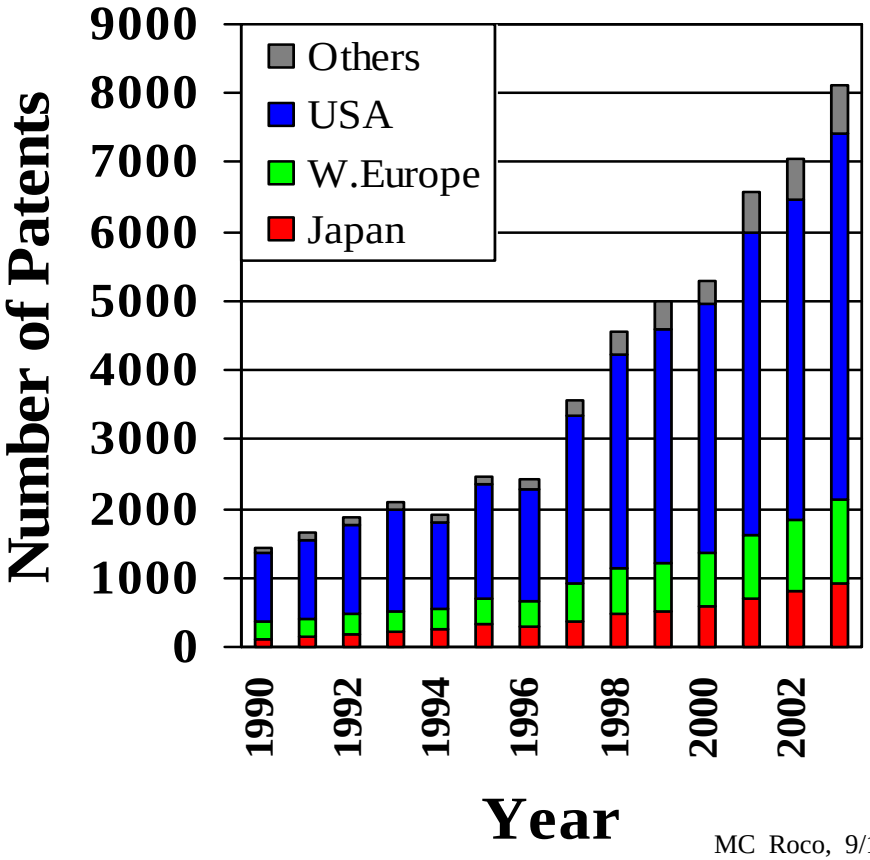
Exponential growth (USPTO database)

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

Using "Title-claims" search:
<u>nanotechnology claims</u>



Using "Full-text" search:
<u>nanotechnology claims,</u>
<u>or/and NSE tools and methods</u>



Defining the vision for the second strategic plan (II)

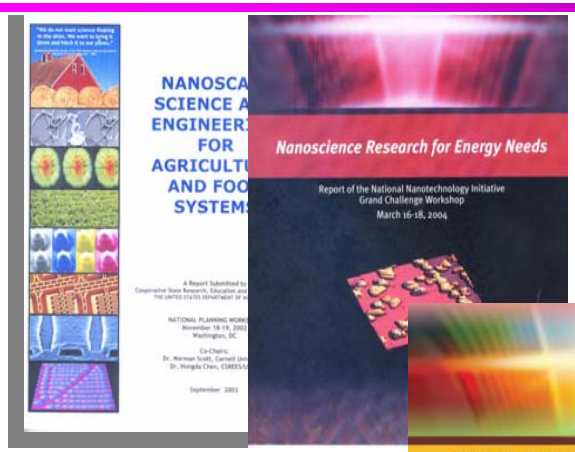
National Nanotechnology Initiative

2004

2004:
10-year
vision/plan

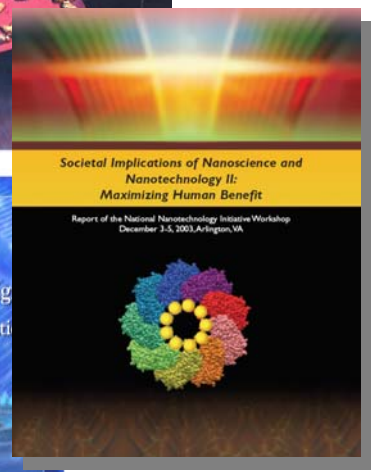
Government
Plan (annual)

Agriculture
and Food

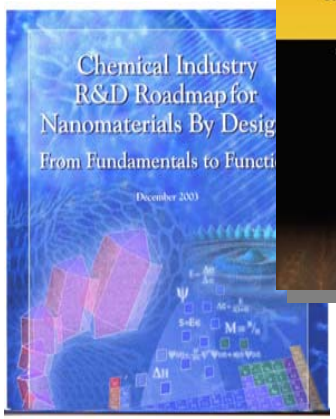


Energy

Societal
Implications
2004



Reports



Survey
manufacturing

Other topical reports
on www.nano.gov

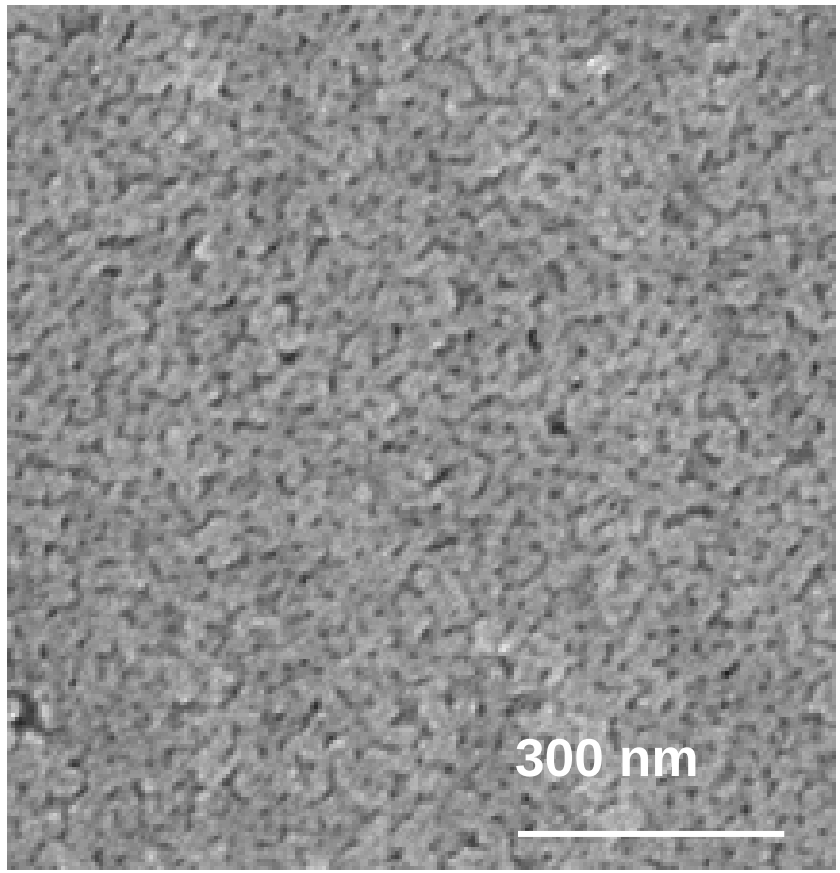
2004: <u>Update 10 year vision, and develop strategic plan</u>

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)*

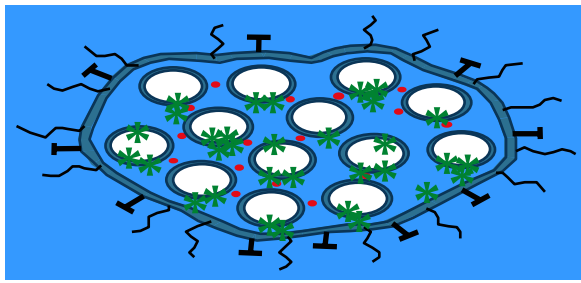
Example: Hypersonic plasma 20 nm particle deposition for hard coatings and patterning on surfaces (S. Girshick, University of Minnesota)



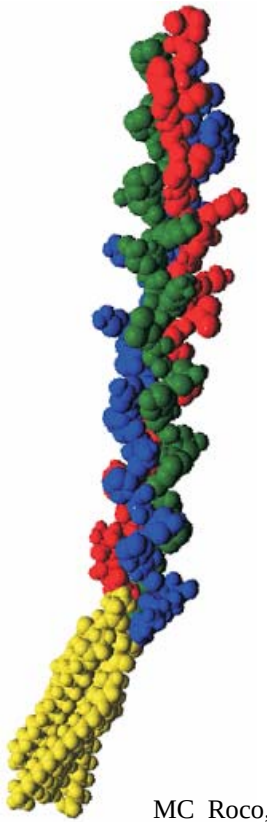
Example:

Synthesis and control of nanomachines

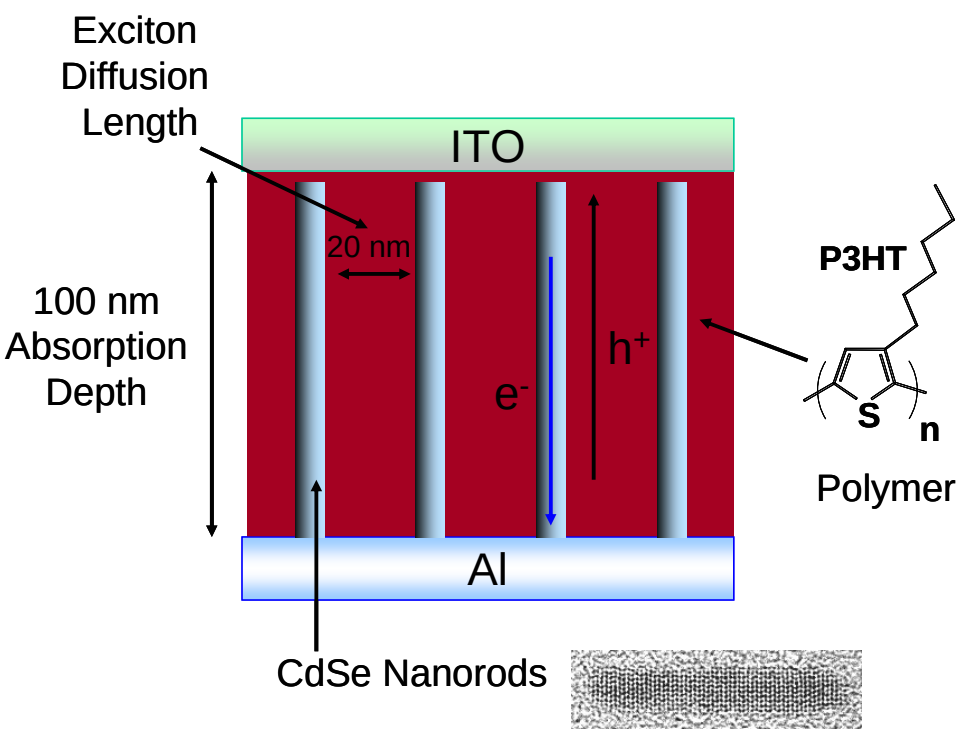
(examples NSE in 2004, www.nseresearch.org - 300 projects)



- **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 be activated by external electromagnetic fields (UCB)
- **Light driven molecular motors** (U. Nevada)
- **Combinatorial engineering of nanomachines**, with application to membranes and filters (U. Penn.)
- **Nanoengineering surfaces** for probing viral adhesion (UC Davis)



Energy: Schematic design of the nanorod-polymer solar cell

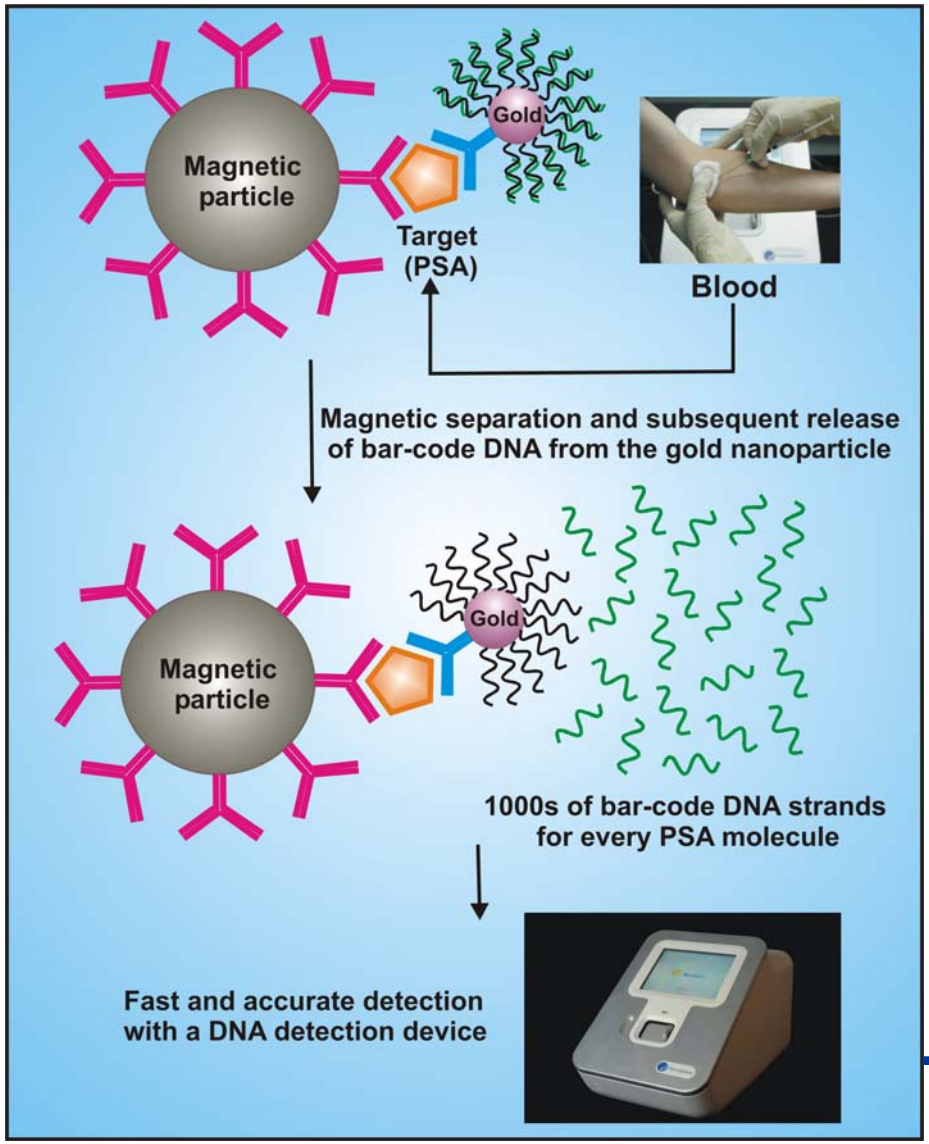


transmission electron micrograph
of a CdSe nanorod at the bottom

(courtesy P. Alivisatos, Univ. California, Berkeley; and Nanosys, Inc.).

Example: NanoBio-Bar-Code Assay,

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

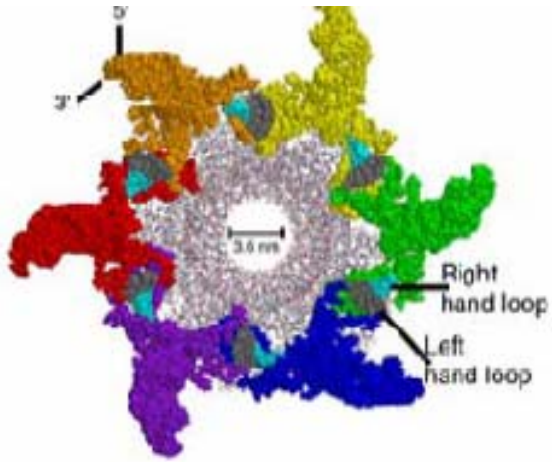


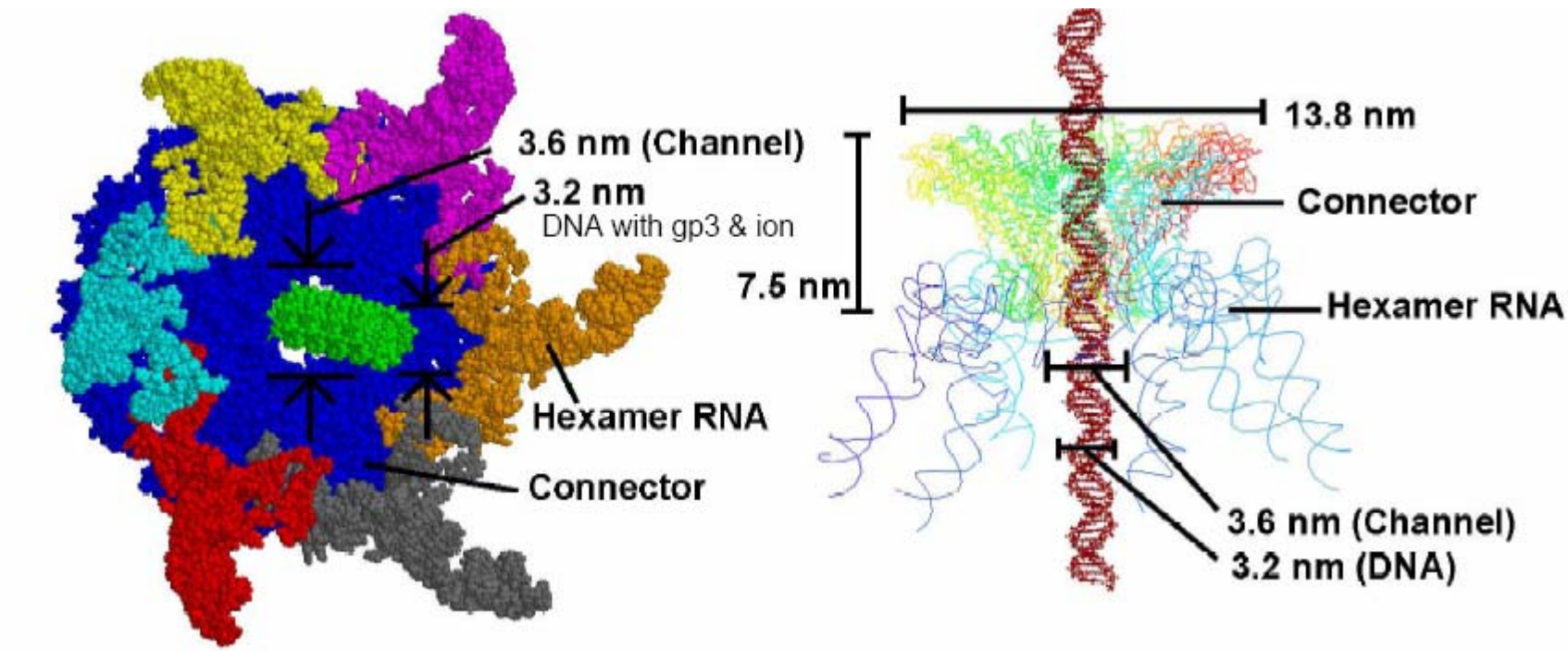
1. **One million times more sensitive than previous technology**
2. **Evaluate new biomarkers for diagnosing and following human diseases (e.g. HIV and Alzheimer's Disease).**
3. **Single-cell protein expression experiments.**
4. **In advance clinical testing**

Example:

Construction of a Viral Nanomotor Driven by a Synthetic RNA

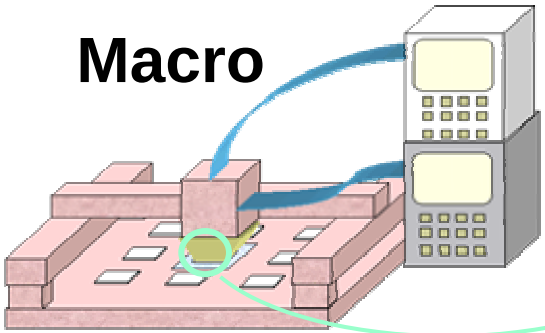
P. Guo, Molecular Virology,
Purdue University, 2004

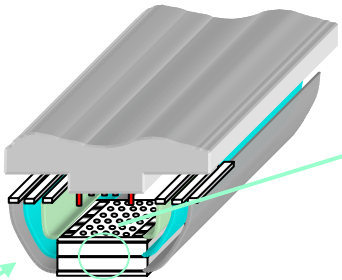




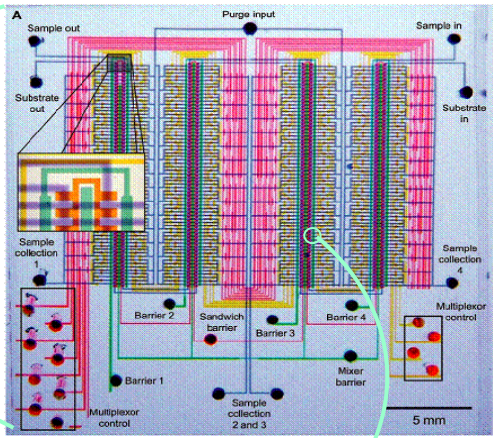
Example: Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems, UIUC, NCSU, Caltech

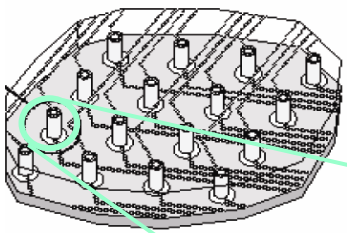
Macro

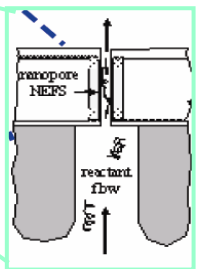




Micro







Nano

Goals - control of composition at nanoscale

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

Research Thrusts

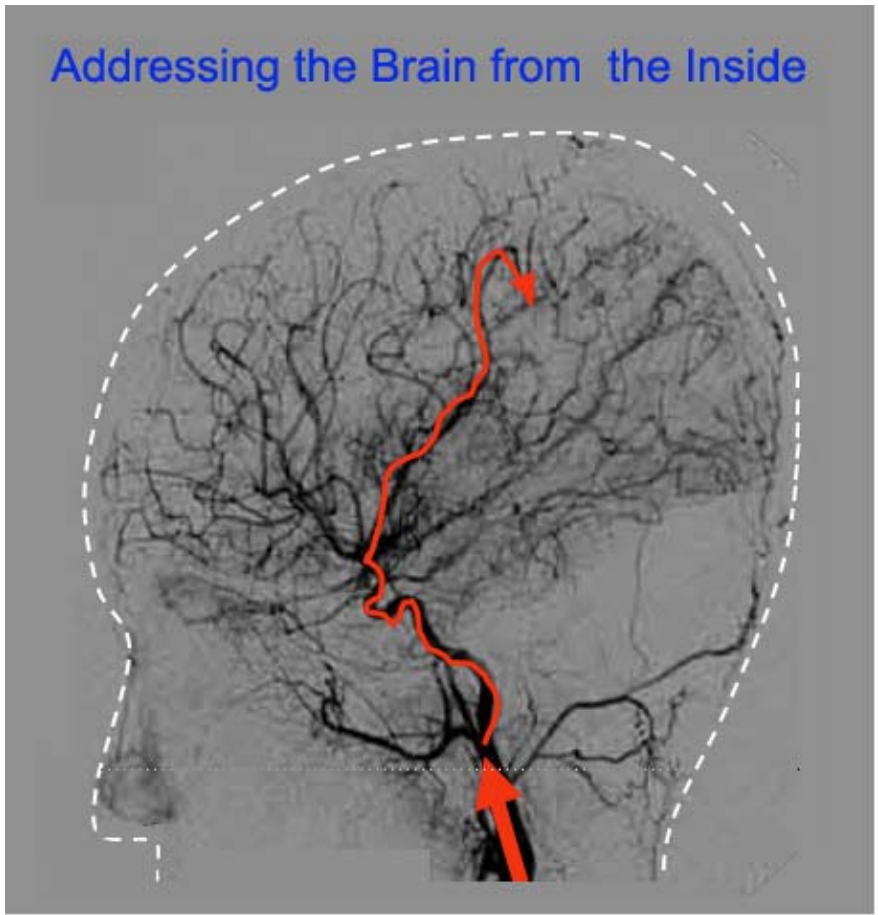
Micro-Nano Fluidic Network Toolbit

Process Sensing and Control

Manufacturing Systems

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

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



Nanostructured polymeric wires, biocompatible, biodegradable and with guidance

Several goals:

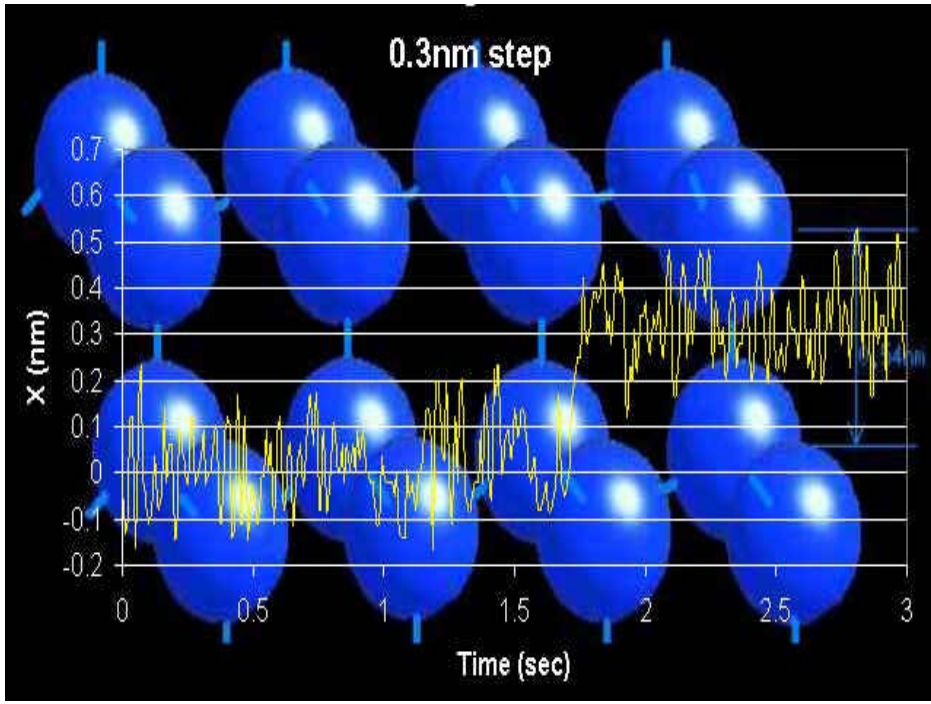
- neuro-to-neuron interaction
- simultaneous multiple probes for describing the system
- treatment Parkinson disease

Example:

Subnanometer resolution on a large domain

Specifications

- **0.1 nanometer resolution (or better)**
- **10.0 nanometer accuracy**
- **1 mm/sec maximum velocity**
- **NSOM, AFM or optical microscope probe**
- **Short term testing with confocal like microscope**



Eight - pass interferometer

NCSU, R. Hocken

Domain

•25 mm x 25 mm lateral travel

•100 micrometers vertical travel

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.

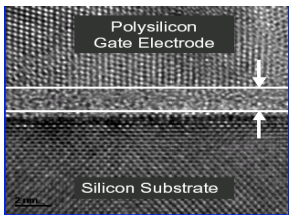
Life-cycle biocompatible/sustainable development

Education: nanoscale instead of microscale-based

Challenge 2015: Transistor beyond/integrated CMOS under 10 nm

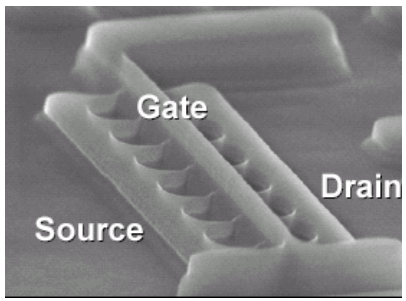
- In the 70s, 80s and 90s
  Geometrical scaling was the major driver

- 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

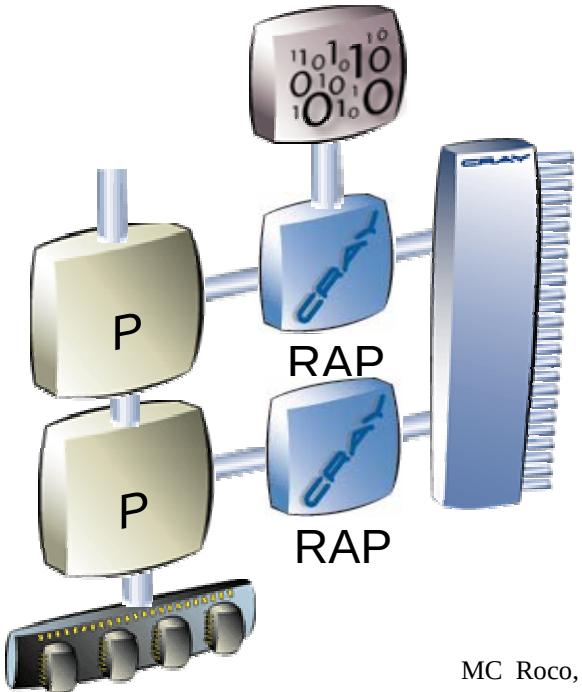
In addition, to explore beyond CMOS:

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

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

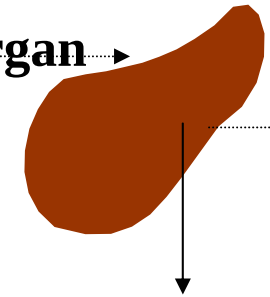
~ 2015 (Cray target):
10-100,000 TFLOPS

Examples of levels for intervention of nanobiotechnology

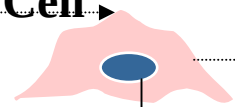
in human life extension

Human

Organ



Cell



Molecule

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

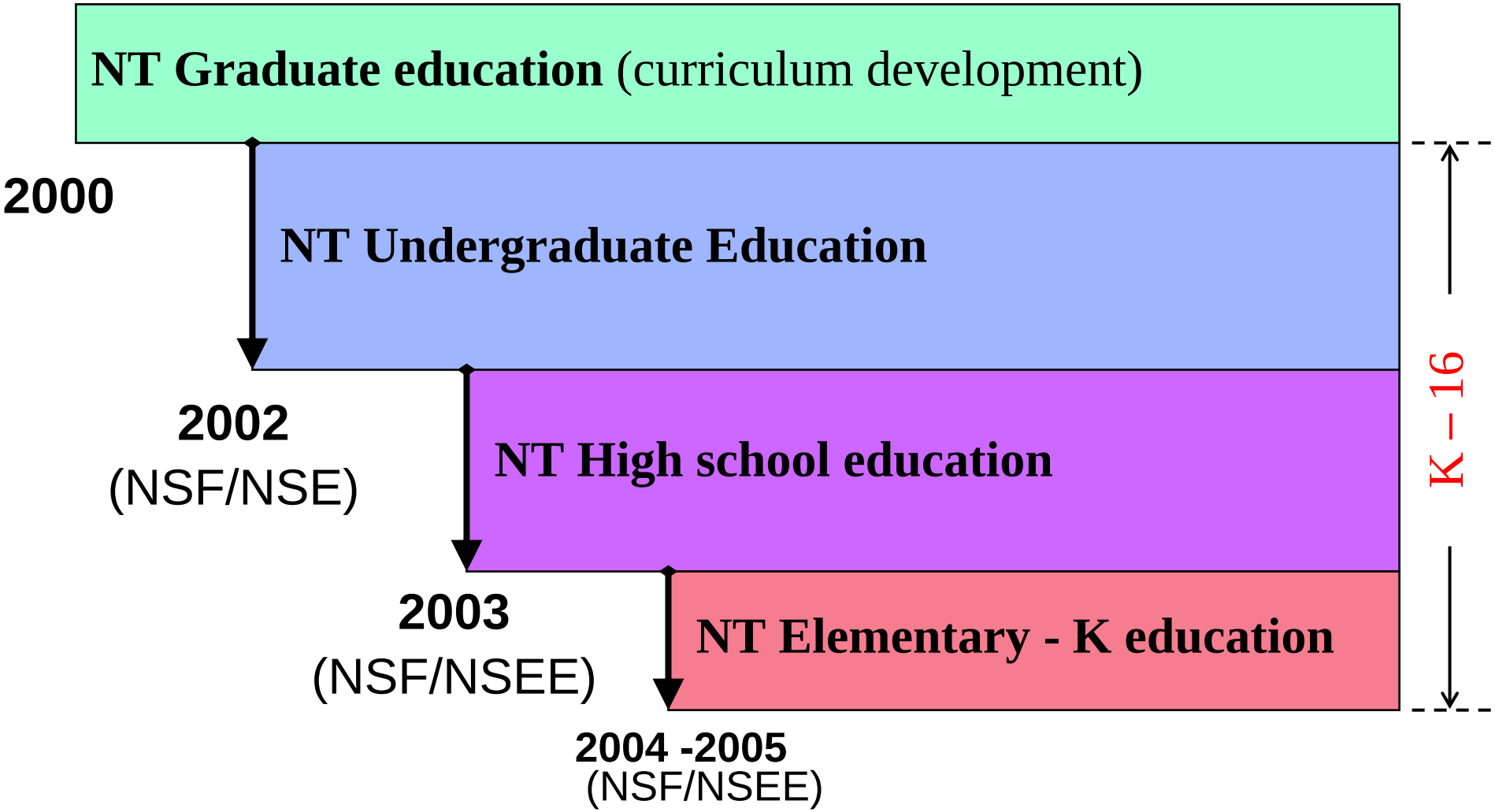
- Artificial organs
- Sensors for in vivo monitoring
- Localized drug delivery
- Neural stimulation
- Cardiac therapies

- Improved cell-material interactions
- Scaffolds for tissue eng.
- Genetic therapies
- Cell ageing
- Stem cell therapies

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

(NBIC Report, 2002)

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



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

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

2000

Nanobiotechnology, Cornell (STC)

Network for Computational Nanotechnology, Purdue (7)

Oklahoma Nano Net, OK

2001

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

Institute for Soldier Nanotechnology, MIT

Nanoscience Innovation for Defense, UCSB

Nanoscience Institute, NRL

2002

MRSECs on nanostructures

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

Institute for Nanoelectronics and Computing, Purdue

2003

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)

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

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

2005

Nanotechnology Labs, NIST at MA and CO

Nanotechnology Characterization Lab, NCI

NIOSH

Nanotechnology Center for Learning and Teaching, NU (10)

MC Roco, 9/16/05

NNI-Industry Consultative Boards for Advancing Nanotech

Key for development of nanotechnology, Reciprocal gains

- **NNI-Electronic Industry (SRC lead), October 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**

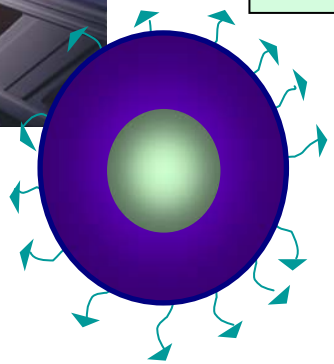
- **In developments: NNI - Pharmaceuticals (Phrma lead)**
  NNI - Automotive industry

Precompetitive Nanotechnology Platforms

- Synergistic development by using **same nanotechnology principles and transforming tools** for various applications
- **Integrate nanoscale knowledge with biotechnology**, **information technology and cognitive sciences** for new tools and treatment concepts
- Accelerate nanotechnology applications using a **"system approach"**
- Establish **multidisciplinary clusters**
- Develop **new mechanisms for information, communication and collaboration** between researchers, industry/hospitals and public

Aircraft Engines

Healthcare



Nanotechnology Platform

NanoTubes and NanoRods

NanoParticles

NanoCeramics

NanoStructured Metal Systems

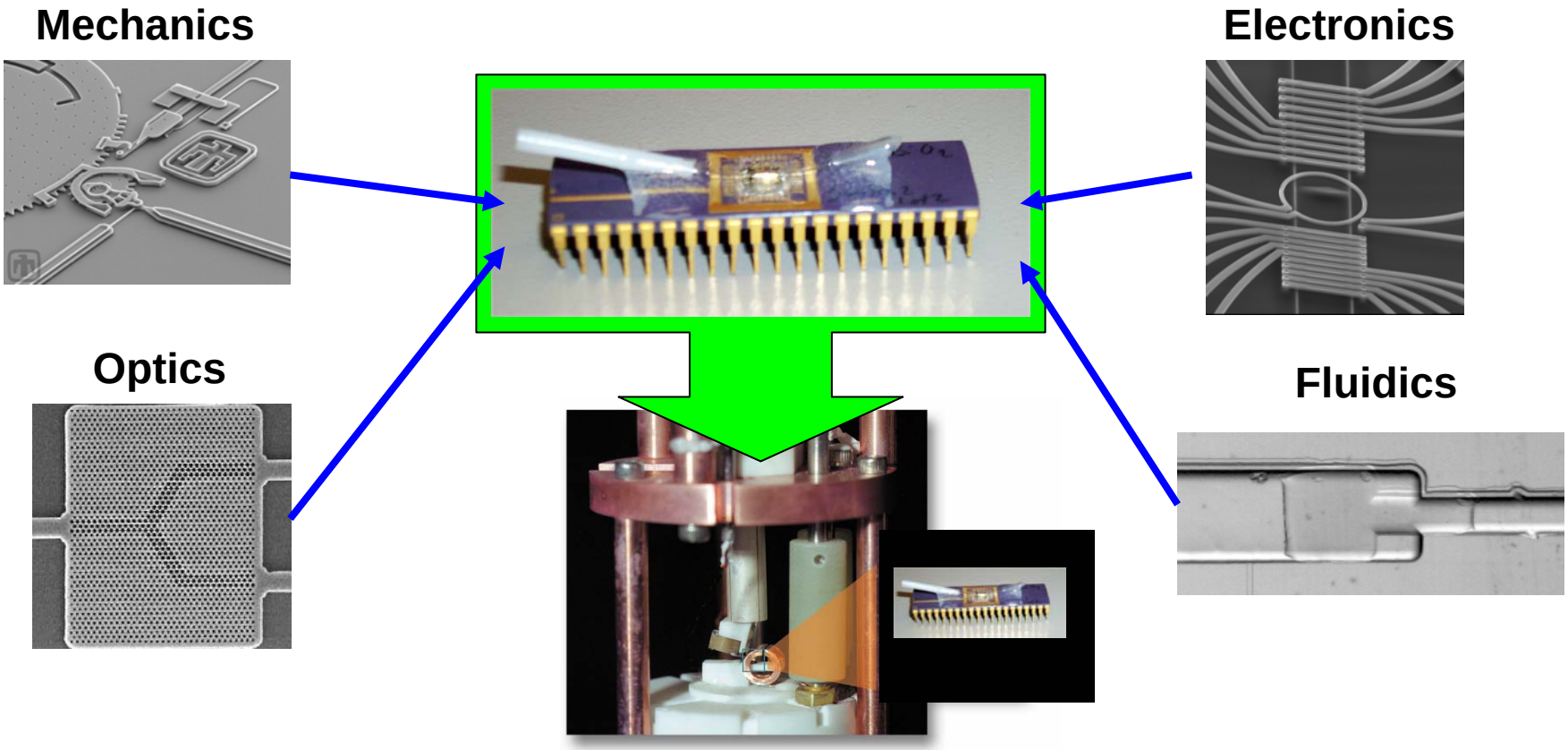
Hybrid Materials

Water

Energy

Nanotechnology at General Electric

CINT Discovery Platforms™: modular micro-labs for nanoscience

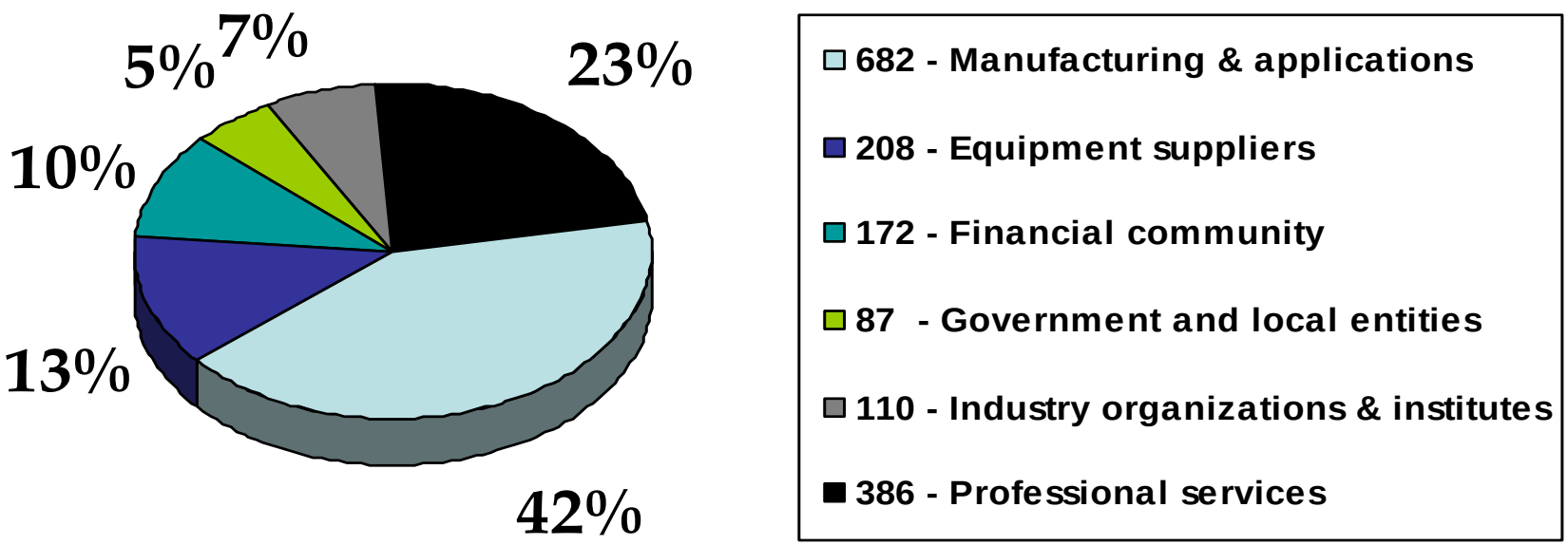


- Multiple in/out signals for stimulation, interrogation
- Standardized, rugged and robust
- “Pop-In” design for instrument compatibility, rapid exchange.
- Parallel architecture for statistics

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)



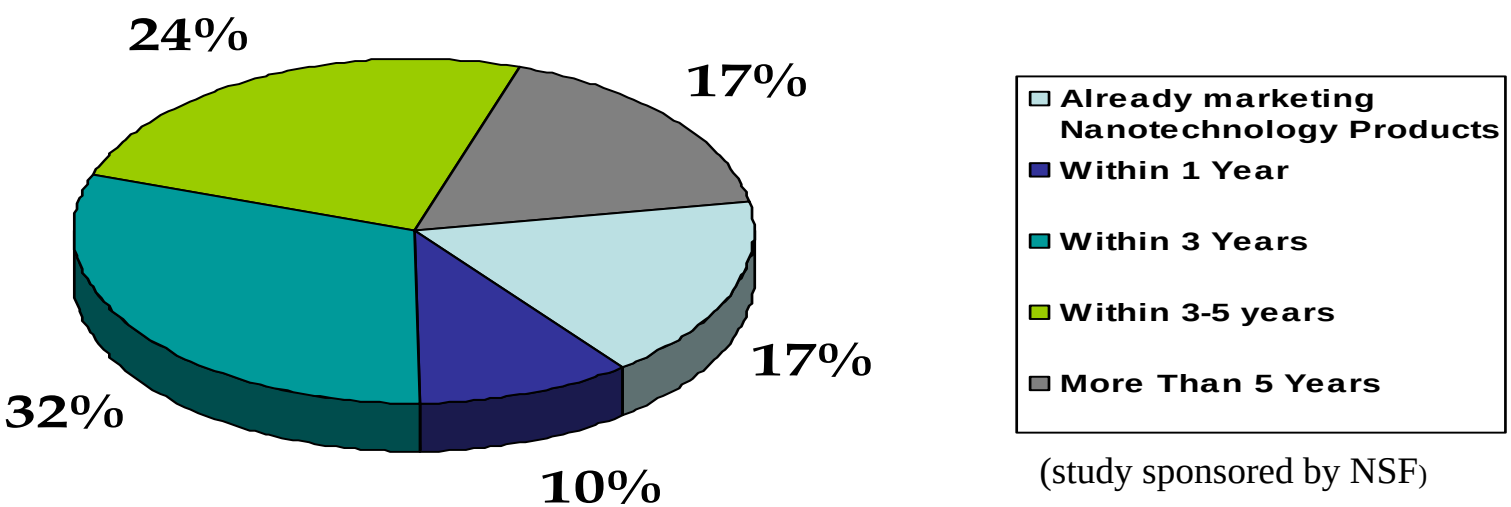
Industry surveys (2)

- 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)

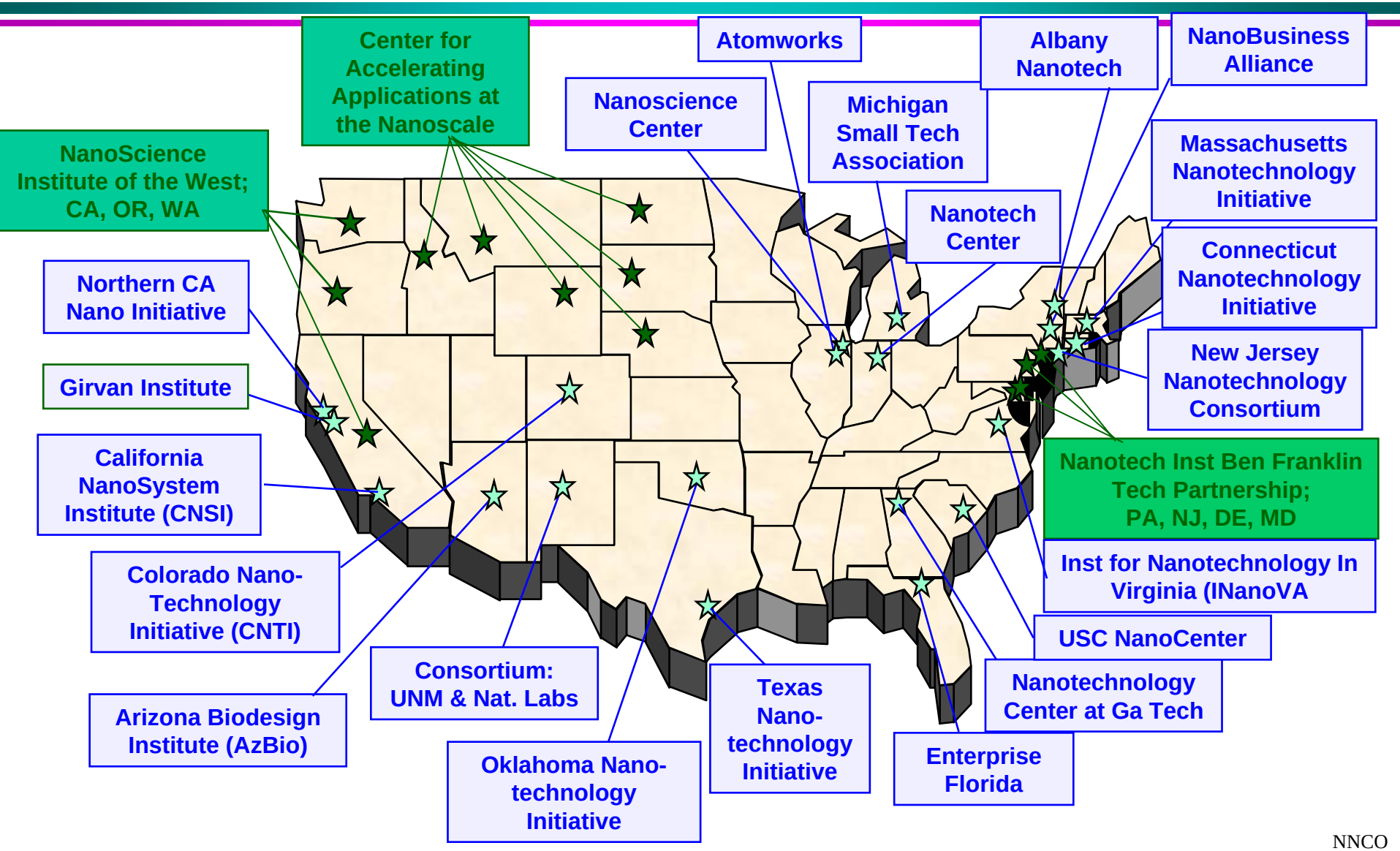
Survey by National Center for Manufacturing Sciences (2005):

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

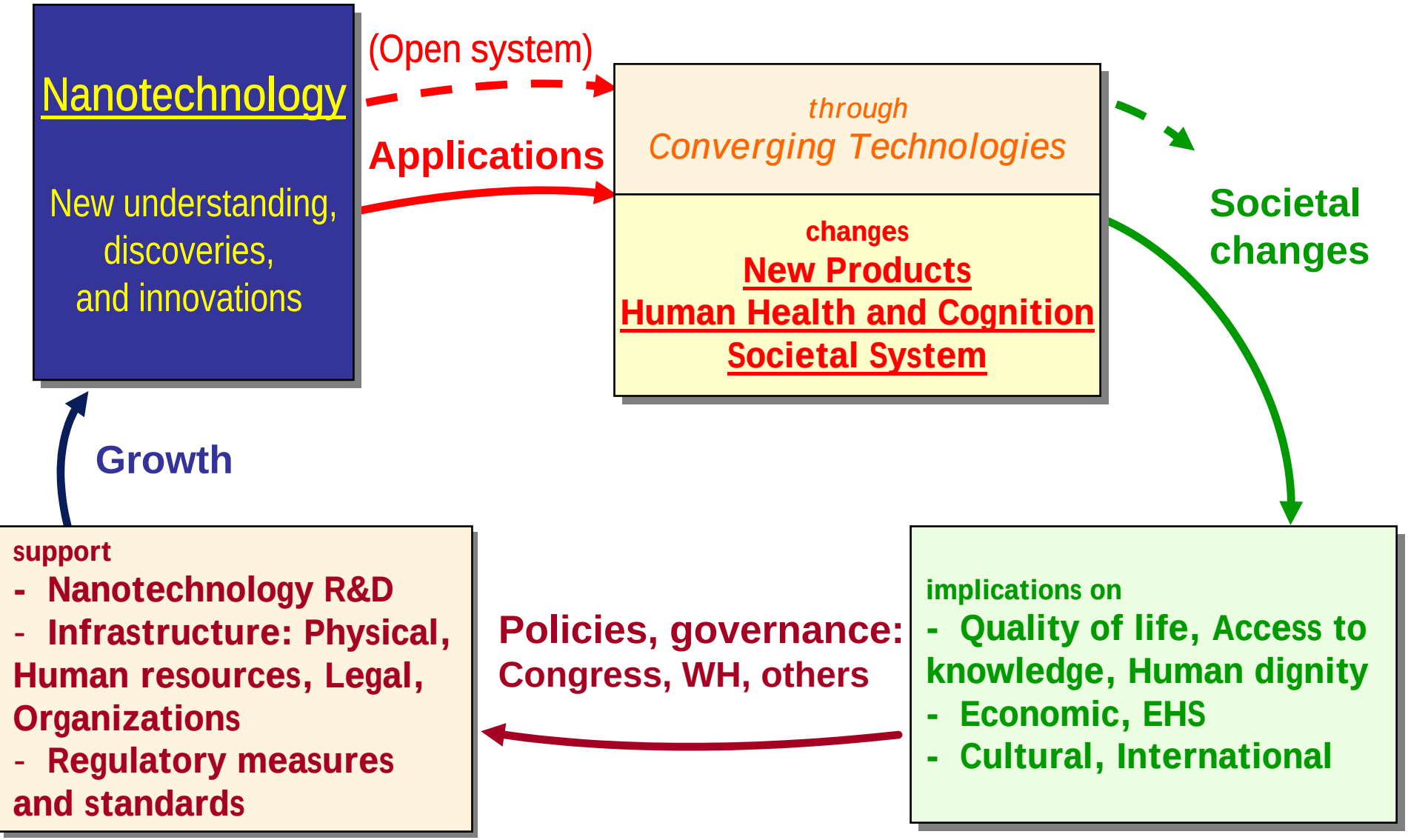


(study sponsored by NSF)

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



NNCO

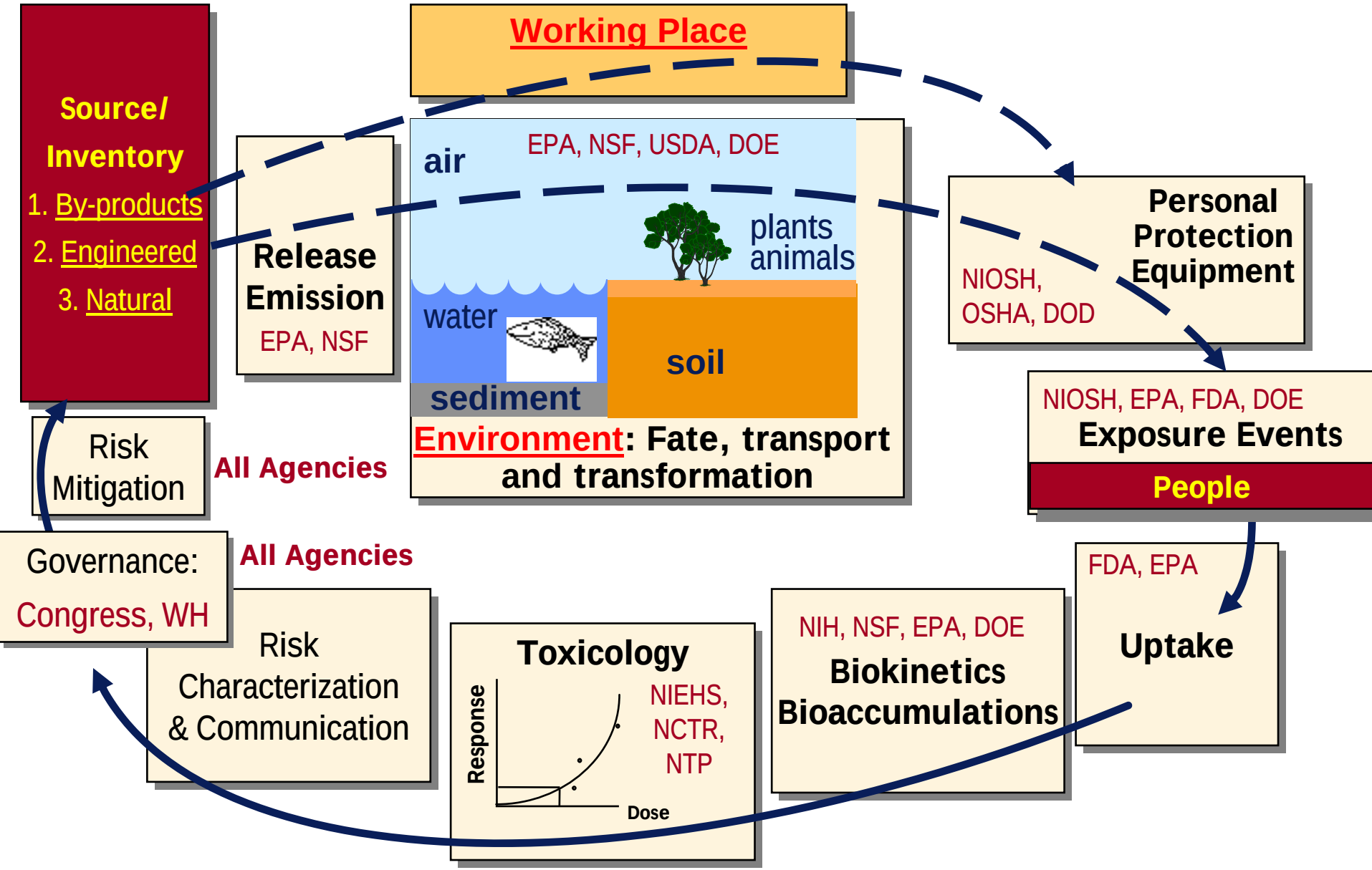


Nanotechnology in Society

J. Nanoparticle Research, 7(2), 2005

M.C. Roco, 9/16/05

B. EHS research and regulatory topics for nanomaterials



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

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**