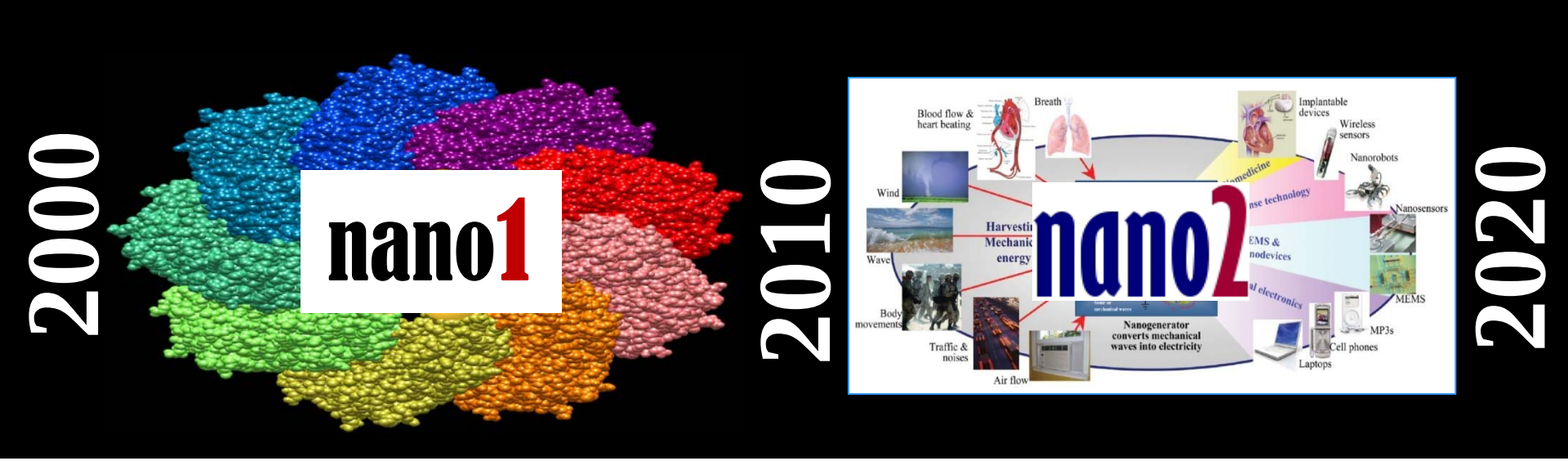


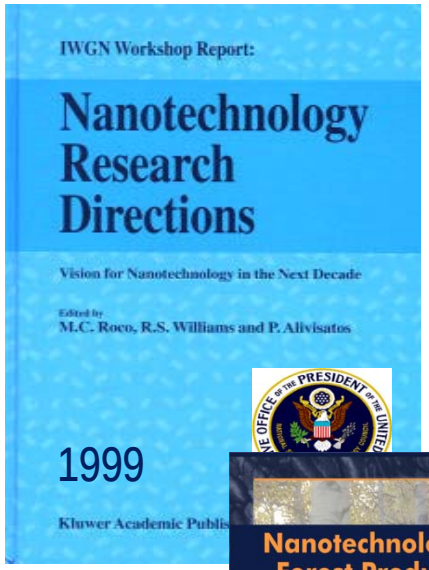
NSF Programs and the Future of Nanotechnology R&D: United States in the global context

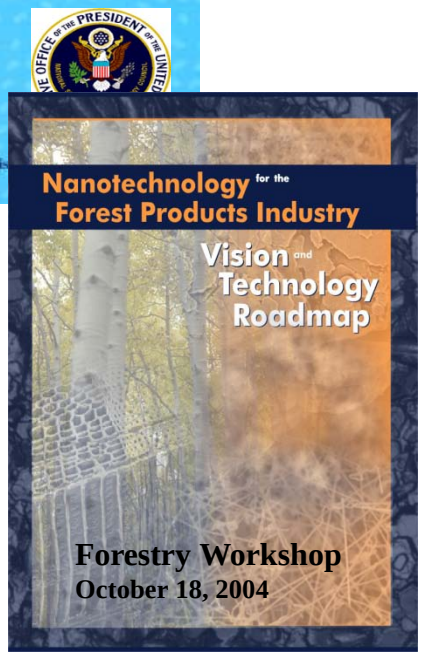
Mike Roco
National Science Foundation and National Nanotechnology Initiative

TAPPI, Washington, D.C., June 6, 2011

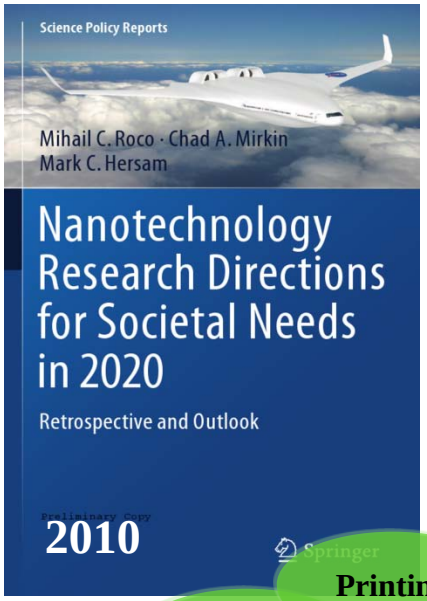
Long-term nanotechnology research directions (2000-2020)

nano1

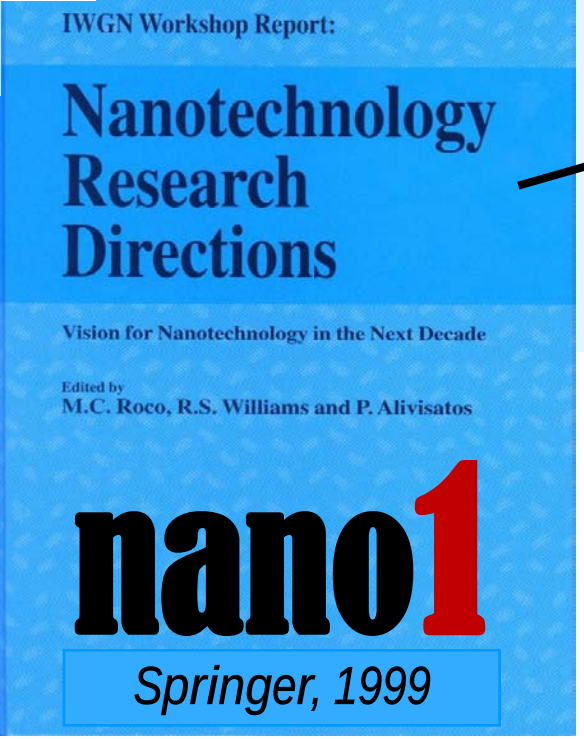




nano2



NSF/WTEC, www.wtec.org/nano2/ ; Springer 2010



"Vision for nanotechnology in the next decade", 2001-2010

http://www.wtec.org/loyola/nano/IWGN.Research.Directions/IWGN_rd.pdf

Systematic control of matter on the nanoscale will lead to a revolution in technology and industry

- *Change the foundations from micro to nano*
- *Create a general purpose technology (similar IT)*

More important than miniaturization itself:

Novel properties/ phenomena/ processes/ natural threshold

Unity and generality of principles

Most efficient length scale for manufacturing, biomedicine

Show transition from basic phenomena and components to system applications in 10 areas and 10 scientific targets

CREATING A NEW FIELD AND COMMUNITY IN TWO FOUNDATIONAL STEPS (2000~2020)

Mass Application of Nanotechnology after ~ 2020

New areas

MATERIALS | ELECTRONICS | HEALTH CARE | ENVIRONMENT | ENERGY | TRANSPORT | MANUFACTURING | SECURITY | INSTRUMENTS

2020

NS&E integration for general purpose technology

~ 2011 ← nano2 → **~ 2020**

Direct measurements; Science-based design and processes; Collective effects; Create nanosystems by technology integration

New disciplines
New industries
Societal impact

Foundational interdisciplinary research at nanoscale

~ 2001 ← nano1 → **~ 2010**

Indirect measurements, Empirical correlations; Single principles, phenomena, tools; Create nanocomponents by empirical design

Infrastructure
Workforce
Partnerships

2000

Nano2 Report, 2010, p. XXXVII

Nano 2020 Report

Panel of U.S. experts

Input from 250 leading nanotechnologists from 35 countries

5 brainstorming workshops

Peer review

Public comment

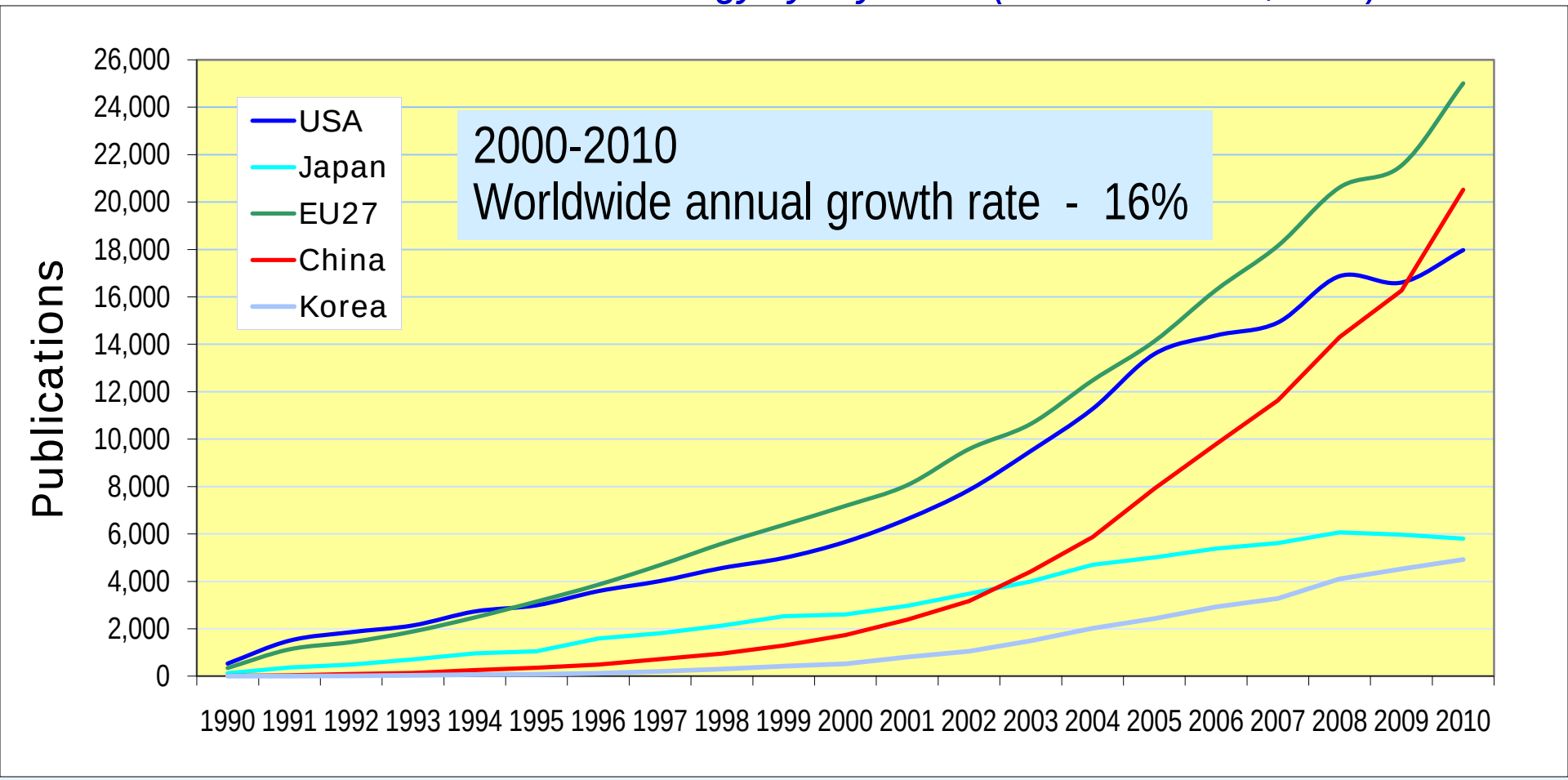
Open source

2000-2010
Estimates show an average growth rate of key nanotechnology indicators of 16% - 33%

World (US)	People -primary workforce	SCI papers	Patents applicat-ions	Final Products Market	R&D Funding public + private	Venture Capital
2000 *(actual)*	~ 60,000 (25,000)	18,085 (5,342)	1,197 (405)	~ $30 B ($13 B)	~ $1.2 B ($0.37 B)	~ $0.21 B ($0.17 B)
2010 *(actual)*	~ 600,000 (220,000)	78,842 (17,978)	~ 20,000 (5,000)	~ $300 B ($110 B)	~ $18 B ($4.1 B)	~ $1.3 B ($1.0 B)
2000 - 2010 average growth	~ 25% (~23%)	~ 16% (~13%)	~ 33% (~28%)	~ 25% (~24%)	~ 31% (~27%)	~ 30% (~35%)
2015 *(estimation in 2000)*	~ 2,000,000 (800,000)			~ $1,000B ($400B)		
2020 *(extrapolation)*	~ 6,000,000 (2,000,000)			~ $3,000B ($1,000B)		
Evolving Topics	*Research frontiers change from passive nanostructures in 2000-2005, to active nanostructures after 2006, and to nanosystems after 2010*					

Nanotechnology publications in the Science Citation Index (SCI) 1990 - 2010

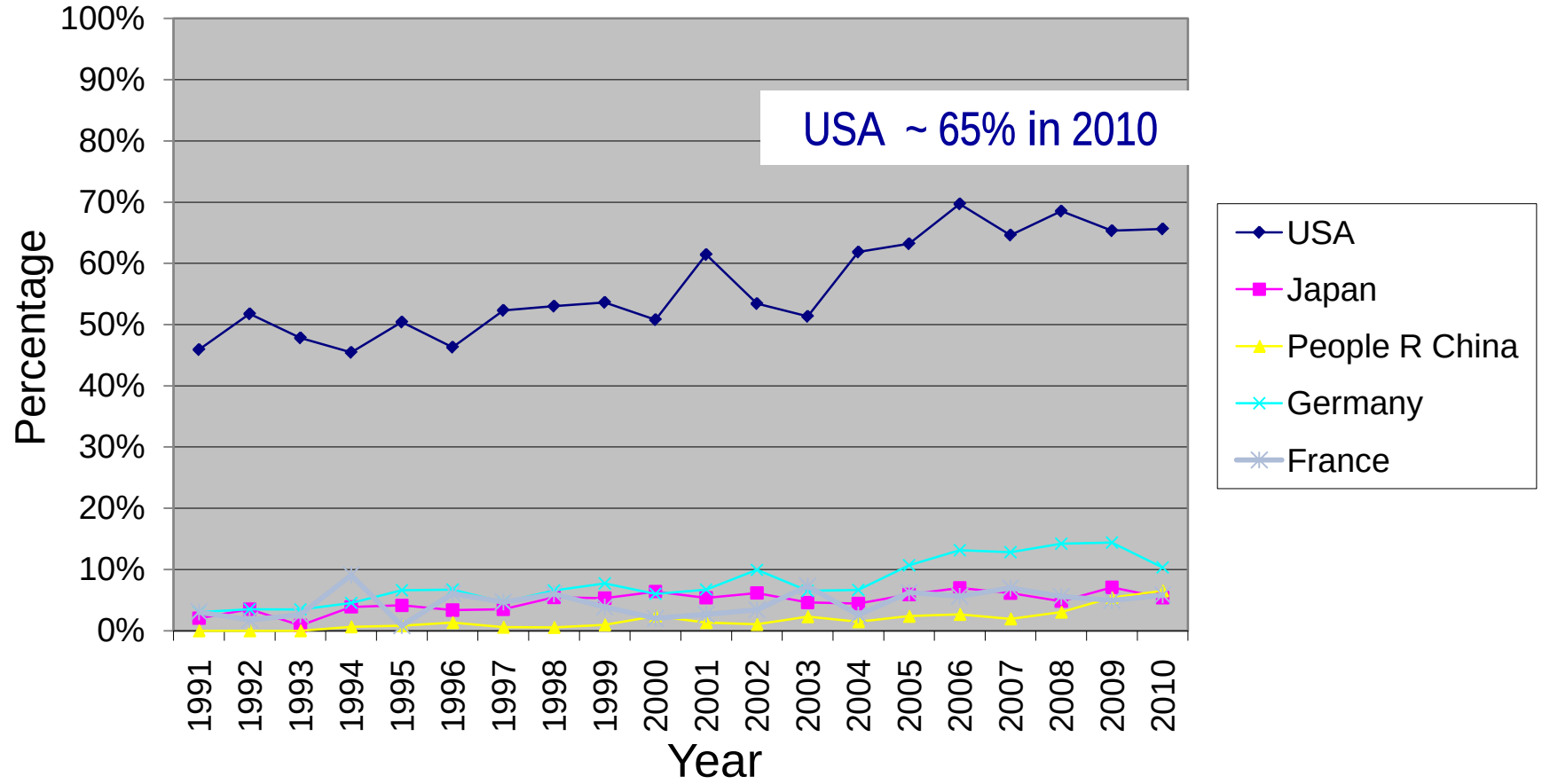
Data was generated from online search in Web of Science using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen and Roco, 2011)



Rapid, uneven growth per countries

Percent contribution by country to nanotechnology publications in Science, Nature, and Proc. NAS

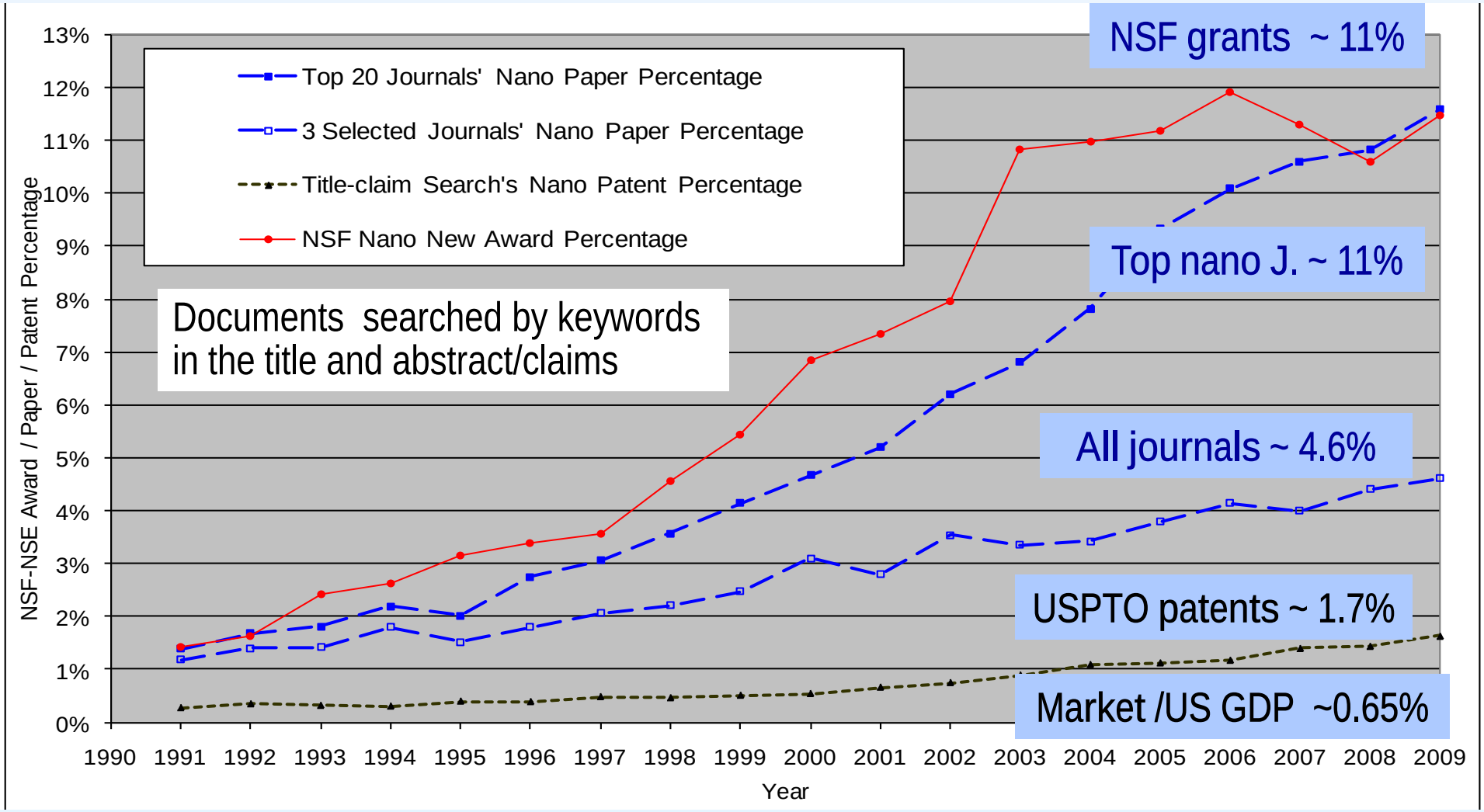
Title-abstract search (Chen and Roco, 2011)



U.S. maintain the lead in highly cited publications

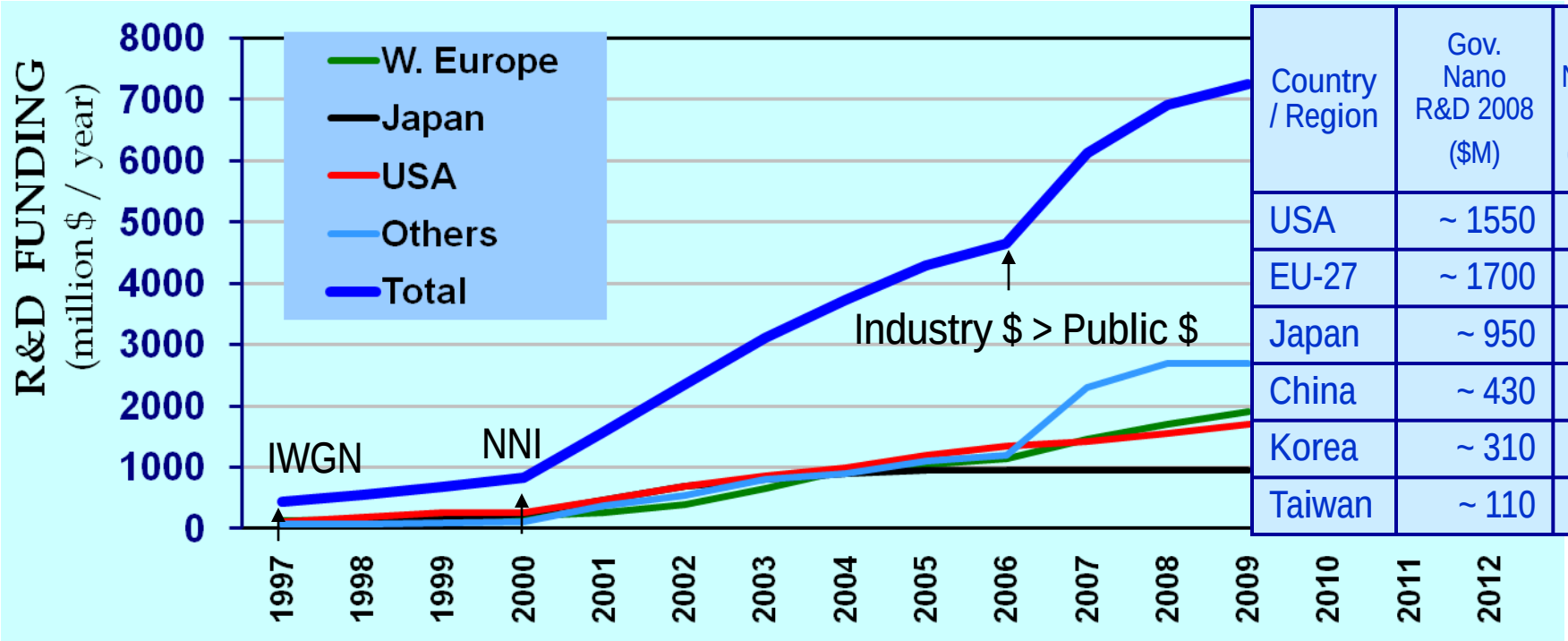
Percentage of nanotechnology content in NSF awards, ISO papers and USPTO patents (1991-2009)

(update after Encyclopedia Nanoscience, Roco, 2008)



Similar, delayed penetration curves: for R&D funding /papers /patents /products

2000-2009
Changing international context:
federal/national government R&D funding (NNI definition)



Country / Region	Gov. Nano R&D 2008 ($M)	Specific Nano R&D 2008 ($/Capita)
USA	~ 1550	~ 5.1
EU-27	~ 1700	~ 4.6
Japan	~ 950	~ 7.3
China	~ 430	~ 0.4
Korea	~ 310	~ 6.0
Taiwan	~ 110	~ 4.5

Seed funding 1991 - 1997

NNI Preparation vision/benchmark

1st Generation products passive nanostructures

2nd Generation active nanostructures

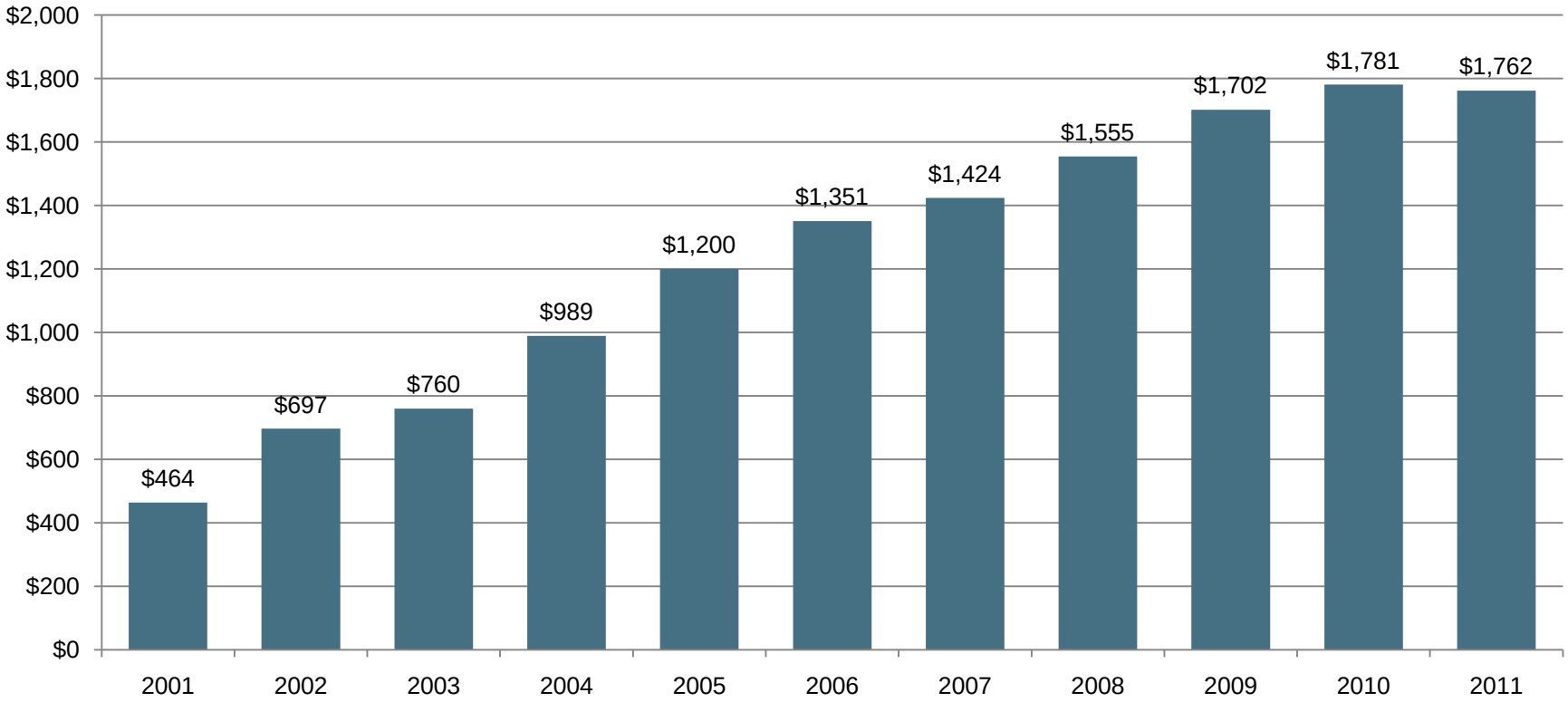
3rd Generation nanosystems

Rapid, uneven growth per countries

2001-2010

NNI budget information

- **NNI expenditures* have grown from $464 million in FY '01 to an FY '11 request of nearly $1.8 billion.****



*** All numbers shown above are actual spending, except 2010, which is estimated spending for the current year and 2011 , which is requested amount for next year (FY '09 figure shown here does *not* include ~$500 million in additional ARRA funding).**

**** 2011 figure shown here does *not* include DOD earmarks included in previous yrs. ($117 M '09)**

2001-2010

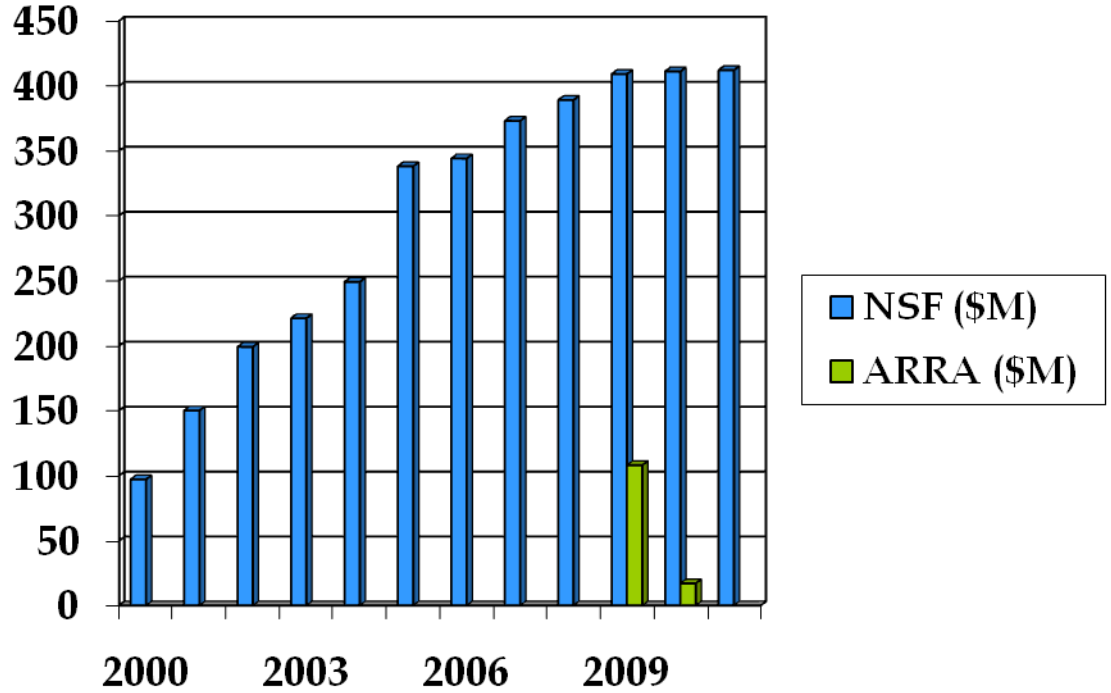
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

www.nsf.gov/nano , www.nano.gov

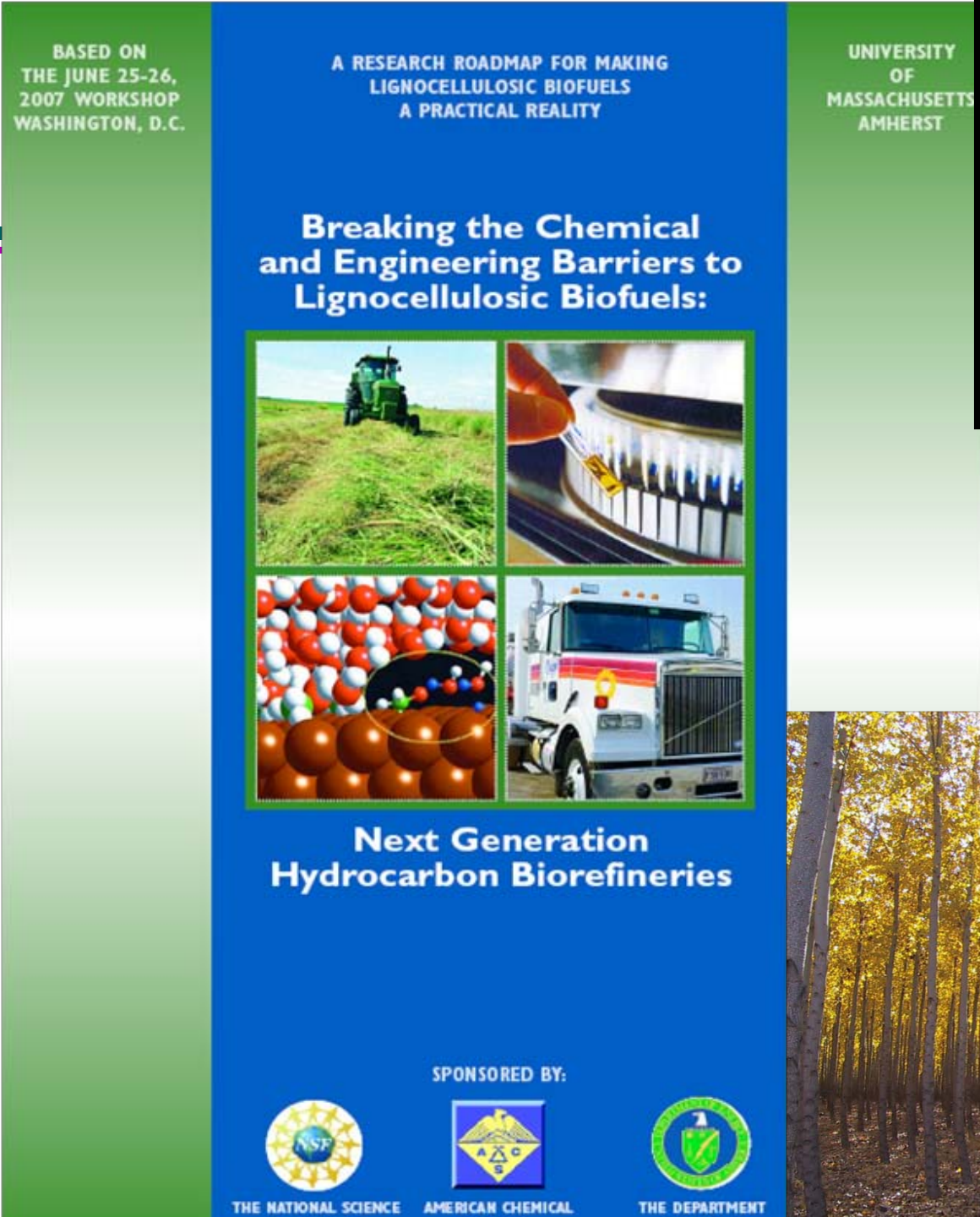
FY 2011 Budget Request $412M

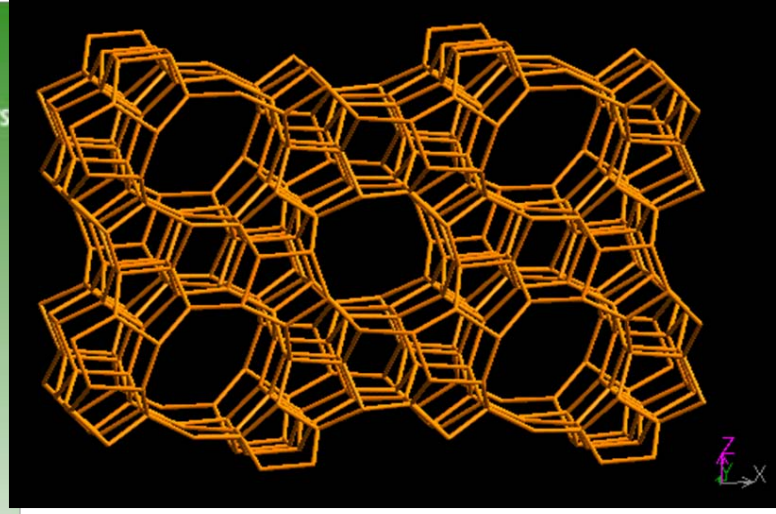
- Fundamental research ~ 5,000 active projects
- Establishing the infrastructure - 26 large centers, 2 user facilities, teams
- Training and education >10,000 students and teachers/y; ~ $30M/y

Fiscal Year	NSF	
2000	$97M	
2001	$150M	
2002	$199M	
2003	$221M	
2004	$254M	
2005	$338M	
2006	$344M	
2007	$373M	
2008	$389M	
2009	$409M	+ $108M (ARRA) = $517M
2010	$411M	+ $17M (ARRA) = $428M

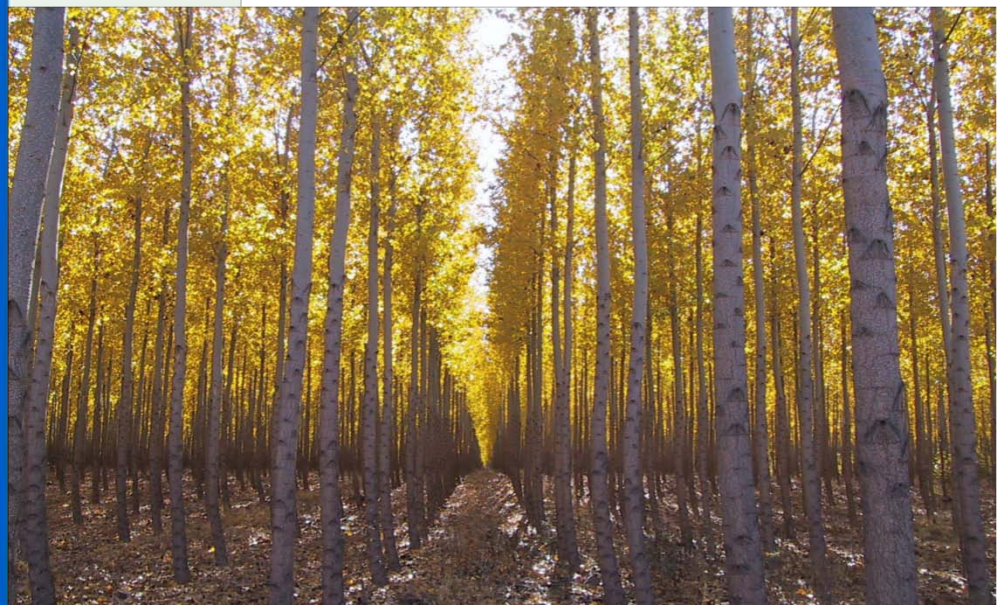


2011: $412M, nano EHS $33M; Request FY 2012 -$456M





Use of zeolites as catalysts to covert biomass in fuel



2000-2010 Outcomes

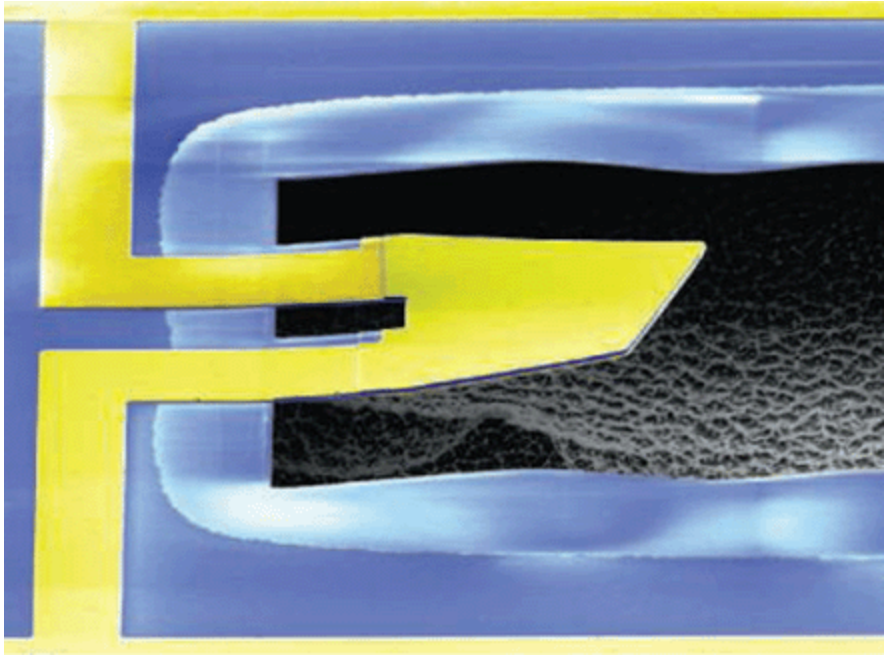
- Remarkable scientific discoveries than span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of 1D - 4D nanostructured building blocks for devices and systems

- New S&E fields have emerged such as: *spintronics, plasmonics, metamaterials, carbon nanoelectronics, molecules by design, nanobiomedicine, branches of nanomanufacturing, and nanosystems*

- Technological breakthroughs in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; expansion into energy resources and water filtration, agriculture and forestry; and integration of nanotechnology with other emerging areas such as quantum information systems, neuromorphic engineering, and synthetic and system nanobiology

The First Quantum Machine

Science 17 December 2010: vol. 330 no. 6011 1604



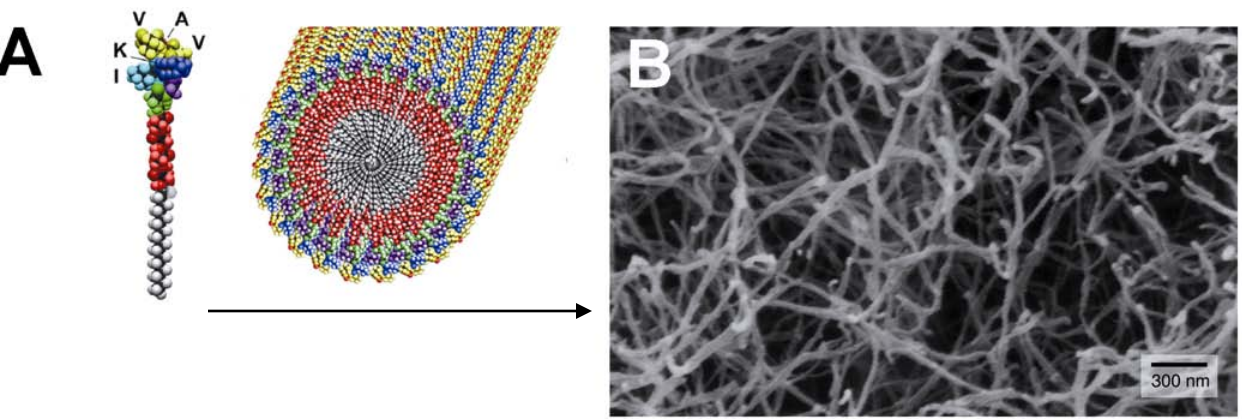
The simplest quantum states of motion with a vibrating device was measured (the board of aluminum is as long as a hair is wide)

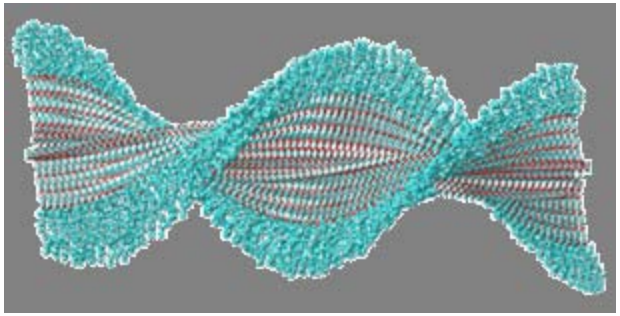
Aaron O'Connell and Andrew Cleland, UCSB, 2010

Example 4th generation (in research)

Designing molecules for hierarchical selfassembling

EX: - Biomaterials for human repair: nerves, tissues, wounds (Sam Stupp, NU)

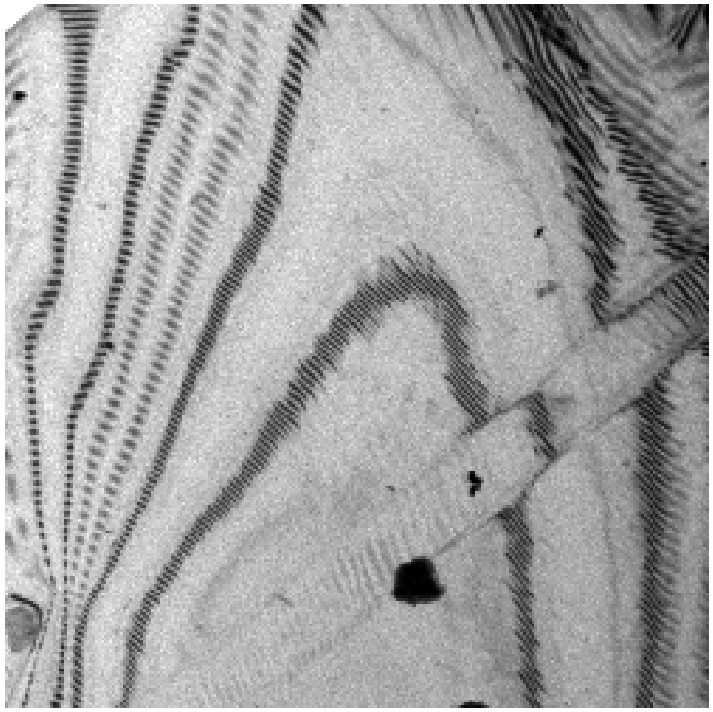




- New nanomachines, robotics - DNA architectures (Ned Seeman, Poly. Inst.)
- Designed molecules for self-assembled porous walls (Virgil Percec, U. PA)
- Self-assembly processing for artificial cells (Matt Tirrell, UCSB)
- Block co-polymers for 3-D structures on surfaces (U. Mass, U. Wisconsin)

4D Microscope Revolutionizes the Way We Look at the Nano World

A. Zewail, Caltech, and winner of the 1999 Nobel Prize in Chemistry



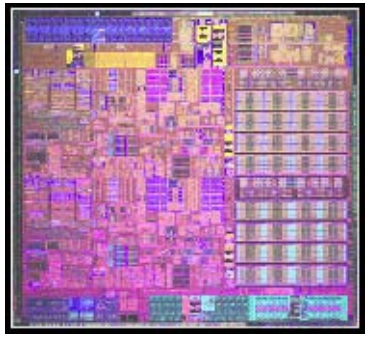
Nanodrumming of graphite, visualized with 4D microscopy.

Use of ultra short laser flashes to observe fundamental motion and chemical reactions in real-time (timescale of a femtosecond, 10^{-15}s), with 3D real-space atomic resolution.

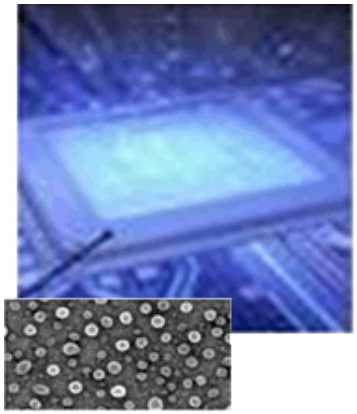
Allows for visualization of complex structural changes (dynamics, chemical reactions) in real space and real time. Such visualization may lead to fundamentally new ways of thinking about matter

http://ust.caltech.edu/movie_gallery/

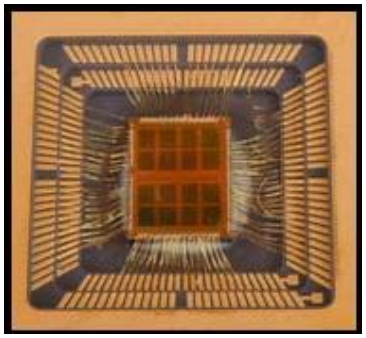
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



32 nm CMOS processor technology by Intel (2009)

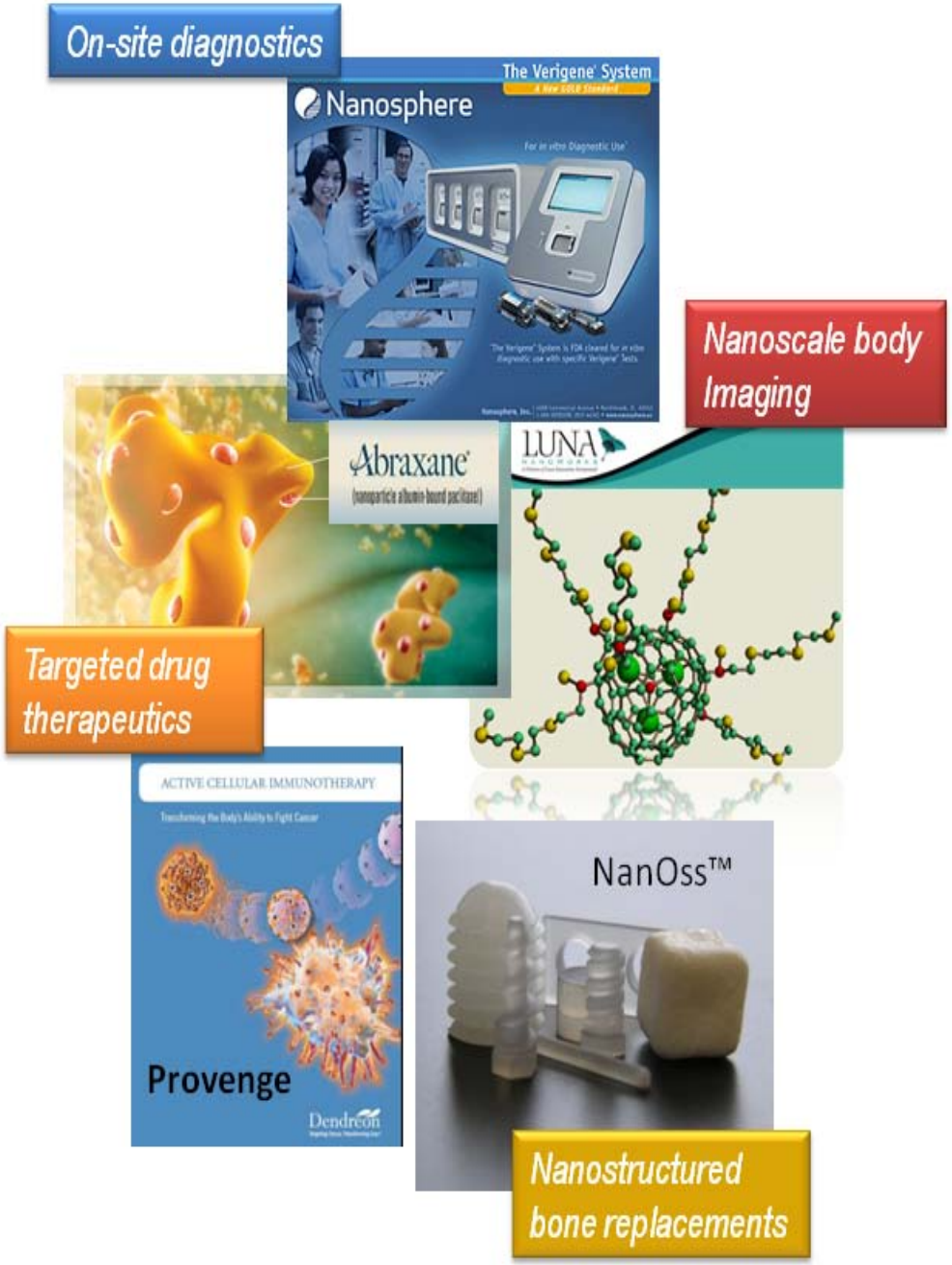


90 nm thin-film storage (TFS) flash flexmemory by Freescale (2010)



16 megabit magnetic random access memory (MRAM) by Everspin (2010)

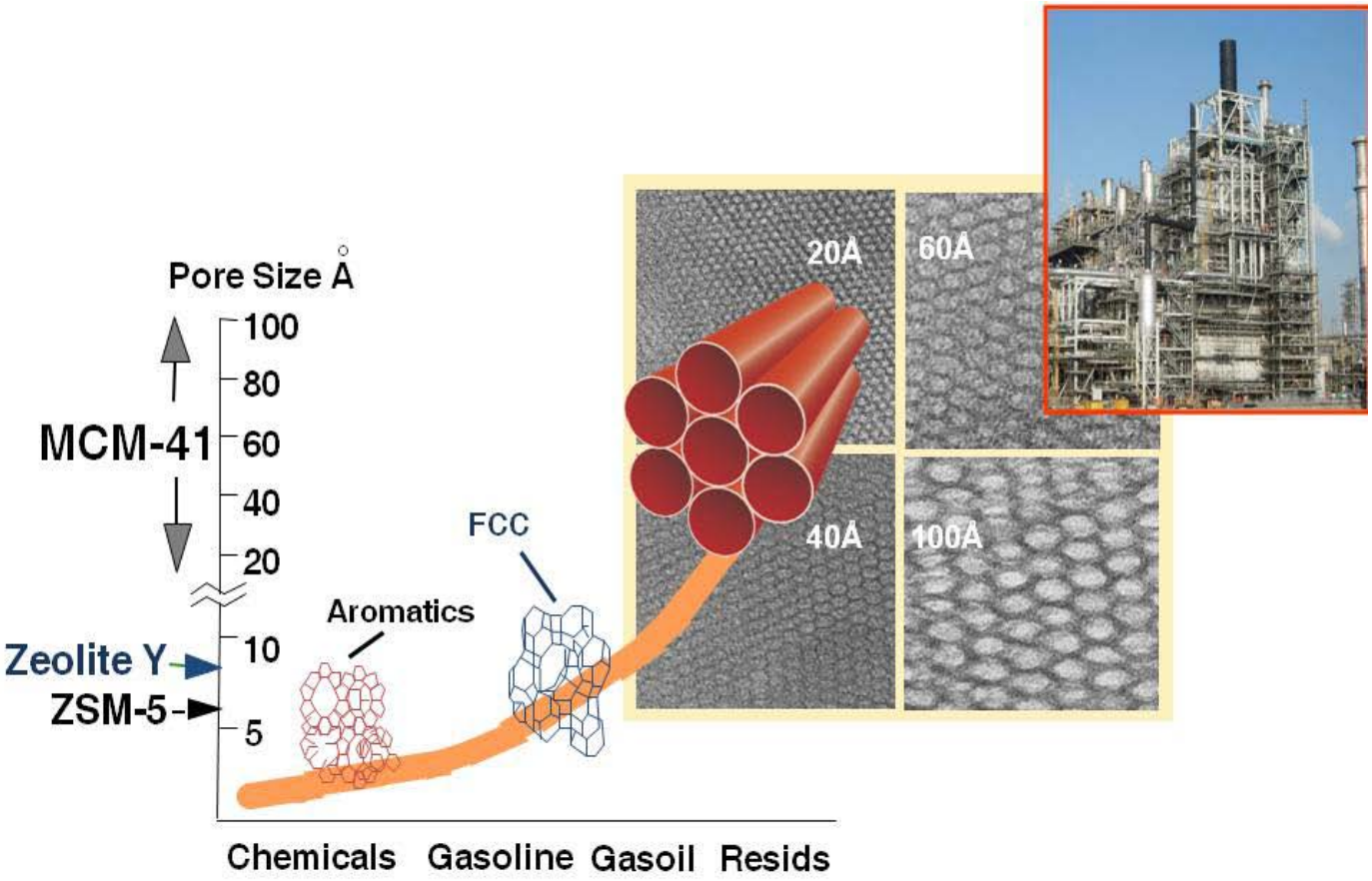
Nano2 Report, 2010, p. XII



Nano2 Report, 2010, p. XIV

Examples of nanotechnology incorporated into commercial healthcare products, in production in 2010

Examples of nanotechnology in commercial catalysis products for applications in oil refining, in production in 2010



Redesigned since 2000 mesoporous silica materials, like MCM-41, along with improved zeolites, are used in a variety of processes such as fluid catalytic cracking (FCC) for producing gasoline from heavy gas oils, and for producing polyesters. Nano-engineered materials now constitute 30–40% of the global catalyst market

Nano2 Report, 2010, p. XVII

Examples of Penetration of Nanotechnology in Several Industrial Sectors

The market percentage and its absolute value affected by nanotechnology are shown for 2010

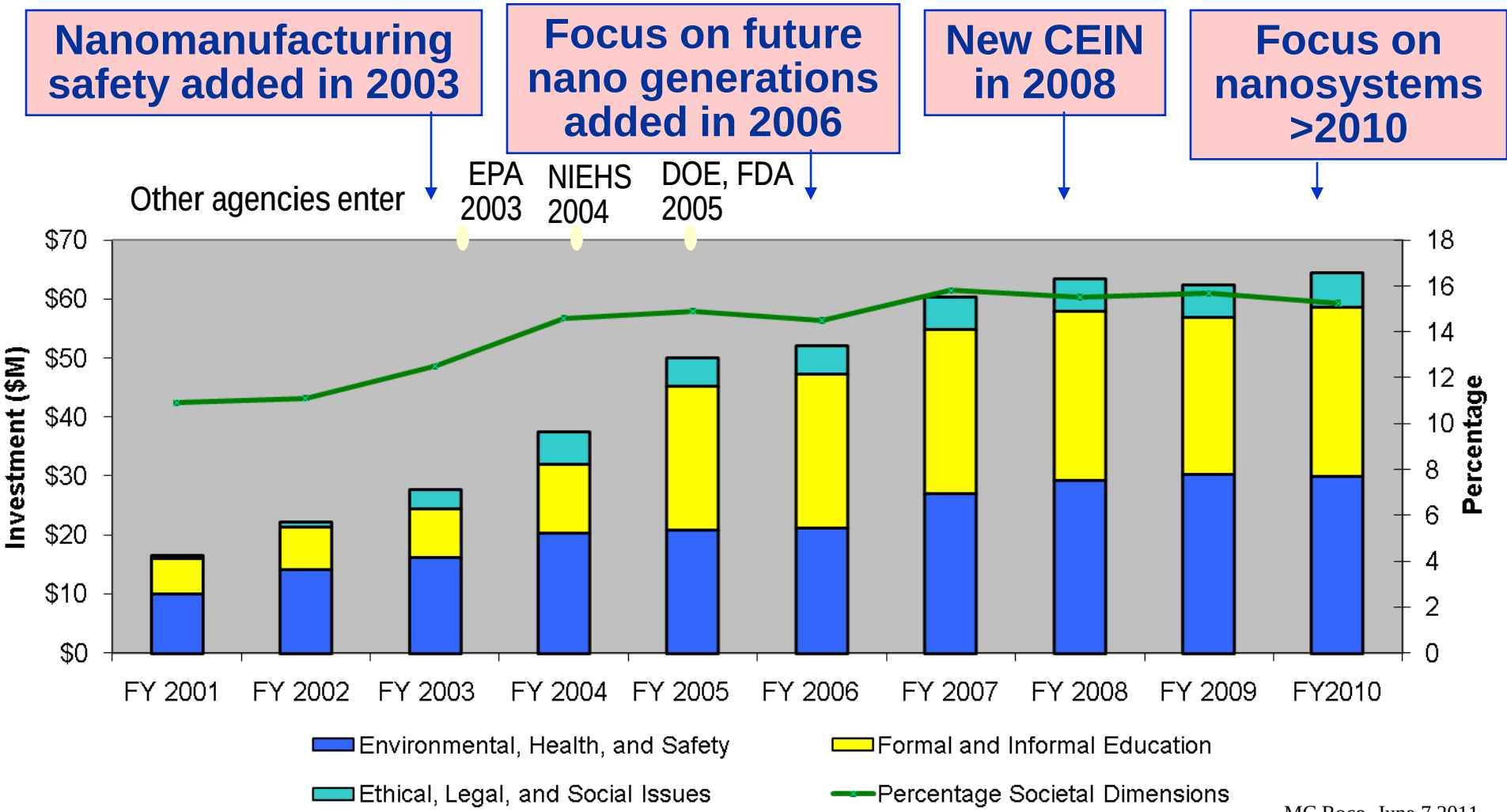
U.S.	2000	2010	Est. in 2020
Semiconductor industry	0 (with features < 100 nm) 0 (new nanoscale behavior)	60% (~$90B) 30% (~$45B)	100% 100%
New nanostructured catalysts	0	~ 35% (~35B impact)	~ 50%
Pharmaceutics (therapeutics and diagnostics)	0	~ 15% (~$70B)	~ 50%
Wood	0	0	~ 20%

Nano2 Report, 2010, p. XXXVI

2000-2010: Sustainable Development

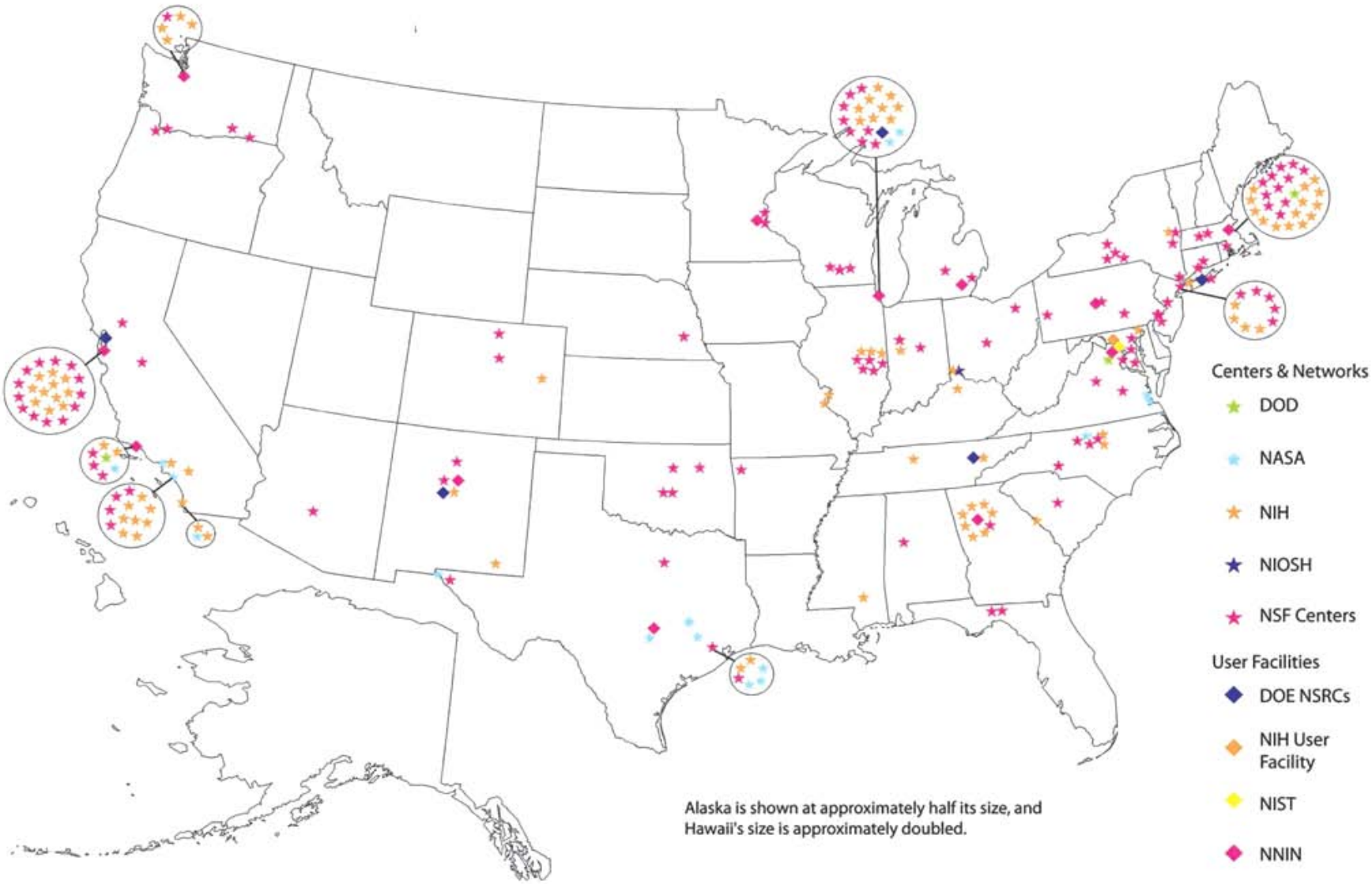
- Nanotechnology has provided solutions for about half of the new projects on energy conversion, energy storage, and carbon encapsulation in the last decade
- Entirely new families have been discovered of nanostructured and porous materials with very high surface areas, including metal organic frameworks, covalent organic frameworks, and zeolite imidazolate frameworks, for H storage and CO_2 separations
- A broad range of polymeric and inorganic nanofibers for environmental separations (membrane for water and air filtration) and catalytic treatment have been synthesized
- Testing the promise of nanomanufacturing for sustainability
- Evaluating renewable materials and green fuels

NSF Investment in Nanotechnology Implications for Safety and Society



MC Roco, June 7 2011

About 100 major NNI centers, networks, user facilities



Ten Nanoscale Science and Engineering networks with national outreach

TOOLS

Network for Computational Nanotechnology (2002-) > *90,000 users/ 2008*
National Nanotechnology Infrastructure Network (2003-) *4,600 users/ 2007*

Nationwide Impact

TOPICAL

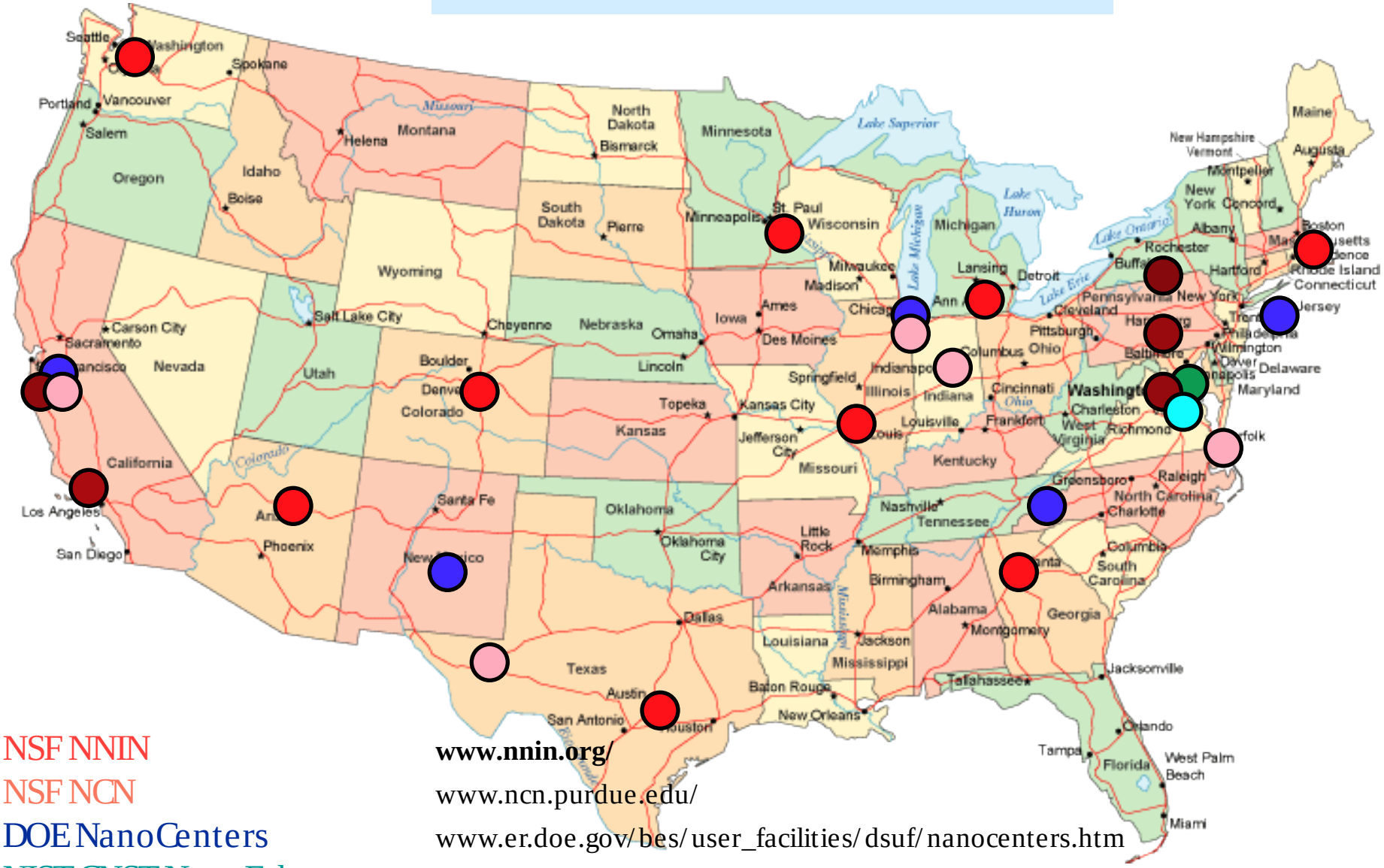
Nanotechnology Center Learning and Teaching (2004-2011)
Nanoscale Informal Science Education Network (2005-) *>200 sites/ 5yr*
Network for Nanotechnology in Society (2005-) *Involves academia,public,industry*
Nanotech Applications and Career Knowledge (2008-) *– nanotechnology educ.*
National Nanomanufacturing Network (2006-) 4 NSETs , DOD centers, and NIST
Environmental Implications of Nanotechnology (2008-) with EPA

GENERAL RESEARCH AND EDUCATION

NSEC Network (2001-) *19 research and education centers*
MRSEC Network (2001-) about 2/3 cover NSE

U.S. Infrastructure

NNI R&D User Facilities



NSF NNIN

NSF NCN

DOE NanoCenters

NIST CNST NanoFab

NIH NCI NCL

www.nnin.org/

www.ncn.purdue.edu/

www.er.doe.gov/bes/user_facilities/dsuf/nanocenters.htm

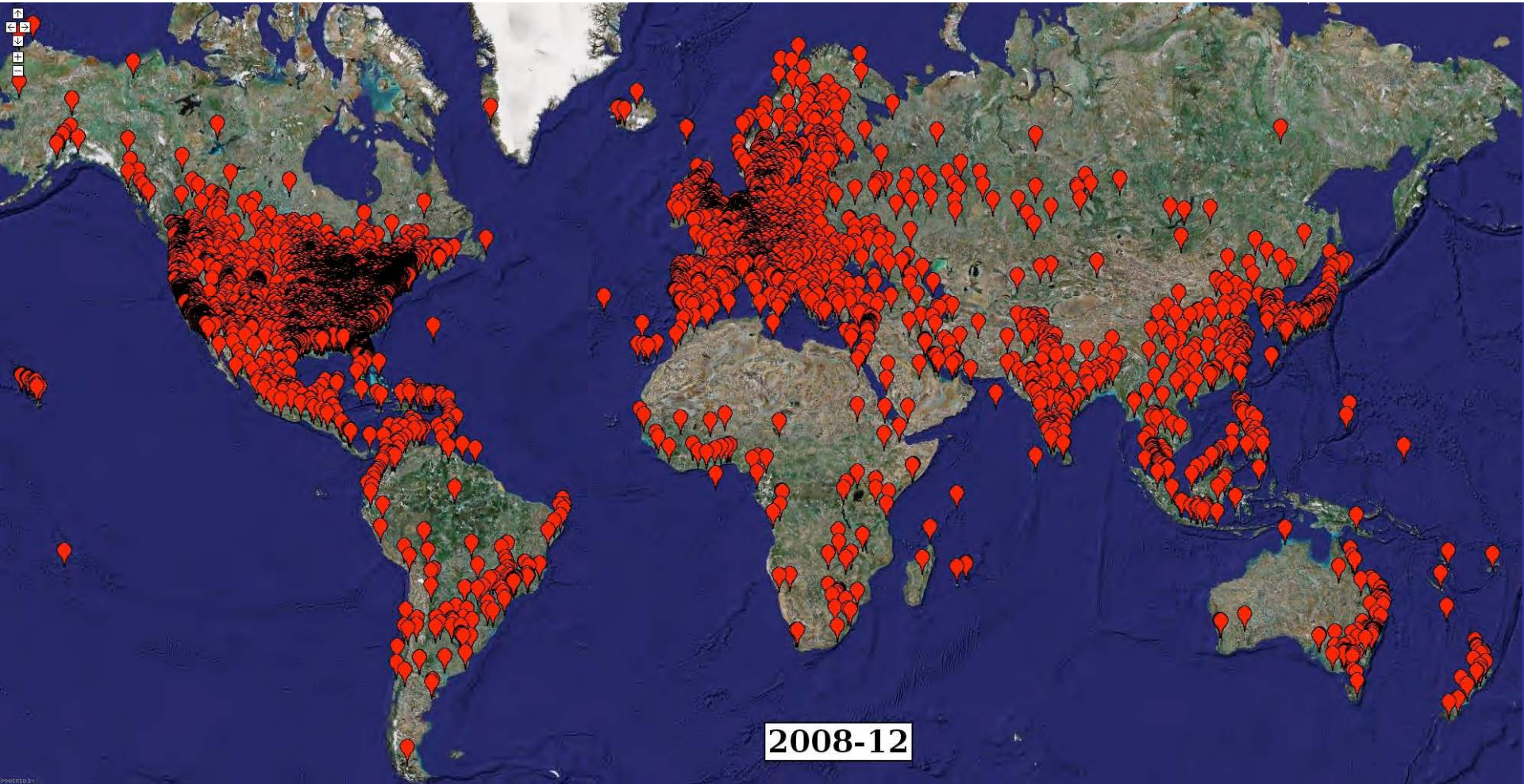
www.cnst.nist.gov/nanofab/nanofab.html

ncl.cancer.gov/

"Nanotechnology Research Directions for ..2020" , 2010, p. XVIII

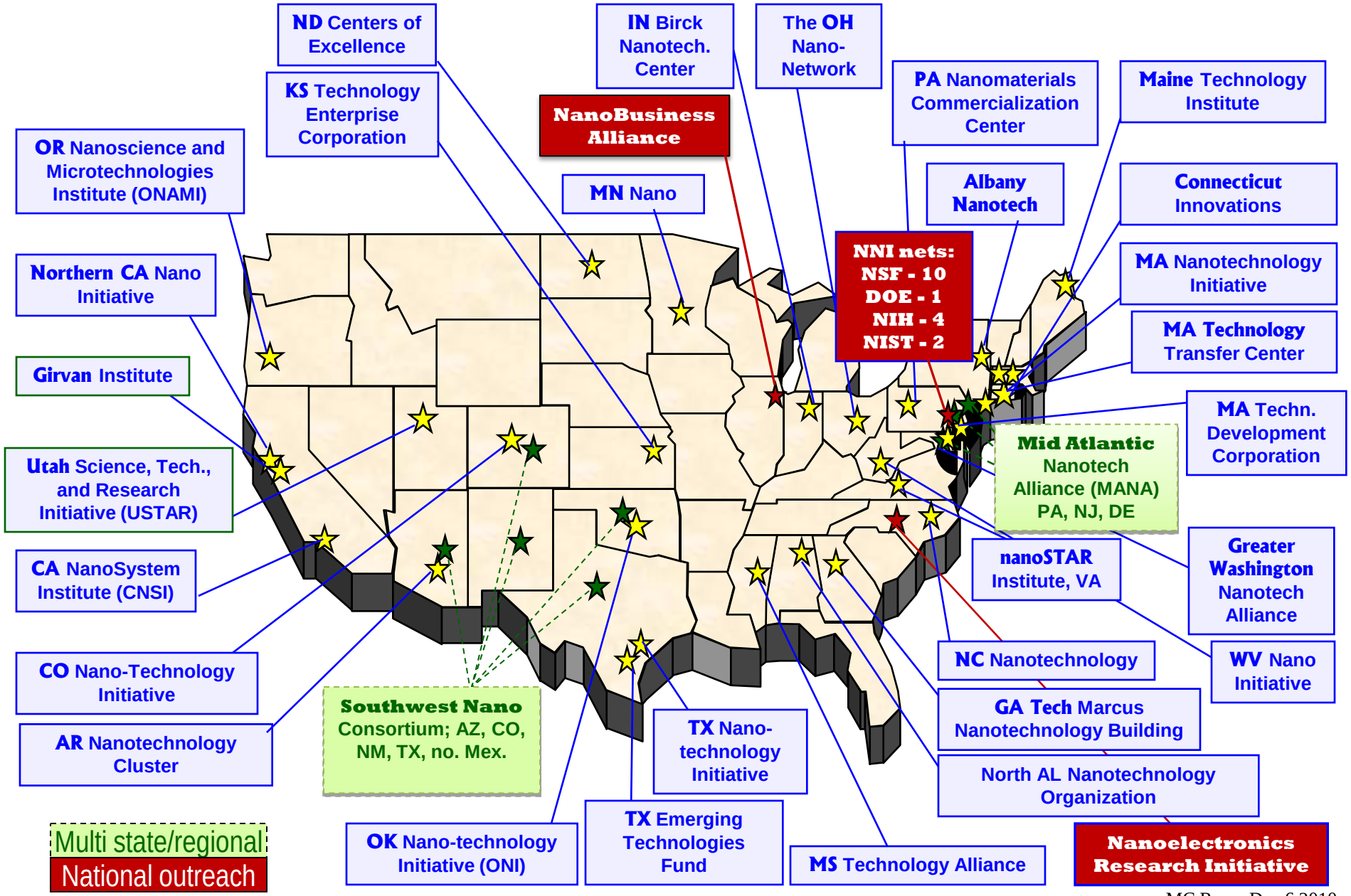
Support global eco-systems via COLLABORATION

NETWORK FOR COMPUTATIONAL NANOTECHNOLOGY
nanoHUB.org is a resource for the global Nanotechnology Community.
The map below indicates a red-peg for every nanoHUB user on the planet.



2009 Nanotechnology Regional, State, and Local Initiatives (34)

http://www.nano.gov/html/funding/businessops.html#RSLI



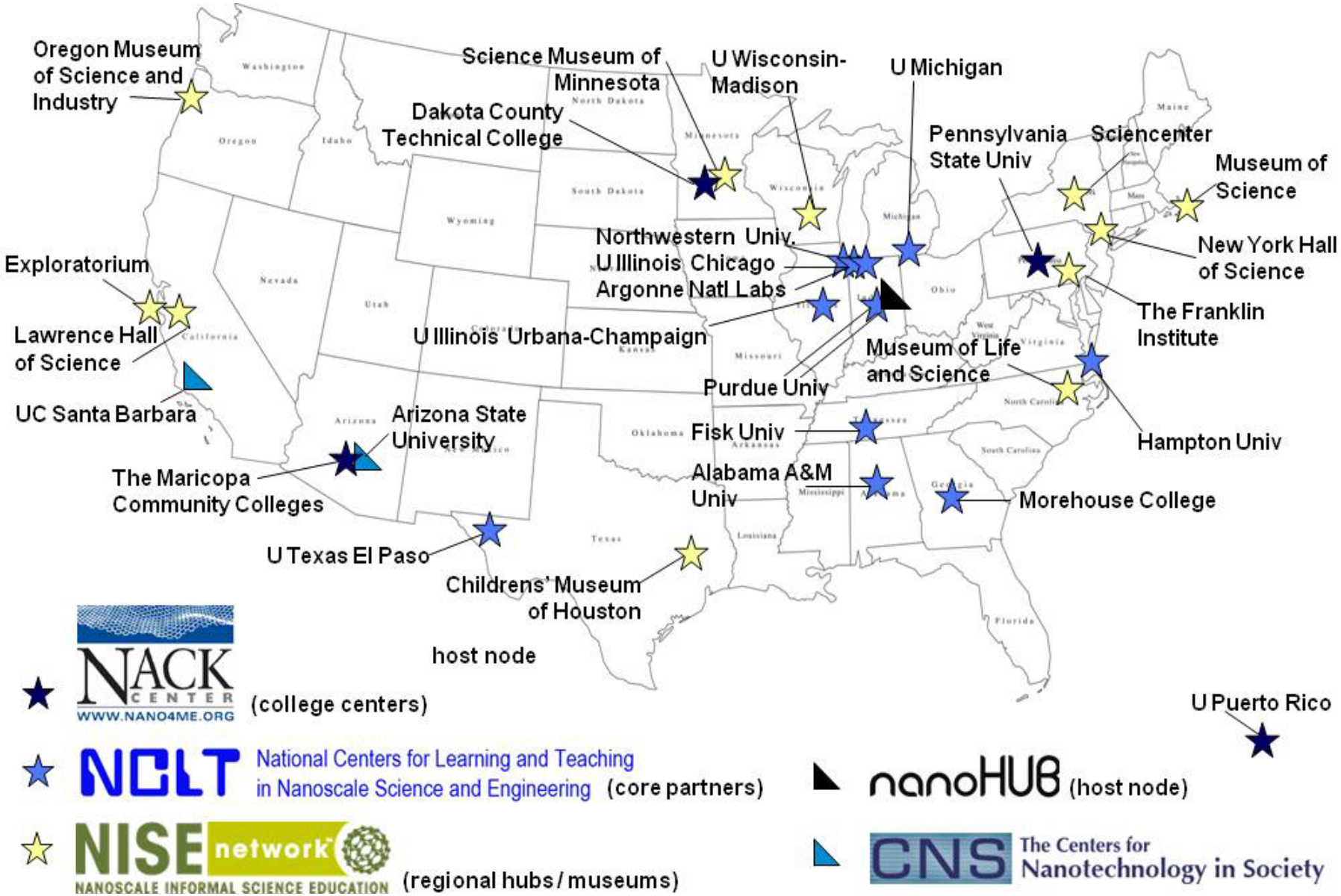
MC Roco, Dec 6 2010

NSF investment in nanoscale science and engineering education, moving over time to broader and earlier education and training

2000	Graduate Education Programs (curriculum development)
2002	Undergraduate Education Program
2003	High School Education Programs
2004-2005	K-12 and Informal (museum)
2006	Technological Education Network

"Nanotechnology Research Directions for ..2020" , 2010, p. 360

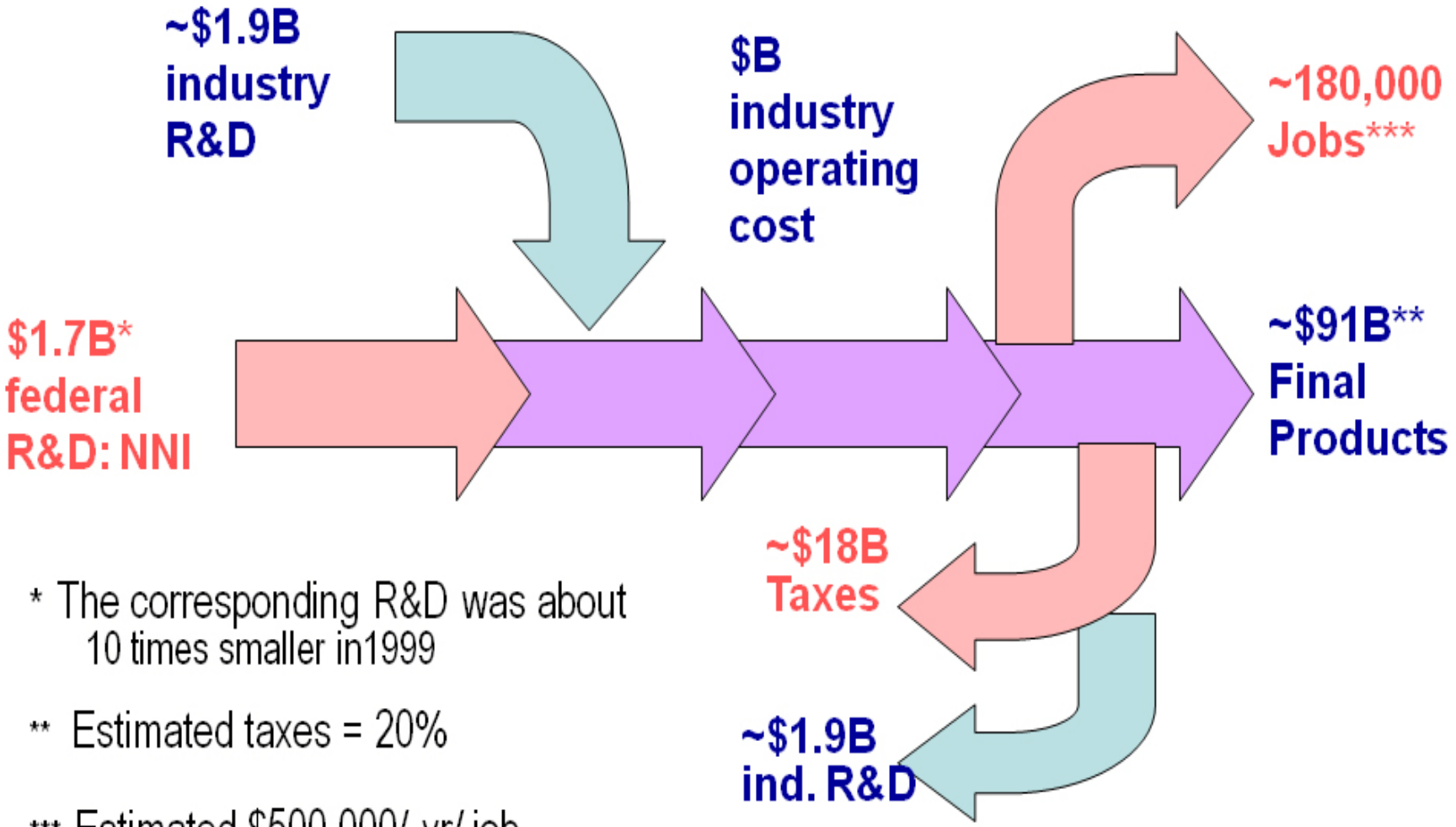
Key NNI education networks in 2010



"Nanotechnology Research Directions for ..2020" , 2010, p. XVIII

MC Roco, Dec 6 2010

Estimation of Annual Implications of U.S. Federal Investment in Nanotechnology R&D (2009)

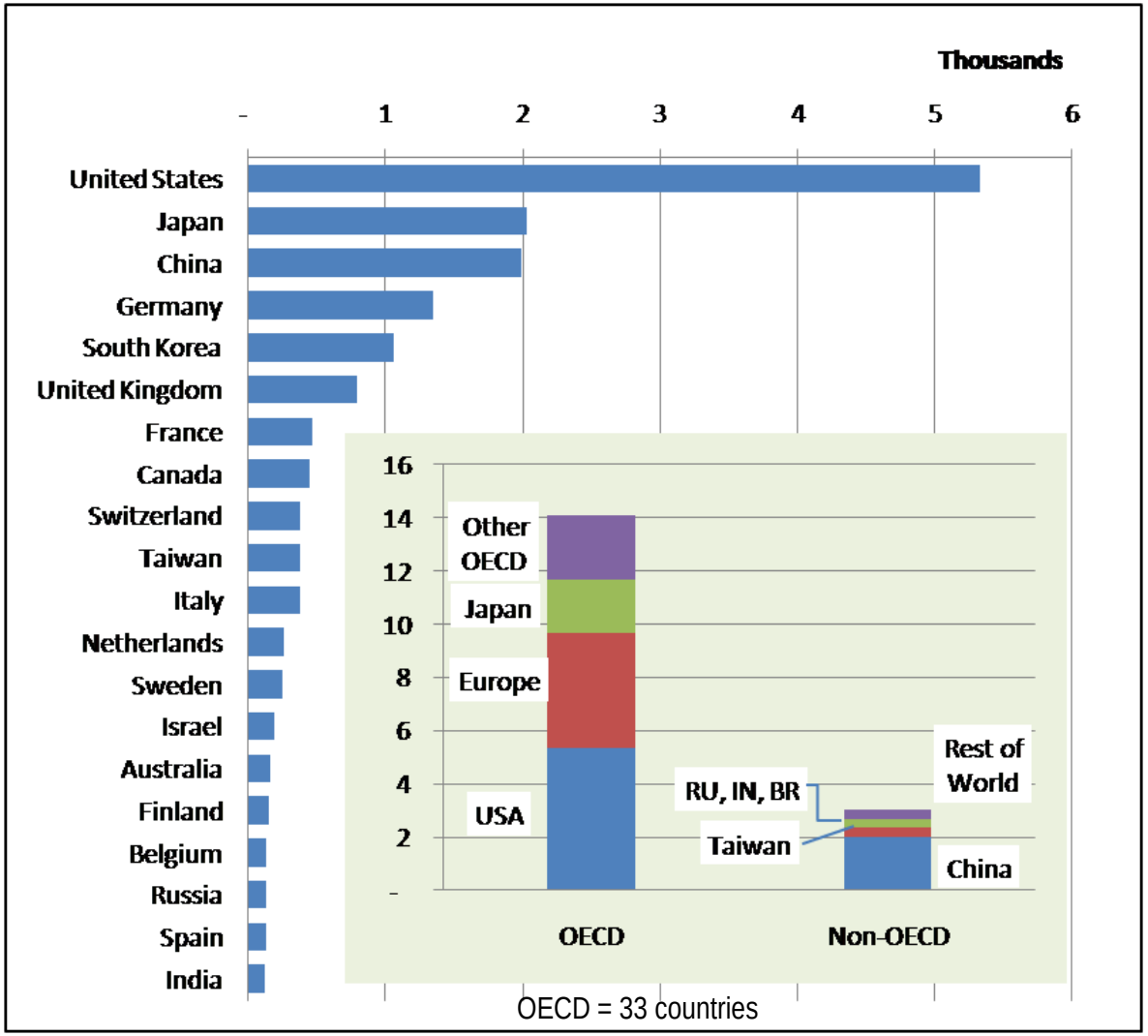


* The corresponding R&D was about 10 times smaller in1999

** Estimated taxes = 20%

*** Estimated $500,000/ yr/ job

Corporate Entry in leading countries (i.e. company has products, articles and/or patents), 1990-2009



Nano2 Report, 2010, p. 411 Courtesy Phil Shapira, Jan Youtie and Luciano Kay

University-Industry-government partnerships (Public-private hybrids)

- Nanoelectronics Research Initiative, U.S.
- U. Albany College of Nanoscale Science and Engineering, U.S.

- Grenoble center, France
- IMEC/ Aachen/ Eindhoven triangle
- University-Industry-Government Tsukuba Nano Center
- Industrial Technology Research Institute, Taiwan

University-Industry Demonstration Partnerships (Academies, U.S.).
Ex: TurboNegotiator (www.turbo.sitesetup.net) a software tool that would facilitate the negotiation of industry-university research agreements

Not fully realized objectives after ten years

- General methods for **"materials by design"** and composite materials (because the direct TMS and measuring techniques methods were not ready)

- **Sustainable development projects** - only energy projects received significant attention in the last 5 years; Nanotechnology for water filtration and desalination only limited; Delay on nanotechnology for climate research (because of insufficient support from beneficiary stakeholders?)

- **Widespread public awareness of nanotechnology** – awareness low ~30% in U.S.; Challenge for public participation

On target in 2010, even if doubted in 2000

- **Steep, quasi-exponential growth of papers** (16%) **and patents** (33%); at rates higher than the averages in all fields
- **Nanotechnology stimulated interdisciplinary research and education**, creating numerous multidisciplinary projects, organizations, and communities
- **Increased nanotechnology R&D investment** (government and private-sector) ~ 30% annual growth rate (because vertical and horizontal development); **International coordination and collaboration** (collective after 2004)

Better than expected after ten years

- ✓ Major industry involvement after 2002-2003
  Ex: >5,400 companies with papers/patents or products (US, 2008); NBA in 2002; Keeping the Moore law continue 10 years after serious doubt raised din 2000

- ✓ Unanticipated discoveries and advances in several S&E fields: plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, quantum information ..

- ✓ The formation / strength of the international community, including in nanotechnology EHS and ELSI that continue to grow

Main lessons learned after ten years

- Need continued, focused investment on **theory, direct measuring and simulation, and integration** at the nanoscale. Nanotechnology still in the formative phase
- Besides nanostructured metals, polymers and ceramics, **classical industries can provide excellent opportunities**, such as in: textiles, wood and paper (cellulose) , plastics, agricultural and food systems. Improved mechanisms for public-private partnerships to establish consortia or platforms are needed
- Need to increase **multi-stakeholder and public participation** in nanotechnology governance, role of public perception

Planning NNI "signature initiatives" with nanomanufacturing components in FY 2012

Sustainable Nanomanufacturing

$ 84M (NSF $35.4M; DOE $35.3M; NIST $7.4M; NASA $5M; USDA/FS $0.9M)

Nanoelectronics for 2020 and Beyond

$ 98.5M (NSF $50M, DOE $33.8M; NIST $11.7M; NASA $3M)

Nanotechnology for Solar Energy

$ 125.7M (DOE $79.2M; NSF $32M; NIST $11.5M; NASA $2M; USDA/NIFA $1M)

In FY 2012 Request: a new system oriented nano centers

- Nanosystems Engineering Research Centers

  for 5 + 5 years (~ $4 M/year)
- Letter of intend in July 2011 … awards in 2012
- Address major topics from discovery to innovation

Part of the NNI increased focus on improving the innovation ecosystem and translational research in 2011-2012

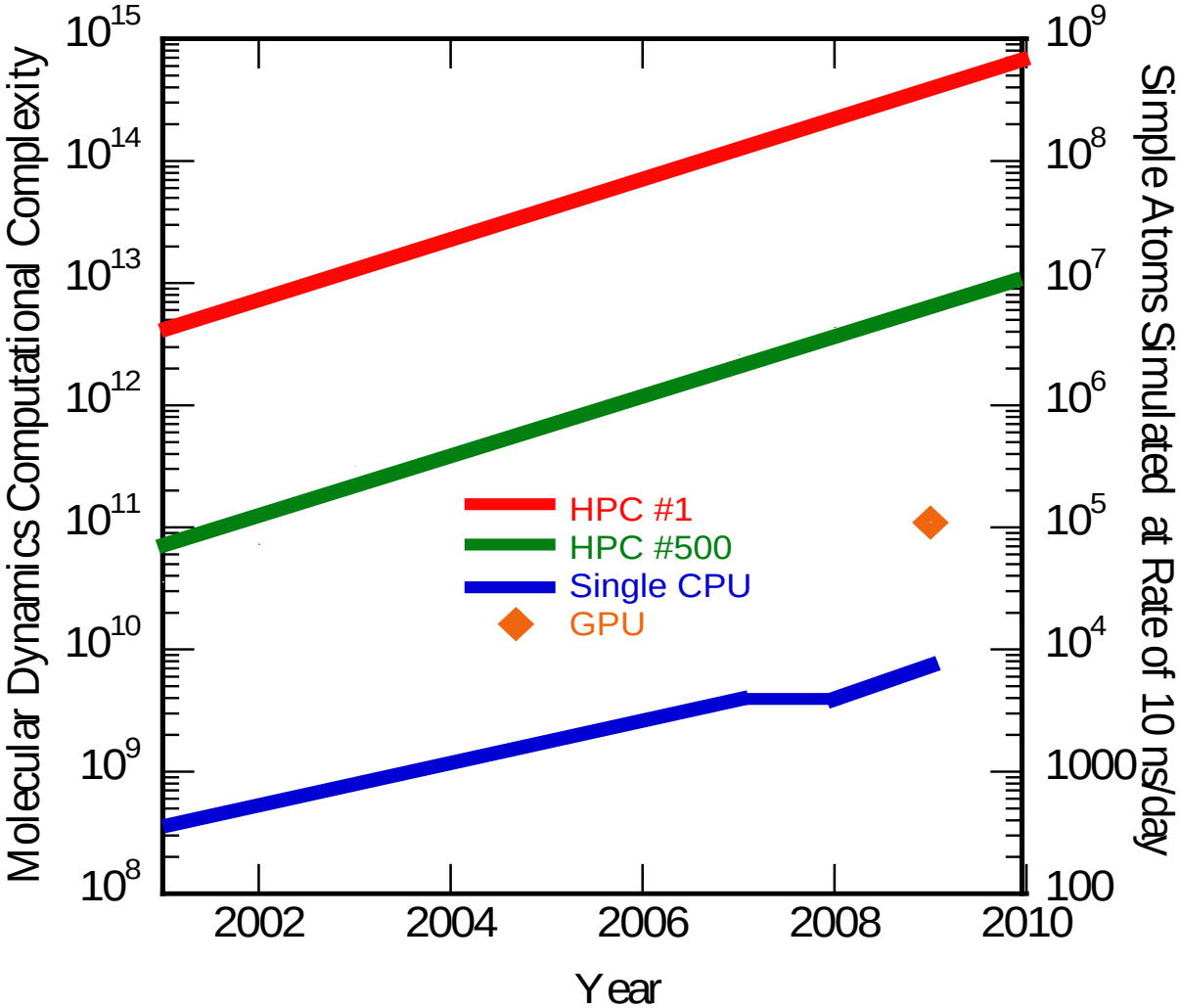
Twelve trends to 2020

www.wtec.org/nano2/

- Theory, modeling & simulation: x1000 faster, essential design
- "Direct" measurements – x6000 brighter, accelerate R&D & use
- A shift from "passive" to "active" nanostructures/nanosystems
- Nanosystems, some self powered, self repairing, dynamic
- Penetration of nanotechnology in industry - toward mass use; catalysts, electronics; innovation– platforms, consortia
- Nano-EHS – more predictive, integrated with nanobio & env.
- Personalized nanomedicine - from monitoring to treatment
- Photonics, electronics, magnetics – new capabilities, integrated
- Energy photosynthesis, storage use – solar economic by 2015
- Enabling and integrating with new areas – bio, info, cognition
- Earlier preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - institutionalization

1. Theory, modeling and simulation - faster, more useful in design

Ex: Growth of computing power on classical molecular dynamics (CMD), 2000-2010



Nano2 Report, 2010, p.5

Left axis:
CMD computational complexity

Right axis:
For monatomic fluid, # of atoms that can be simulated for 10 ns in one day

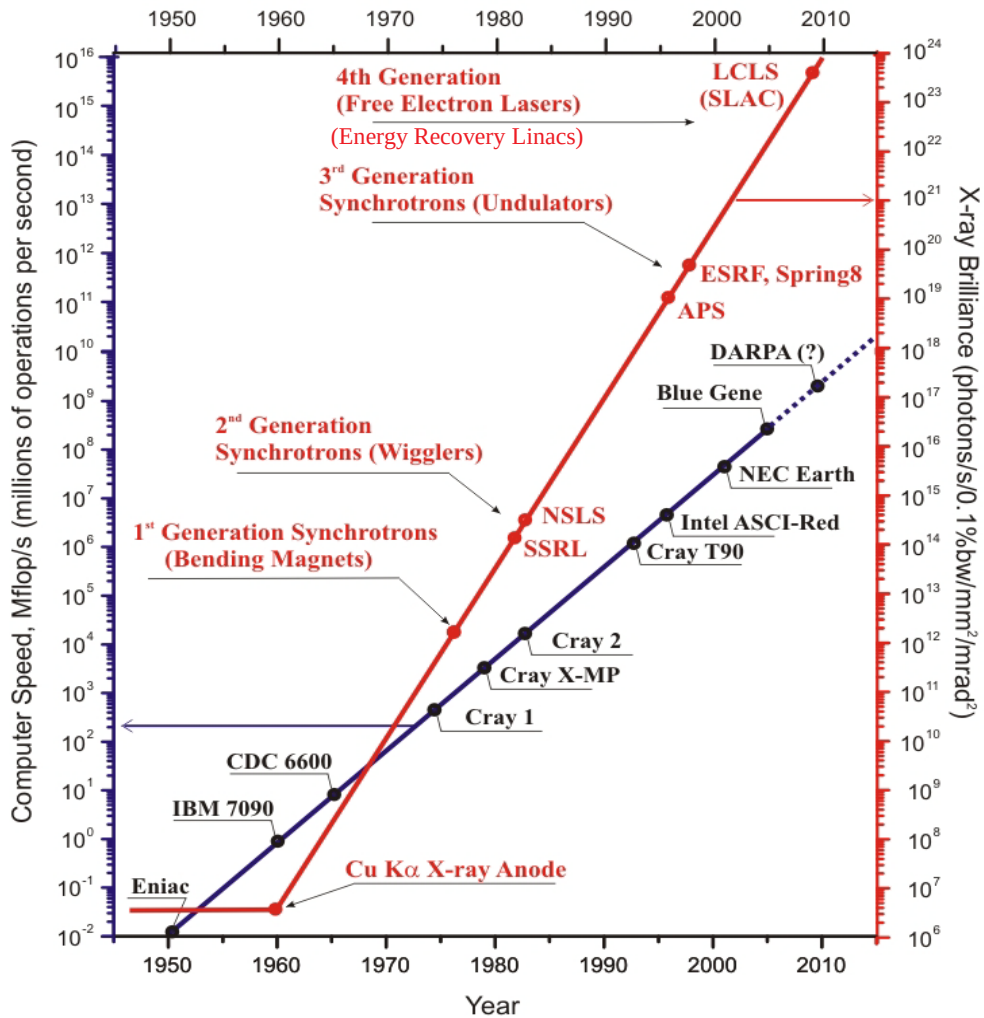
To improvement factor of simulated nano-structure size ~ <u>1000 times in next decade</u>

2. "Direct" measurements and metrology

EX: Exponential law for X-ray Sources: Coherence for 3 D dynamic (~ femtosecond) imaging of structures with atomic precision

Semiconductor Moore's law (black):

2 orders of magnitude in last decade (~100 times)



X-ray source brilliance (red):

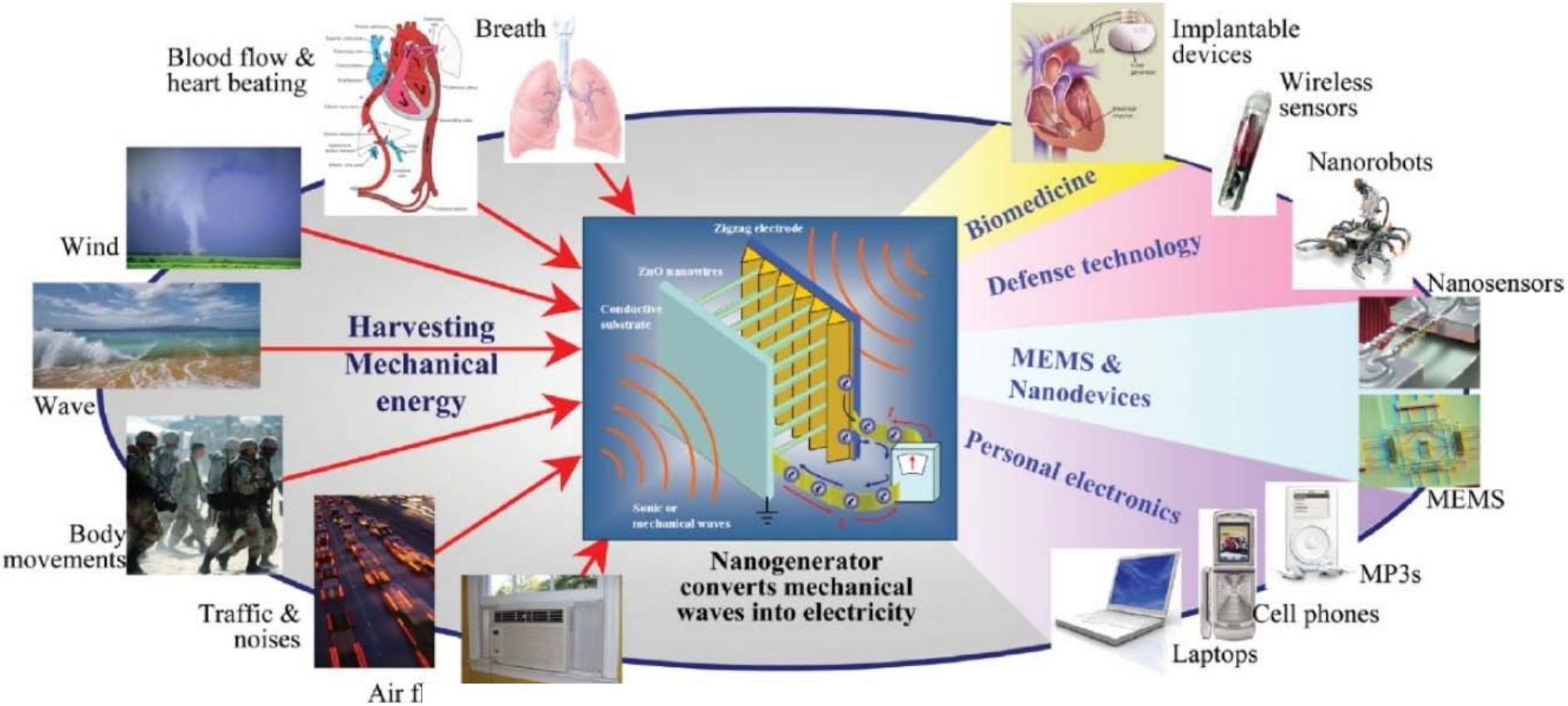
estimated 3.6 orders of magnitude

To increase ~ 5,000 times in next decade

Nano2 Report, 2010, p. 41

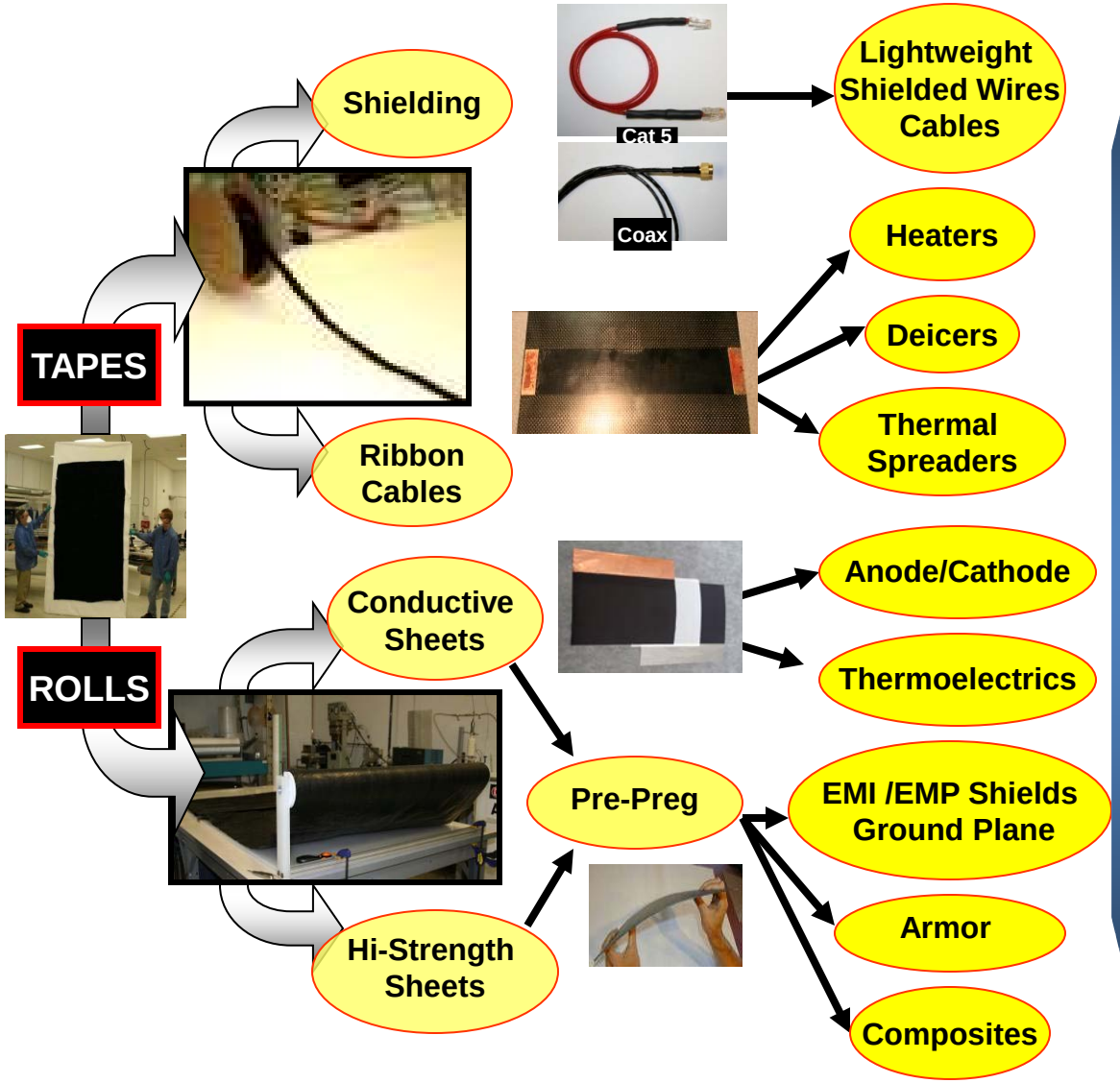
Ex: Self-powered nanosystems

Multifunctional, self-powered nanosystems (using fluid motion, temperature gradient, mechanical energy..) in wireless devices, biomedical systems...



Reference: Z. L. Wang, Adv. Funct. Mater., 2008

Expanded CNT sheet production with broad impact



Commercial and Defense Impact
Multi-Industry Use

Nano2 Report, 2010, p. XLVI. Courtesy R. Ridgley

NSF (2001-): Converging technologies (NBIC) - Examples of new transdisciplinary domains

- **Quantum information science** (IT; Nano and subatomic physics; System approach for dynamic/ probabilistic processes, entanglement and measurement)
- **Eco-bio-complexity** (Bio; Nano; System approach for understanding how macroscopic ecological patterns and processes are maintained based on molecular mechanisms, evolutionary mechanisms; interface between ecology and economics; epidemiological dynamics)
- **Neuromorphic engineering** (Nano, Bio, IT, neurosc.)
- **Cyber-physical systems** (IT, NT, BIO, others)
- **Synthetic & system biology** (Bio, Nano, IT, neuroscience)
- **Cognitive enhancers** (Bio, Nano, neuroscience)

It will be imperative over the next decade to focus on four distinct aspects of nanotechnology development

- How nanoscale science and engineering can improve understanding of nature, generate breakthrough discoveries and innovation, and build materials and systems by nanoscale design – "knowledge progress"
- How nanotechnology can generate economic and medical value —"material progress"
- How nanotechnology can address sustainable development, safety, and international collaboration —"global progress"
- How nanotechnology governance can enhance quality-of-life and social equity —"moral progress"

Several background references

"Nanotechnology Research Directions“, Springer 2000

"Societal Implications of Nanoscience and Nanotechnology", Springer (2001); updated in 2 volumes in 2007

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“Nanotechnology Research Directions for Societal Needs in 2020” Springer (Roco, Mirkin and Hersam 2010)