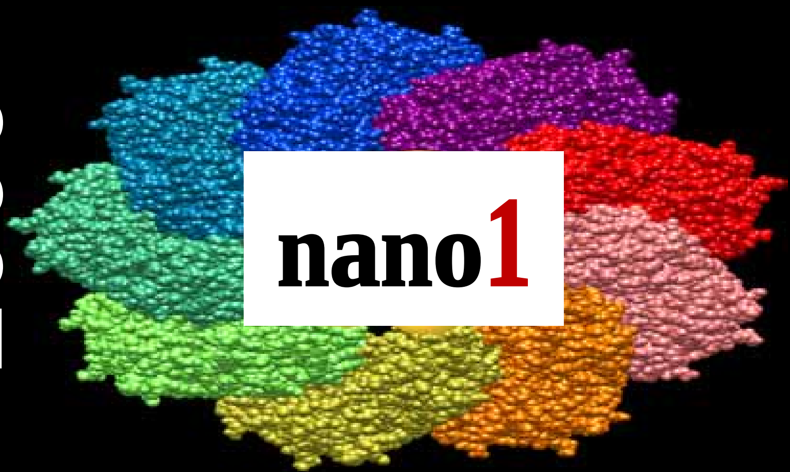
2000



2010

2020

Global Development of Nanotechnology

Mike Roco

National Science Foundation and National Nanotechnology Initiative

Topics

- Nanotechnology timeline: 2000-2020
- Main outcomes & priorities at 10 years
- Nanotechnology & sustainable society
- Outlook for the future

Related publications

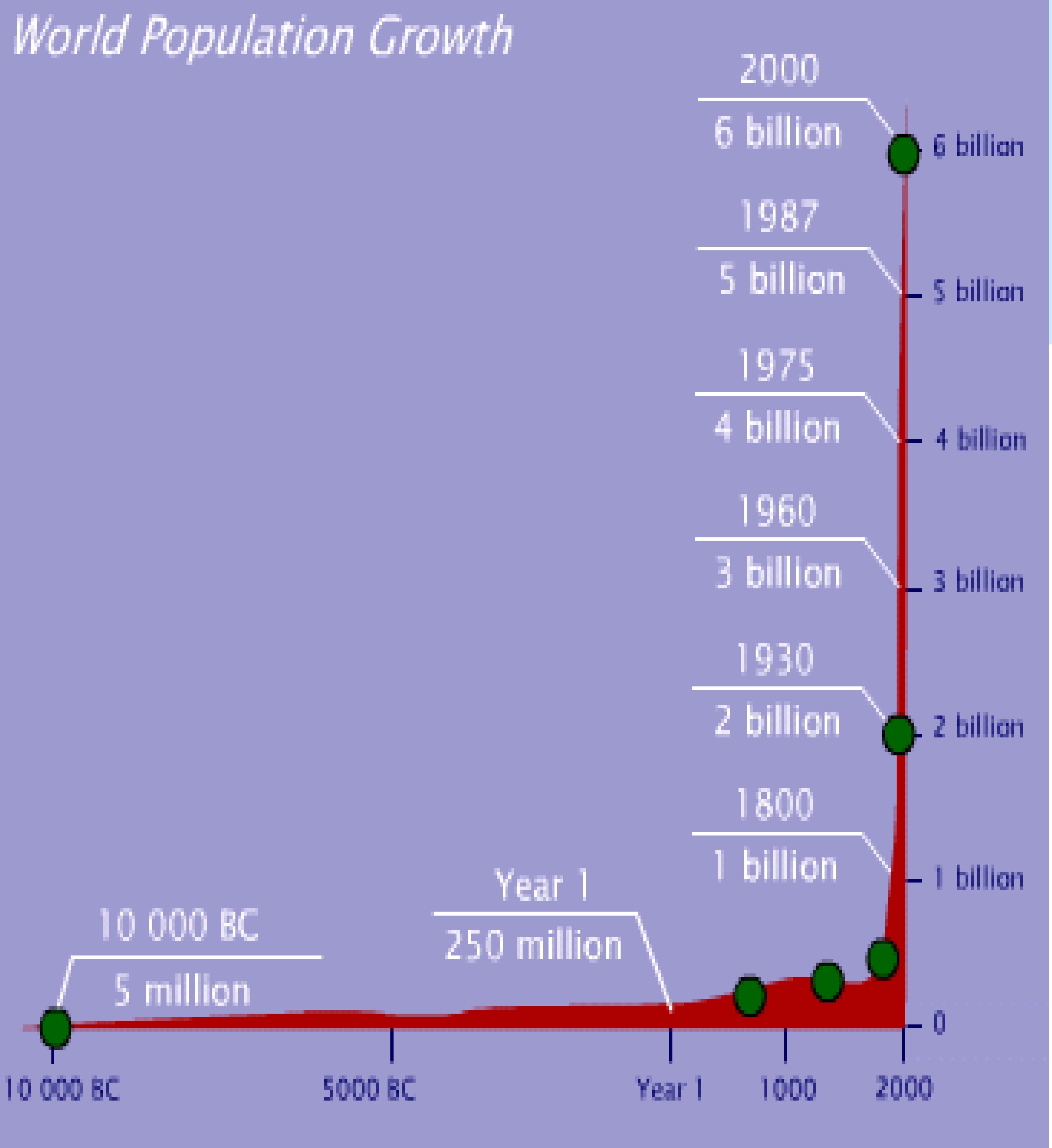
"Nanotechnology: From Discovery to Innovation and Socioeconomic Projects" 2010-2020 (2011)

"The Long View of Nanotechnology development: the NNI at 10 Years" (2011)

"Nanotechnology Research Directions for Societal Needs in 2020" (2011)

"Mapping Nanotechnology Innovation and Knowledge: Global and Longitudinal Patent and Literature Analysis" (2009)

10-year vision documents, 3-year strategic plans, 1-year plans and topical workshops: www.nsf.gov/nano; www.nano.gov



More people with higher expectations

9-10 billion by 2050

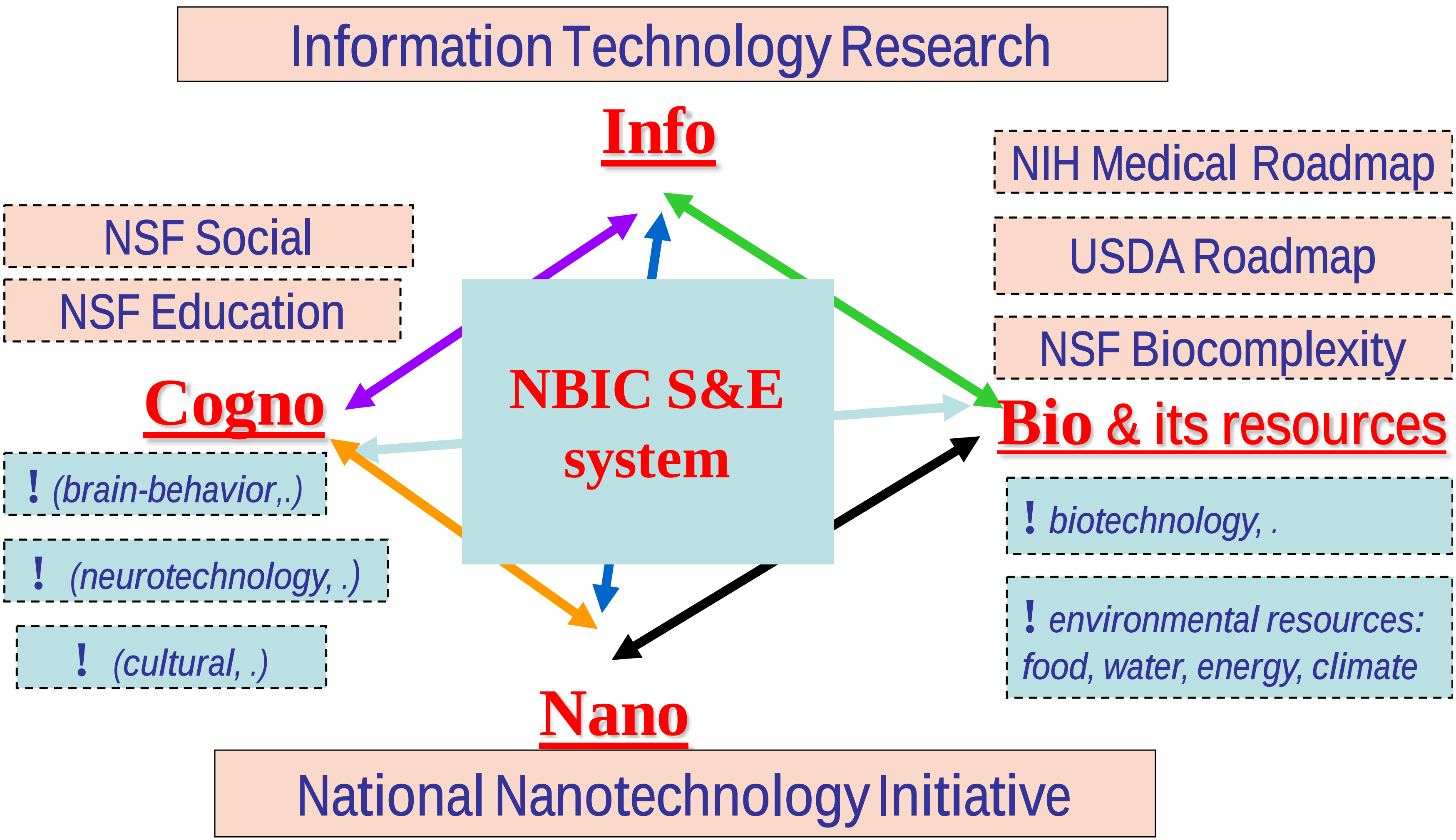
Increased consumption of water, food, energy, materials

Changing society

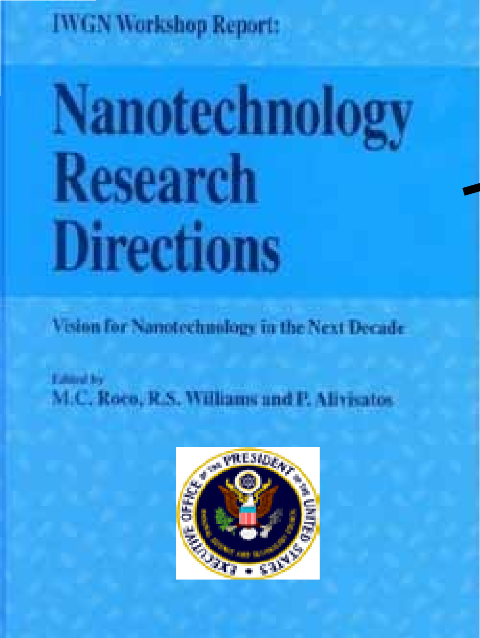
NEED OF RADICALLY NEW TECHNOLOGIES

Converging New Technologies transforming tools

(US overview in 2000-2010 ;
convergence better for *small-scale* than for *large-scale systems*)



MC Roco, 2012 11 04



Springer, 1999

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

based on R&D definition focused on behavior

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

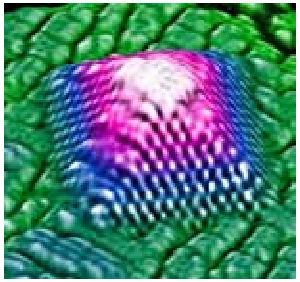
http://www.wtec.org/loyola/nano/IWGN.Research.Directions/IWGN_rd.pdf

Examples of emerging technologies and corresponding U.S. long-term S&T projects

Justified mainly by societal/application factors (examples)

- Manhattan Project, WW2 (centralized, goal focused, simultaneous paths)
- Project Apollo (centralized; goal focused)
- AIDS Vaccine Discovery ("big science" model, Gates Foundation driven)
- IT SEMATECH (Roadmap model, industry driven)

Justified mainly by science and technology potential, following a competitive process



- National Nanotechnology Initiative (bottom-up, science opportunity-born for a general purpose technology)

NNI timeline
(2000-2020)

- Interagency group (11/1996); NNI is proposed at WH (3/1999); Competition OMB (10/1999); PCAST supports NNI (12/1999);
  President Clinton announces NNI in 1/2000

- NNI/NSTC subcommittee established (8/2000); NNI begins (10/2000);
  MOU for NNI coordination and NNCO (1/2001); NanoBusiness Alliance

- President Bush signs 21st Century Nanotechnology R&D Act (12/2003);
  International Dialogue initiated by NNI (6/2004), followed by OECD, ISO

- President Obama approves PCAST (2010) vision for NNI to 2020

- NNI Signature Initiatives (2011 -2015) for creating nanosystems

- Institutionalize NSE (2016-2020) for general purpose technology

Broad societal implications that have justified the investment in nanotechnology

- Knowledge base: better comprehension of nature, matter, life
- Productivity: New technologies, products and industries
  ~ $1 trillion products incorporating nano by 2015 (est. $450B in 2012)
  ~ 2 million nanotech workers by 2015 (est. 900,000 in 2012)
- Improved healthcare and cognition: molecular medicine, global communication and cognition system, brain-machine links
- Sustainability : water, food, energy, materials, clean environment..
  Nanotechnology the best general purpose technology for sustainability: smaller use of resources, precise manufacturing with less pollution, breakthrough technologies for solutions

The World is NOT Currently Achieving Sustainable Development

Every major ecosystem is under threat at different time scales: water, food, risk of climate change, energy, biodiversity, mineral resources, urban communities

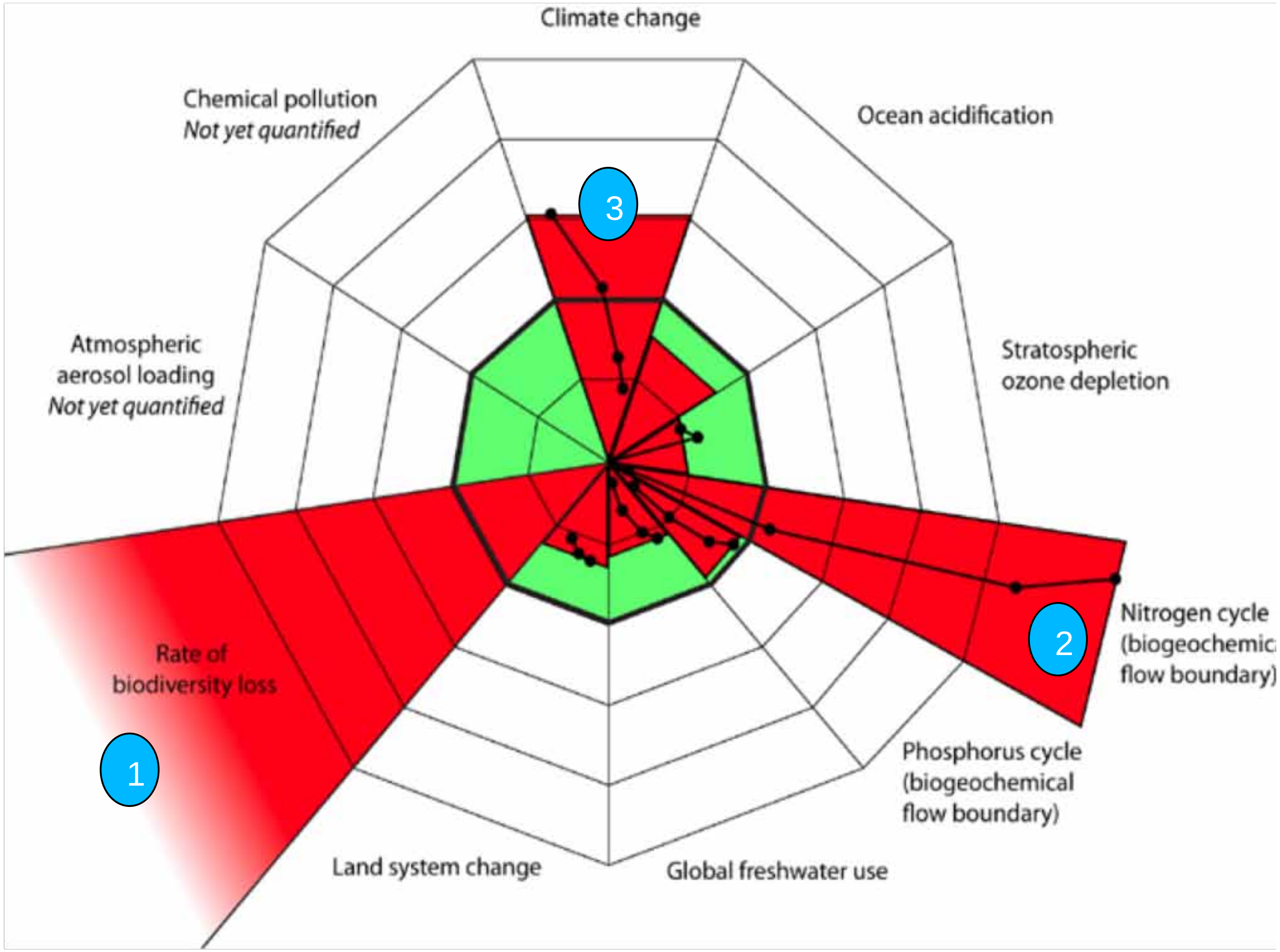
Nanotechnology may offer efficient manufacturing with less resources, less waste, better functioning products

Need for global governance of converging technologies: International Grand Challenge (Note: SNO may contribute)

Nanotechnology Research Directions for Societal Needs in 2020

(NSF/WTEC Report 2010)

addresses interconnected environmental and societal processes



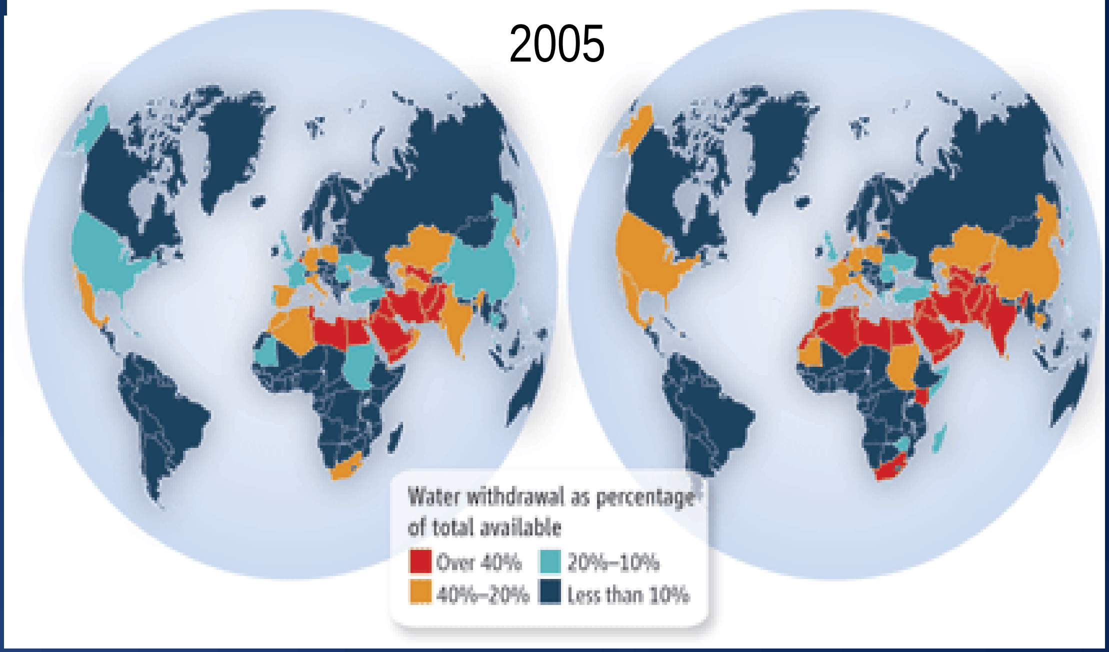
Rockstrom, Nature, 2009

Earth system - coupled and interacting physical, chemical, biological and socioeconomic processes

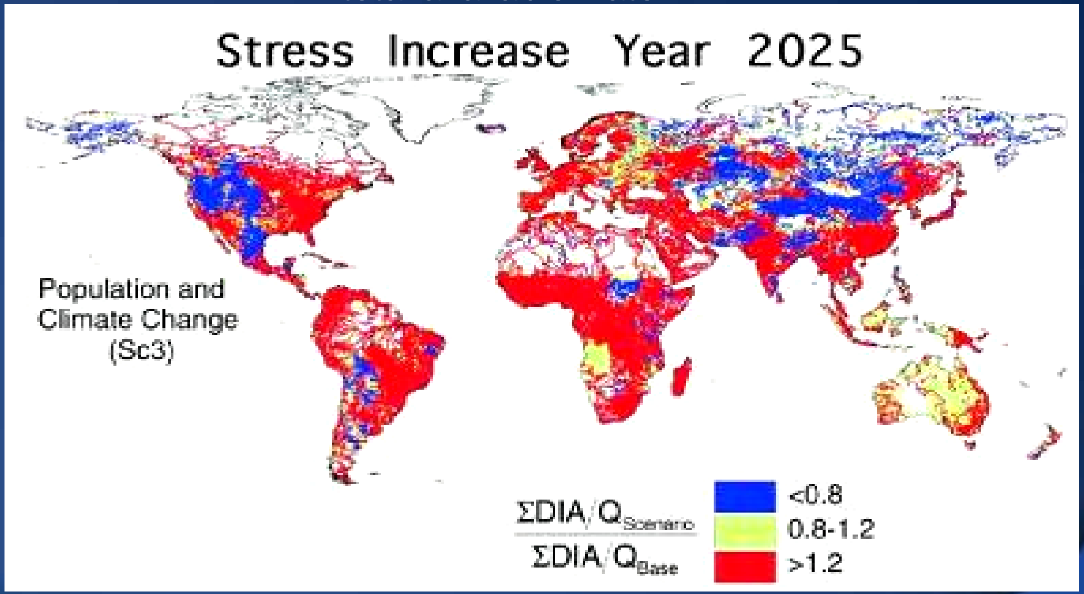
Planetary boundaries estimating a safe operating space for humanity with respect to the functioning of the Earth System

Example of Problems Facing the World

- 1.1 Billion people at risk from lack of clean water
- 35% of people in developing world die from water related problems



World Map showing water consumption world-wide as percentage of total available water.



World Map showing affect of population and climate change on water stress.

Nanoproducts and Nanomanufacturing

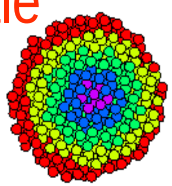
- Fragmentation
- Patterning
- Restructuring of bulk
- Lithography, ..

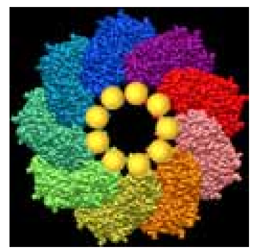
- Interfaces, field & boundary control
- Positioning assembly
- Integration, ..

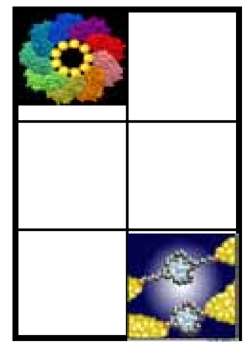
- System engineering
- Device architecture
- Integration, ..

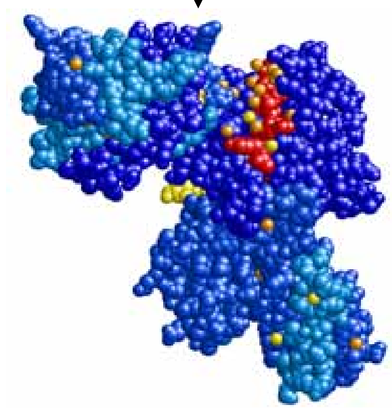
- Nanosystem biology
- Emerging systems
- Hierarchical integration..

From Nanoscale Modules

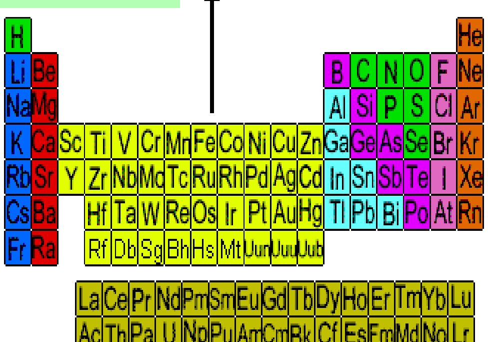








Assembling



- Directed selfassembling,
- Templating,
- New molecules

- Multiscale selfassembling,
- In situ processing, ..

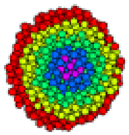
- Eng. molecules as devices,
- Quantum control,
- Synthetic biology..

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

MC Roco, 2012 11 04

Introduction of New Generations of Products and Productive Processes (2000-2020)

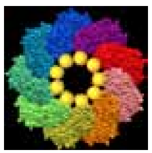
Timeline for beginning of industrial prototyping and nanotechnology commercialization



2000

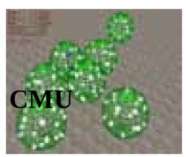
1st: Passive nanostructures (1st generation products)

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



~ 2005

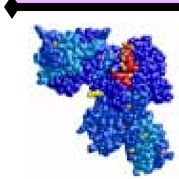
2nd: Active nanostructures Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures



~ 2010

3rd: Nanosystems

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



~ 2015-2020

4th: Molecular nanosystems

Ex: molecular devices ‘by design’, atomic design, emerging functions

Converging technologies

Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

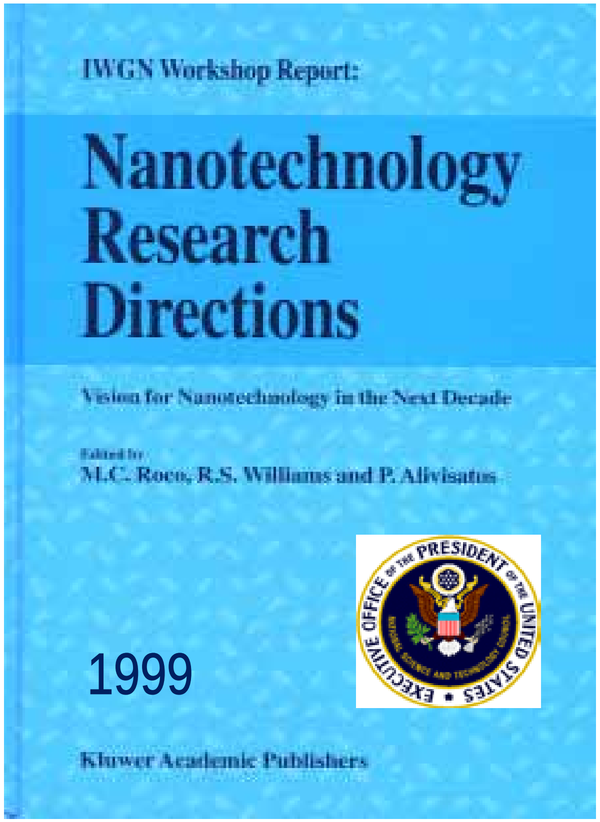
Higher uncertainty & risk

Increase Complexity & Integration

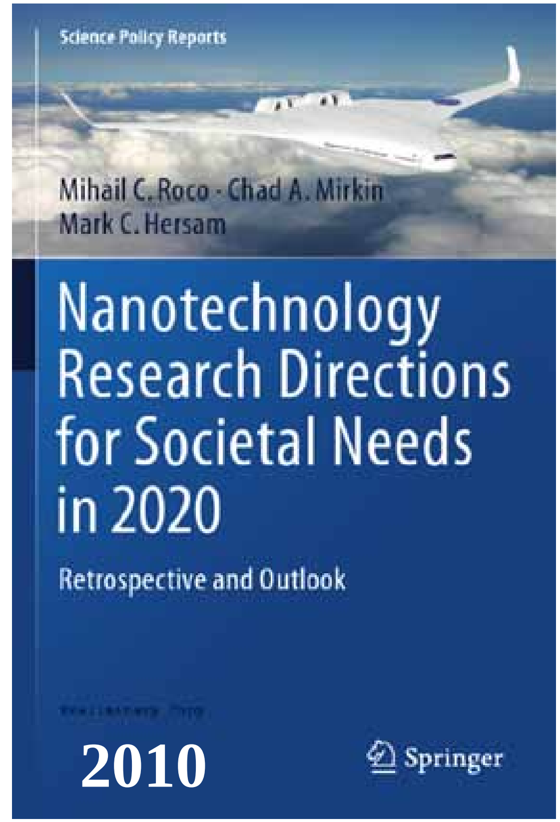
Reference: AIChE Journal, Vol. 50 (5), 2004

Nanotechnology: from discovery to innovation and socioeconomic projects (2000-2020)

nano1 (2000-2010)



nano2 (2010-2020)



NS&E foundational interdisciplinary research Semi-empirical synthesis of nanocomponents	NS&E integration for general purpose technology Science-based nanosystems for societal projects

NSF/WTEC, www.wtec.org/nano2/

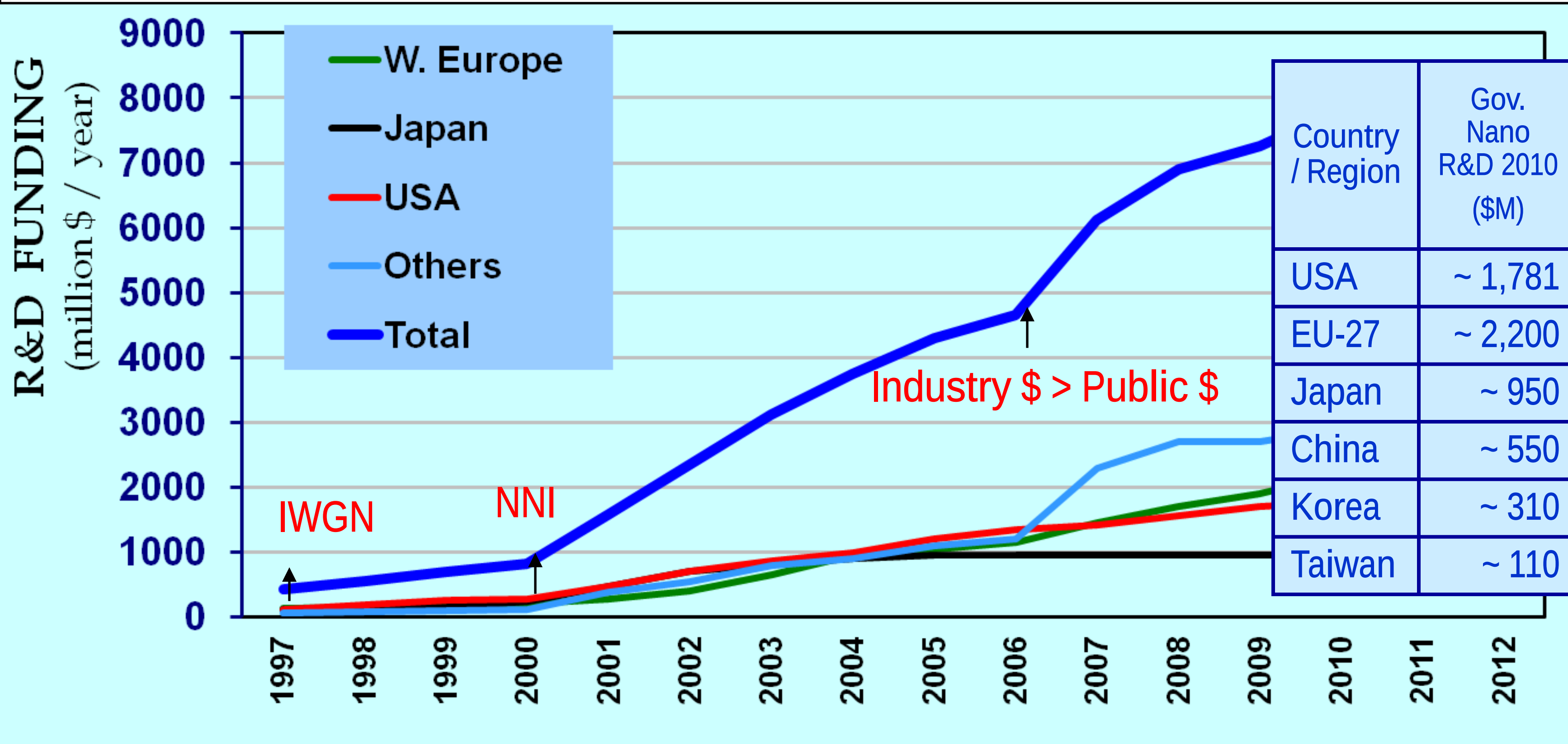
2000-2010
Estimates show an average quasi-exp growth rate of key nanotechnology indicators of 16% - 33%

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*					

2000-2010

Changing international context:

federal/national government R&D funding (NNI definition)



Country / Region	Gov. Nano R&D 2010 ($M)	Specific Nano R&D 2008 ($/Capita)
USA	~ 1,781	~ 5.8
EU-27	~ 2,200	~ 5.9
Japan	~ 950	~ 7.3
China	~ 550	~ 0.5
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

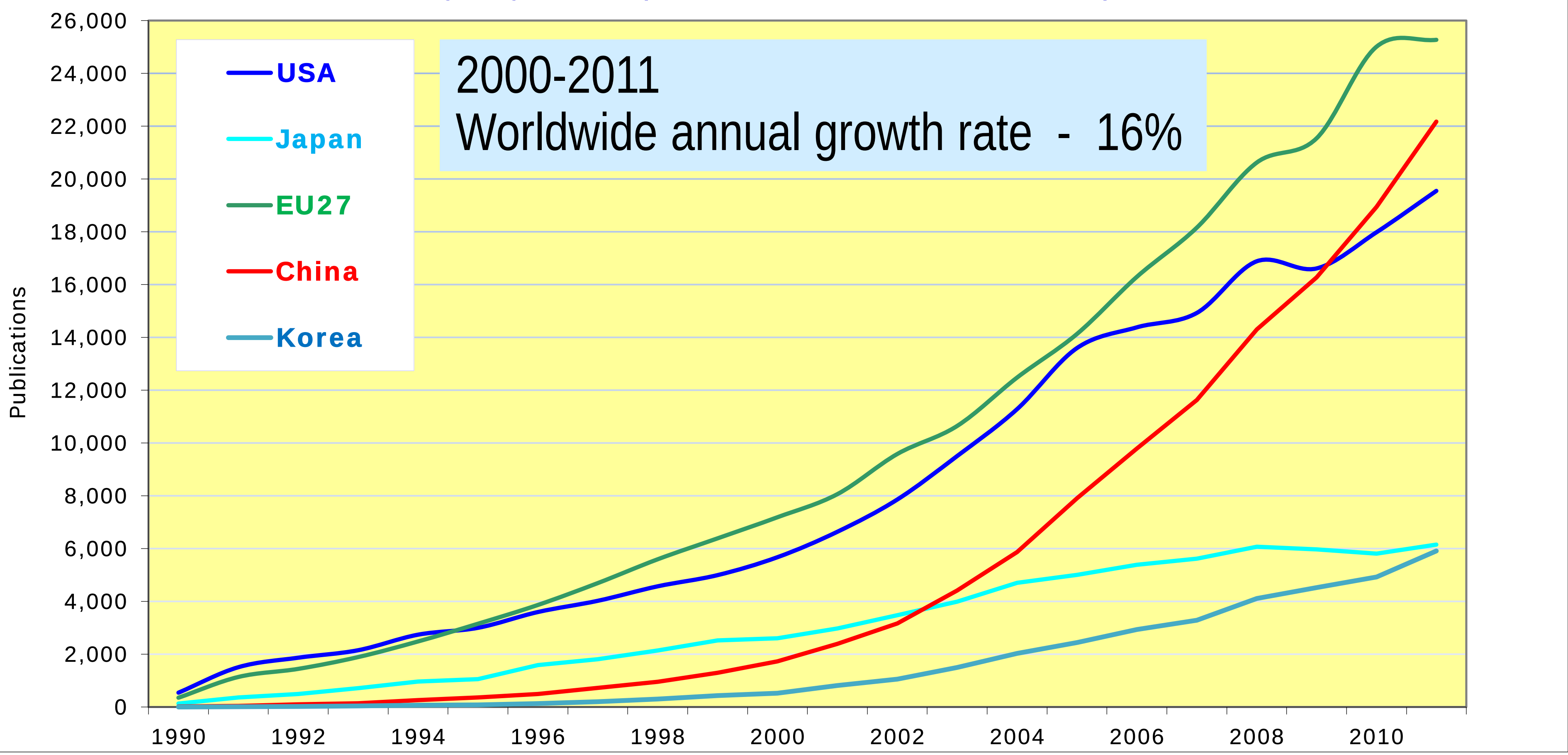
Rapid, uneven growth per countries

MC Roco, 2012 11 04

NANOTECHNOLOGY OUTPUTS AT 10 YEARS

Nanotechnology publications in the Science Citation Index (SCI) 1990 - 2011

Data was generated using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen and Roco, NRC, 2012)

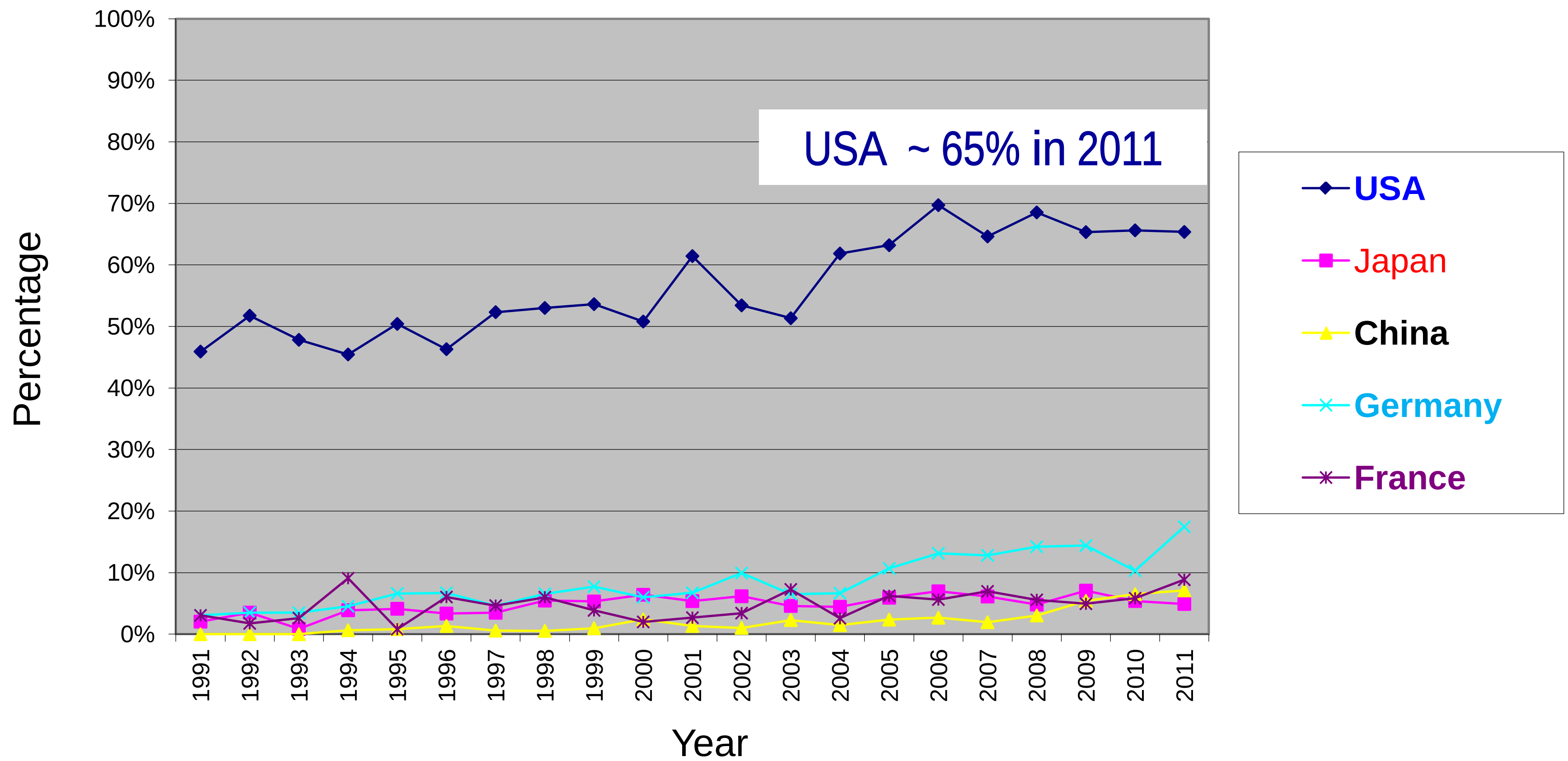


Rapid, uneven growth per countries

MC Roco, 2012 11 04

Percent of nanotechnology publications by country in Science, Nature, and Proceedings of NAS, 1991-2011

Data was generated using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen and Roco, NRC, 2012)



U.S. maintain the lead in highly cited publications

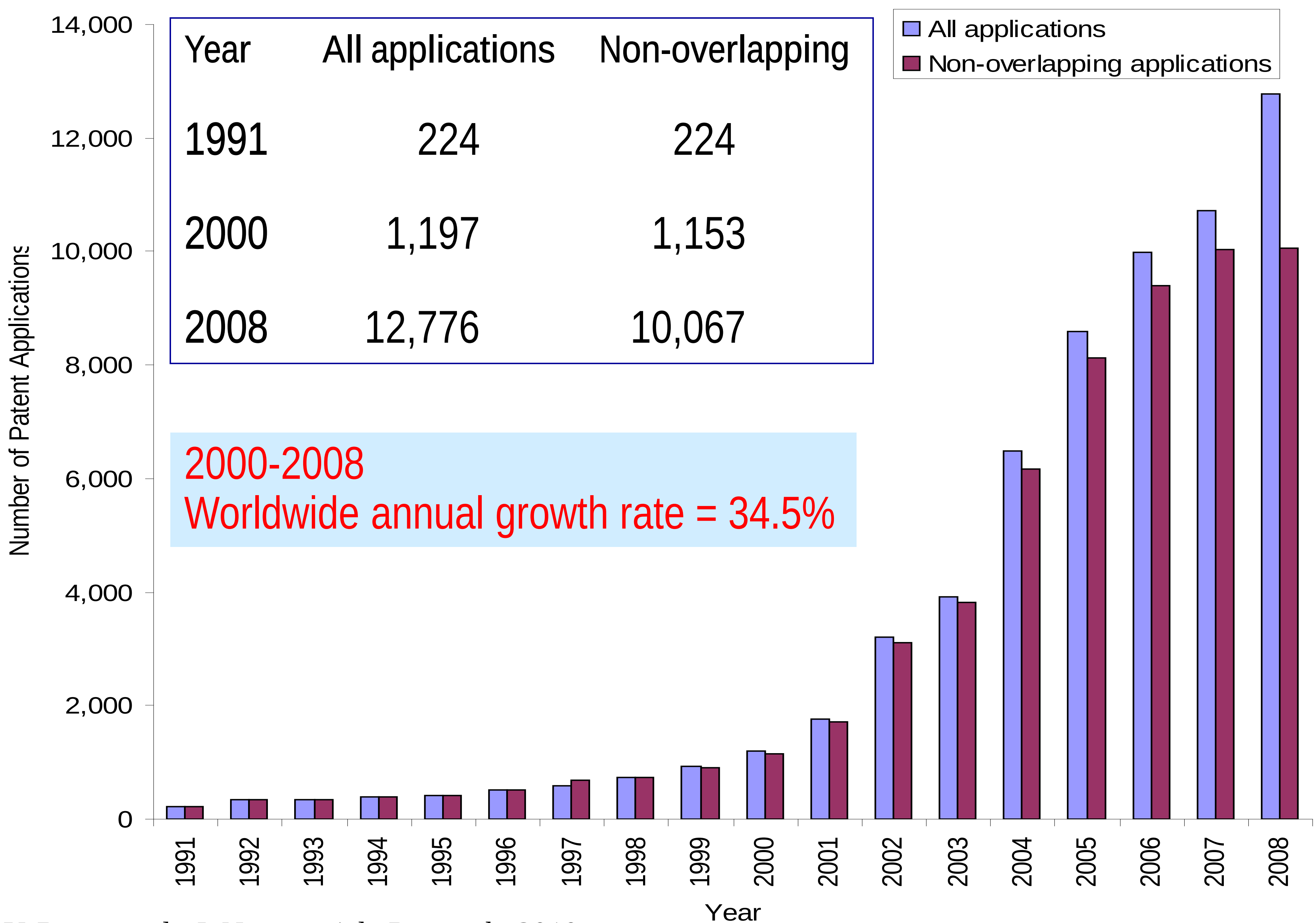
Article citations by NSF Principal Investigators

```
                                 Individual 95% CIs For Mean Based on Pooled StDev
Level          N    Mean   StDev  -------+---------+---------+---------+--
NSF         3615   166.0   693.5                                      (*-)
IBM         1877    53.8   158.8                (*-)
TOP10      33071    27.0   160.2     (*
UC         10097    42.4   233.9         (*
US         85669    31.6   183.2       *
EntireSet 260880    26.2   147.1     (*
Japan      22358    24.2    85.5     *)
European  118429    20.5    94.9    *
Others     63654    15.1    74.5  (*
                                  -------+---------+---------+---------+--
                                        40        80       120       160
```

Chen at al. (2012)

NSF-funded PIs (1991-2010) have a higher number of citations (<u>166 in average</u>) than researchers in other groups: IBM, UC, US (<u>32 in average</u>), Entire world Set (26 in average), Japan, European, Others

WORDWIDE NUMBER OF NANOTECHNOLOGY PATENT APPLICATIONS



Year	All applications	Non-overlapping
1991	224	224
2000	1,197	1,153
2008	12,776	10,067

Y. Dang, et al., J. Nanoparticle Research, 2010

Number of patent citations by NSF P.I.-Inventors

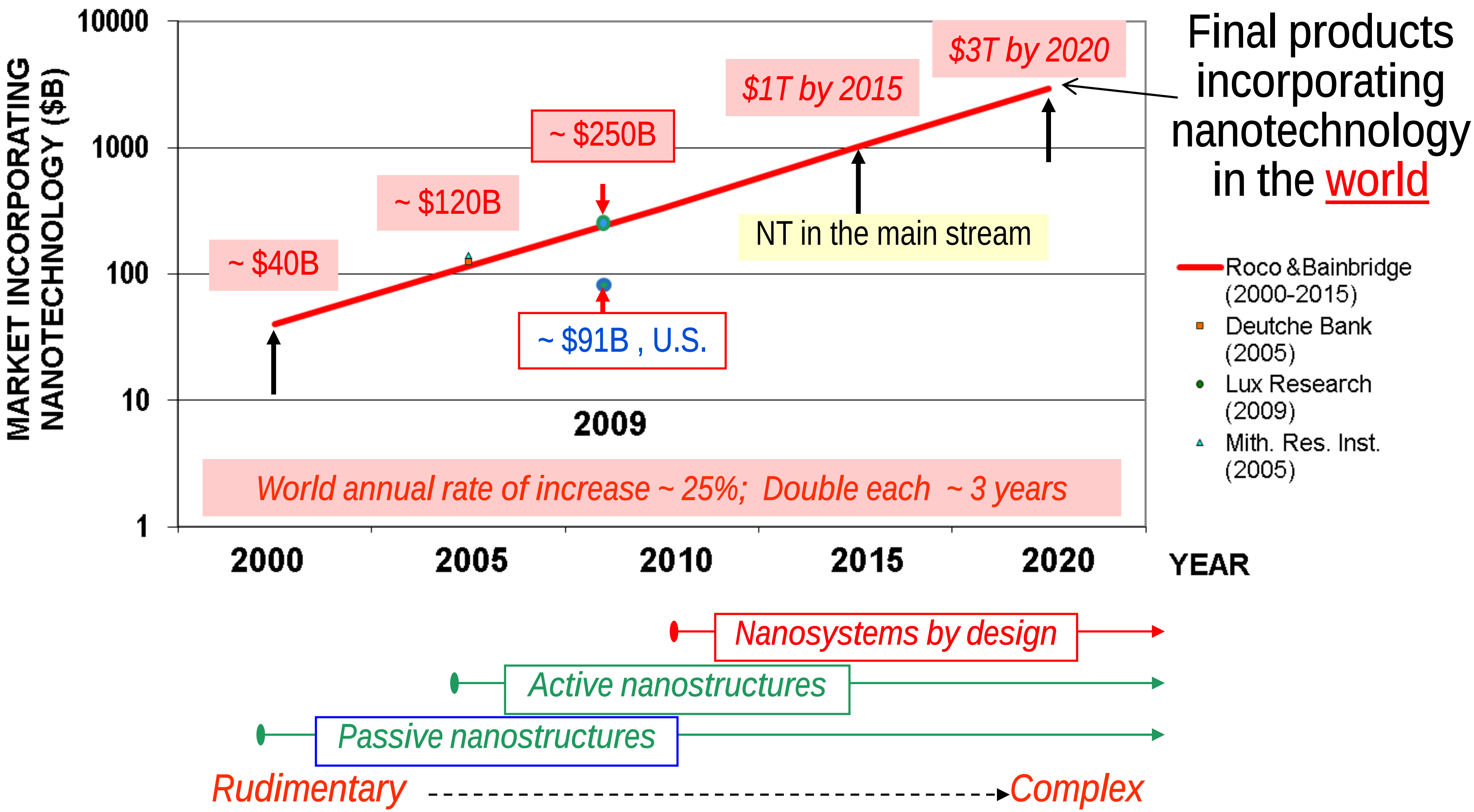
```
                                  Individual 95% CIs For Mean Based on Pooled StDev
Level           N   Mean   StDev  ---------+---------+---------+---------+
NSF          1887  30.93  113.90                                  (--*-)
IBM          3614  10.21   30.04           (-*-)
TOP10       14076  11.65   87.53              (*)
UC           2497  10.29   35.08           (-*-)
US          96962   9.04   51.08           *)
EntireSet  140855   7.32   44.04         *
Japan       20562   3.43   19.43   (*)
European    20211   1.79    9.03 (*)
Others       8133   2.10    9.99 (-*)
                                  ---------+---------+---------+---------+
                                         8.0      16.0      24.0      32.0
```

Chen at al. (2012)

NSF-funded PI-Inventors (1991-2010) have more citations (<u>31 in average</u>) than inventors in the TOP10, UC, IBM, US (<u>9 in average</u>), Entire World Set (7 in average), Japan, Others, and European group

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

(Estimation made in 2000 after international study in > 20 countries)

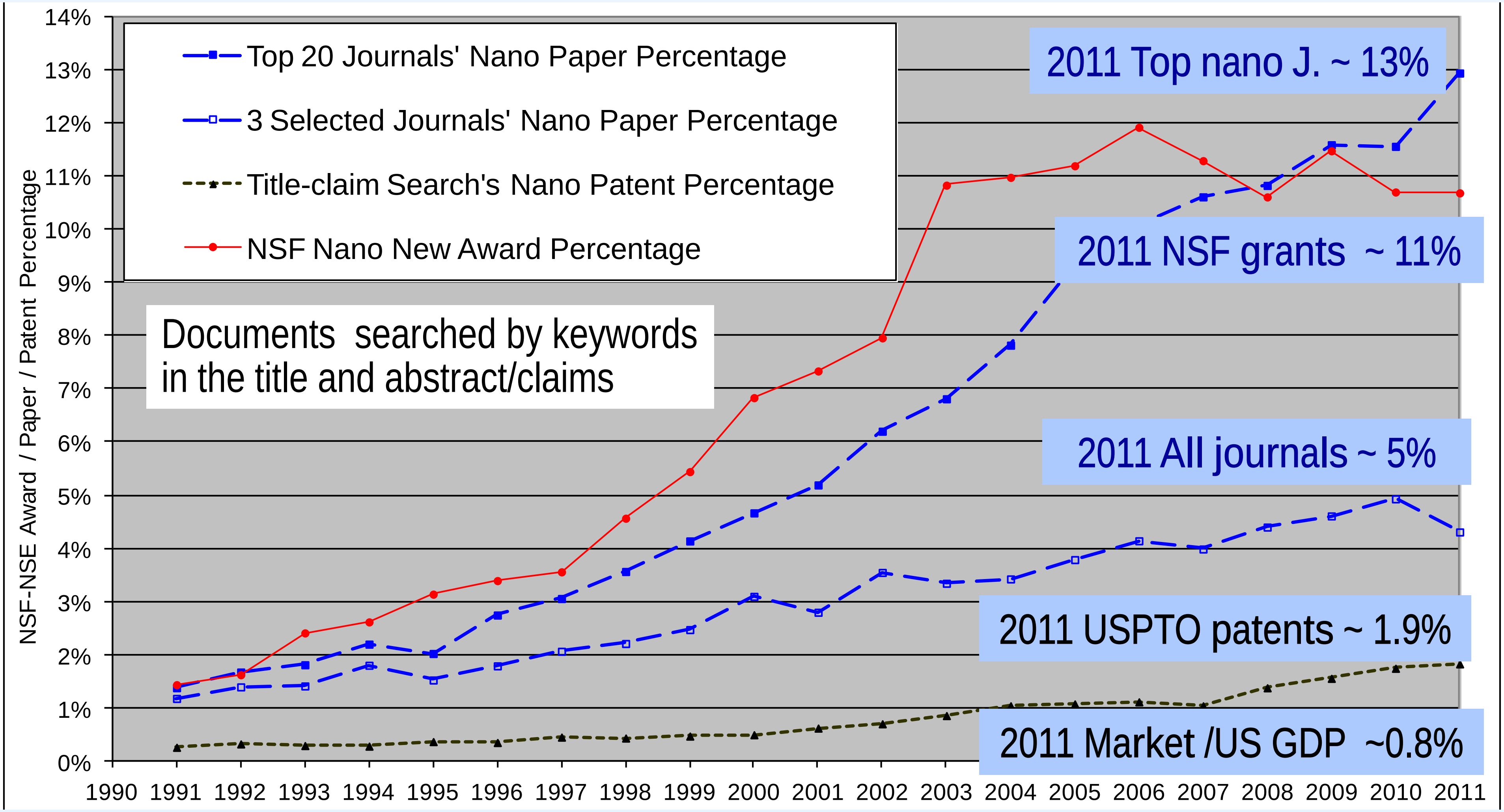


Reference: Roco and Bainbridge, Springer, 2001

MC Roco, 2012 11 04

Percentage of nanotechnology content in NSF awards, ISO papers and USPTO patents (1991-2011)

(update after Encyclopedia Nanoscience, 2012)



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

MC Roco, 2012 11 04

Main nanotechnology outcome at 10 years

- ***Foundational knowledge of nature*** by control of matter at the nanoscale
- ***Global interdisciplinary community*** (~ 600,000 in) for R&D, nano-EHS and ELSI
- ***Science & technology (S&T) breakthroughs***
- ***Novel methods and tools***
- ***Extensive multi-domain infrastructure***
- ***New education & innovation ecosystems***
- ***New industries*** with increased added value
- ***Solutions for sustainable development***

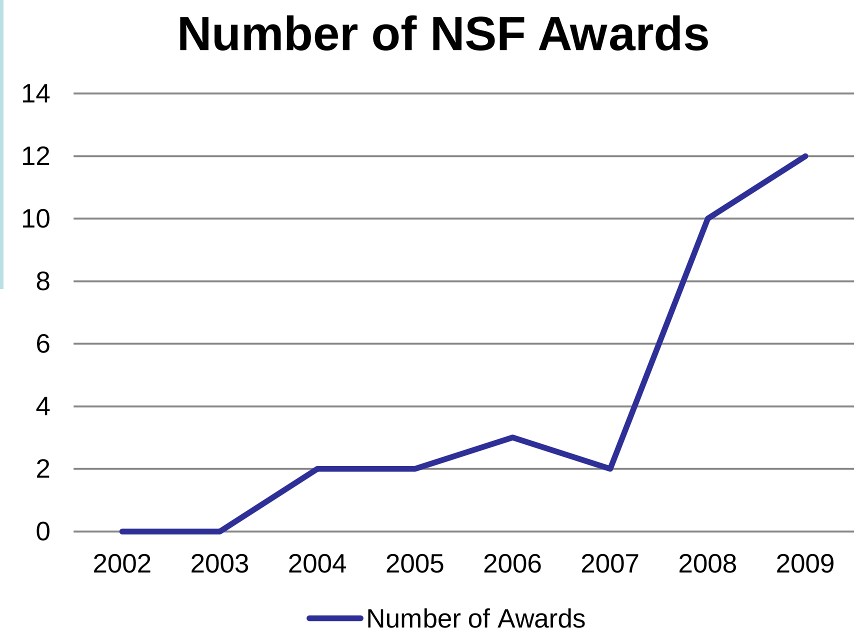
(A) 2000-2010 S&T Outcomes

- *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; Towards periodical table for nanostructures.**

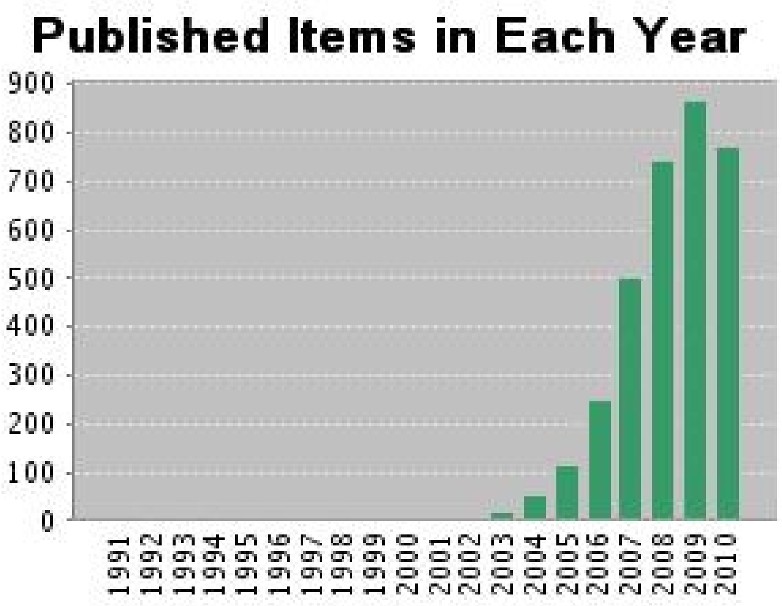
- *New S&E fields have emerged* such as: *spintronics (2001), plasmonics (2004), metamaterials, carbon nanoelectronics, molecules by design, nanofluidics, nanobiomedicine, nanoimaging, nanophotonics, opto-genetics, synthetic biology, branches of nanomanufacturing, and nanosystems*

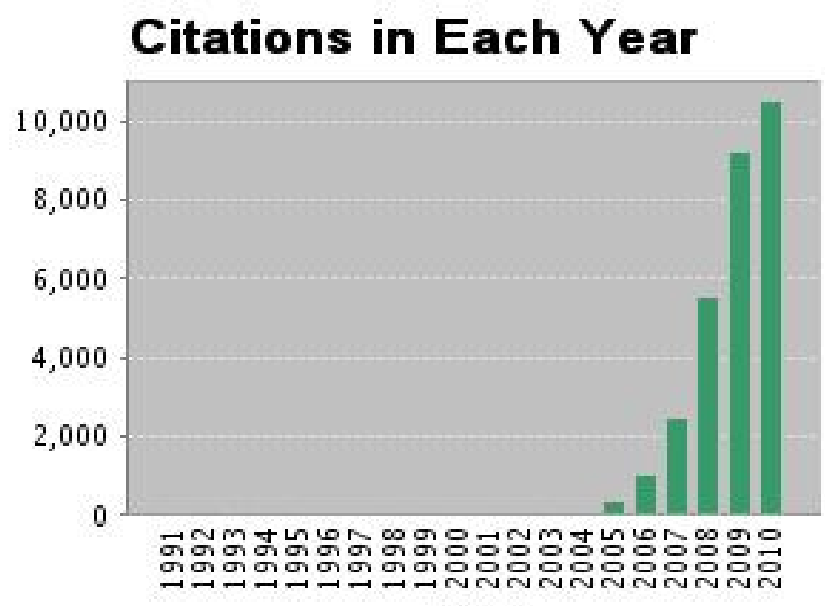
- *Technological breakthroughs* in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; **expansion into** energy resources and water filtration, agriculture and forestry; and **integration of nanotechnology with other emerging areas** such as quantum information systems, neuromorphic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

Example: Emergence of Plasmonics after 2004



Plasmonics: Merging photonics, electronics and materials at nanoscale dimensions

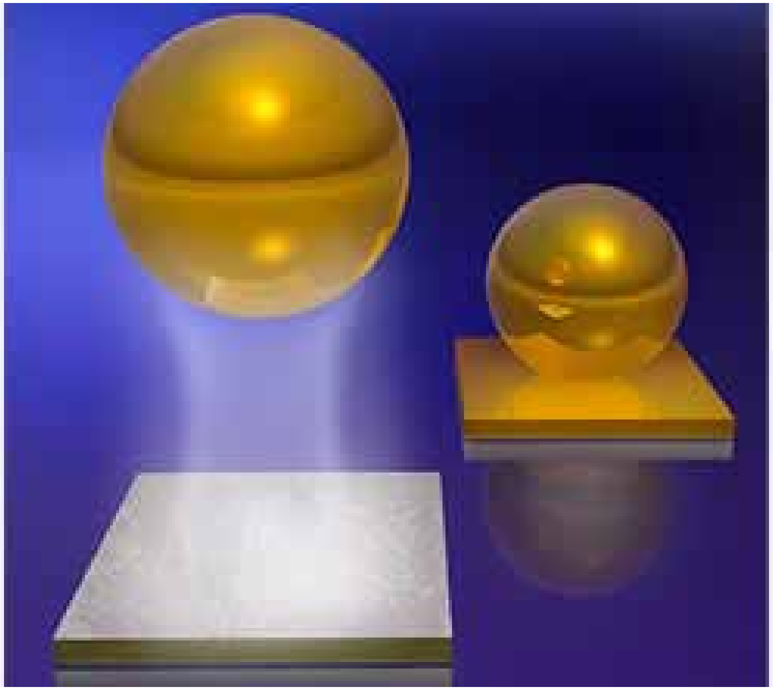




MC Roco, 2012 11 04

Discovery of Nanoscale Repulsion

Federico Capasso, Harvard University



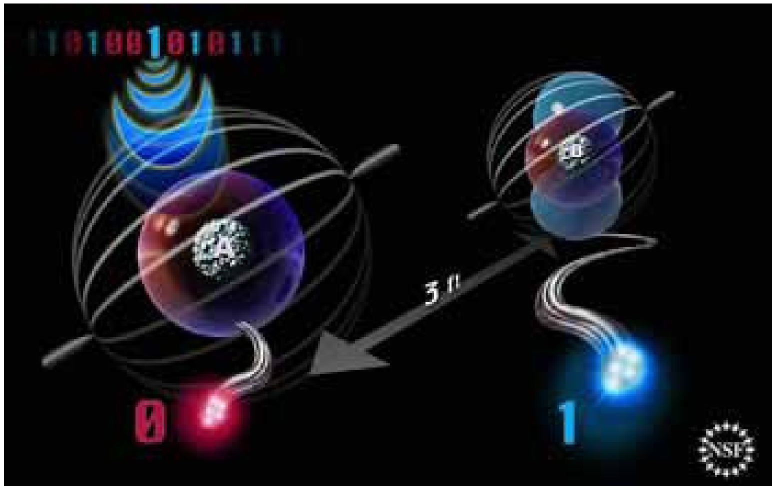
A repulsive force arising at nanoscale was identified similar to attractive repulsive Casimir-Lifshitz forces.

As a gold-coated sphere was brought closer to a silica plate - a repulsive force around one ten-billionth of a newton was measured starting at a separation of about 80 nanometers.

For nanocomponents of the right composition, immersed in a suitable liquid, this repulsive force would amount to a kind of quantum levitation that would keep surfaces slightly apart

How to Teleport Quantum Information from One Atom to Another

Chris Monroe, University of Maryland, NSF 0829424

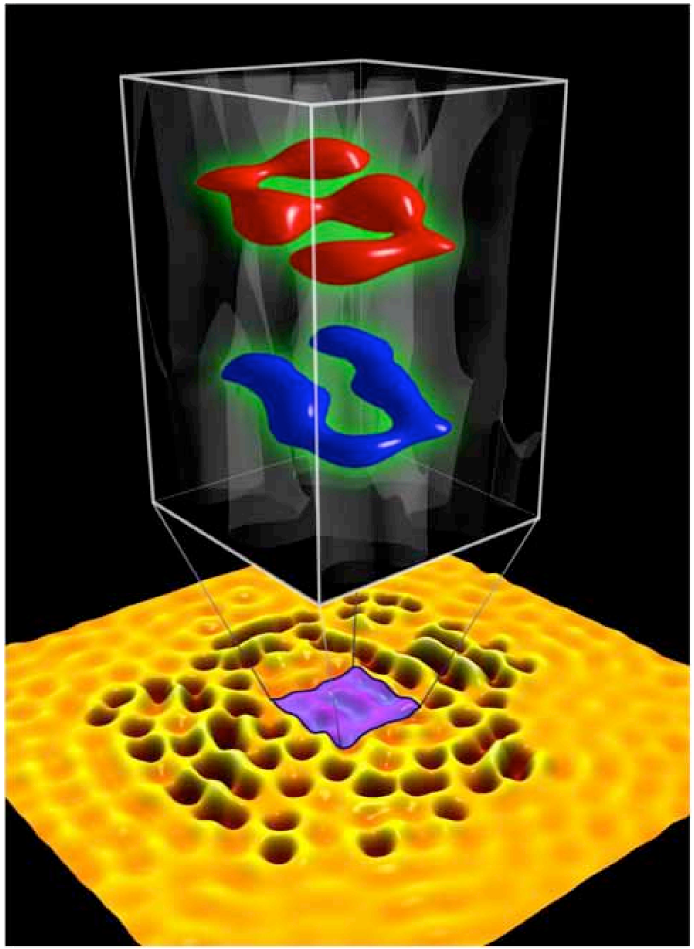


Teleportation carries information between entangled atoms.

Teleportation to transfer a quantum state over a significant distance from one atom to another was achieved.

Two ions are entangled in a quantum way in which actions on one can have an instant effect on the other

Experiments have attempted to teleport states tens of thousands of times per second. But only about 5 times in every billion attempts do they get the simultaneous signal at the beam splitter telling them they can proceed to the final step.



Creating the World's Smallest Letters

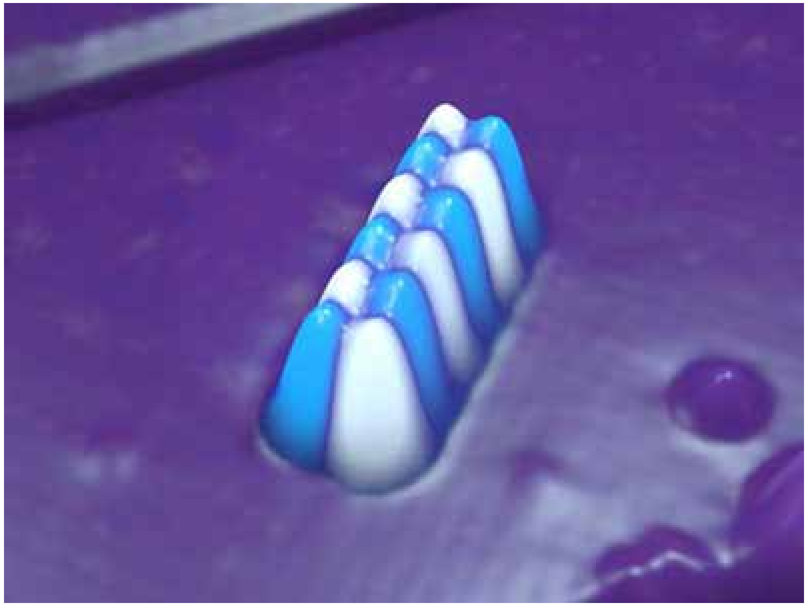
Hari Manoharan, NSF – 0425897, NSEC Stanford U.

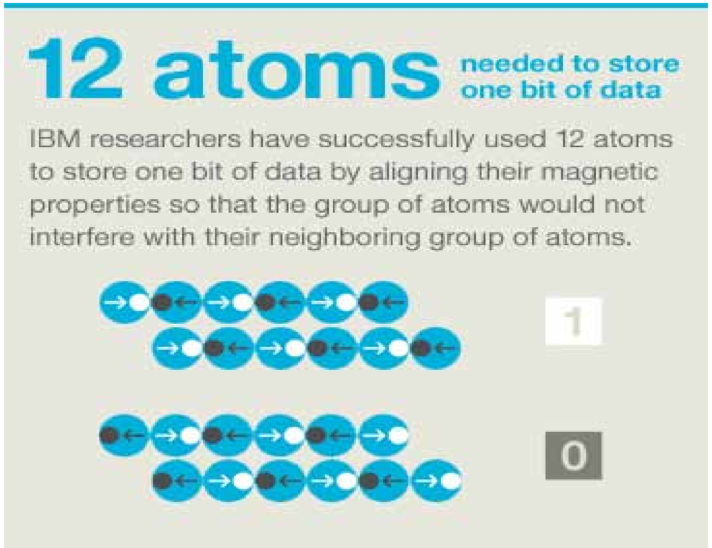
A STM is used to position CO molecules on a copper (111) surface and to read out by 2D illumination the **molecular holographic encoding** spelling the **letters SU of** <u>about 1 nm (0.8 by 1.5 nm) size in 3D</u>

The letters with features as small as 3 A are formed in the interference pattern generated by the 2D surface state electrons from the (111) face of the copper crystal and confined by the CO molecules acting as local gates (quantum holographic encoding)

C. Moon et al., Nature Nanotechnology, 4, (2009)

IBM magnetic storage is at 100 times denser than hard disk drives and solid state memory chips



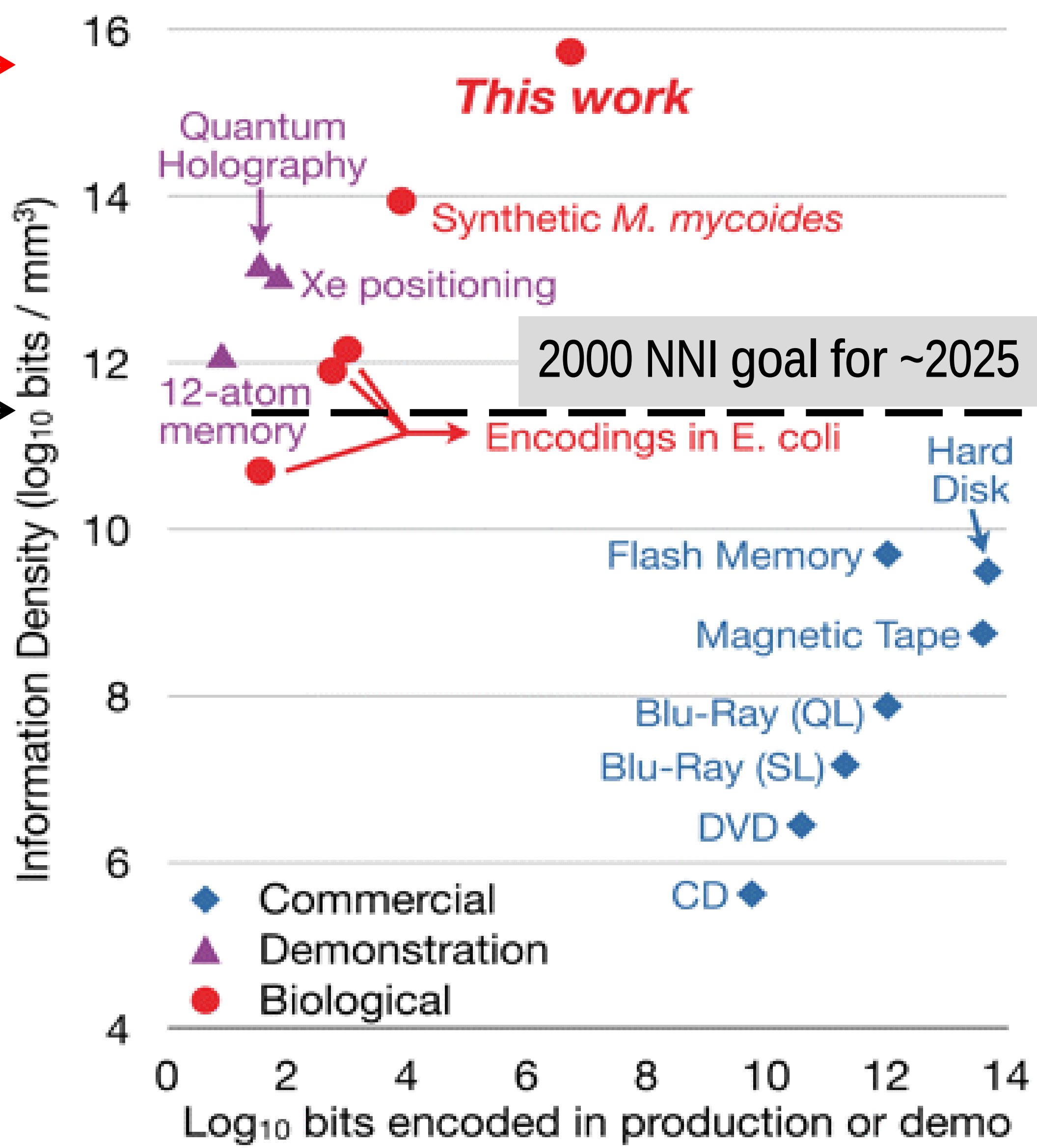


Antiferromagnetic order in an iron atom array on copper nitrate revealed by spin-polarized imaging with a scanning tunneling microscope - area 4 x 16 nm (Bistability in Atomic-Scale Antiferromagnets, Loth, Baumann, C Lutz, Eigler and Heinrich, Science Jan 2012)

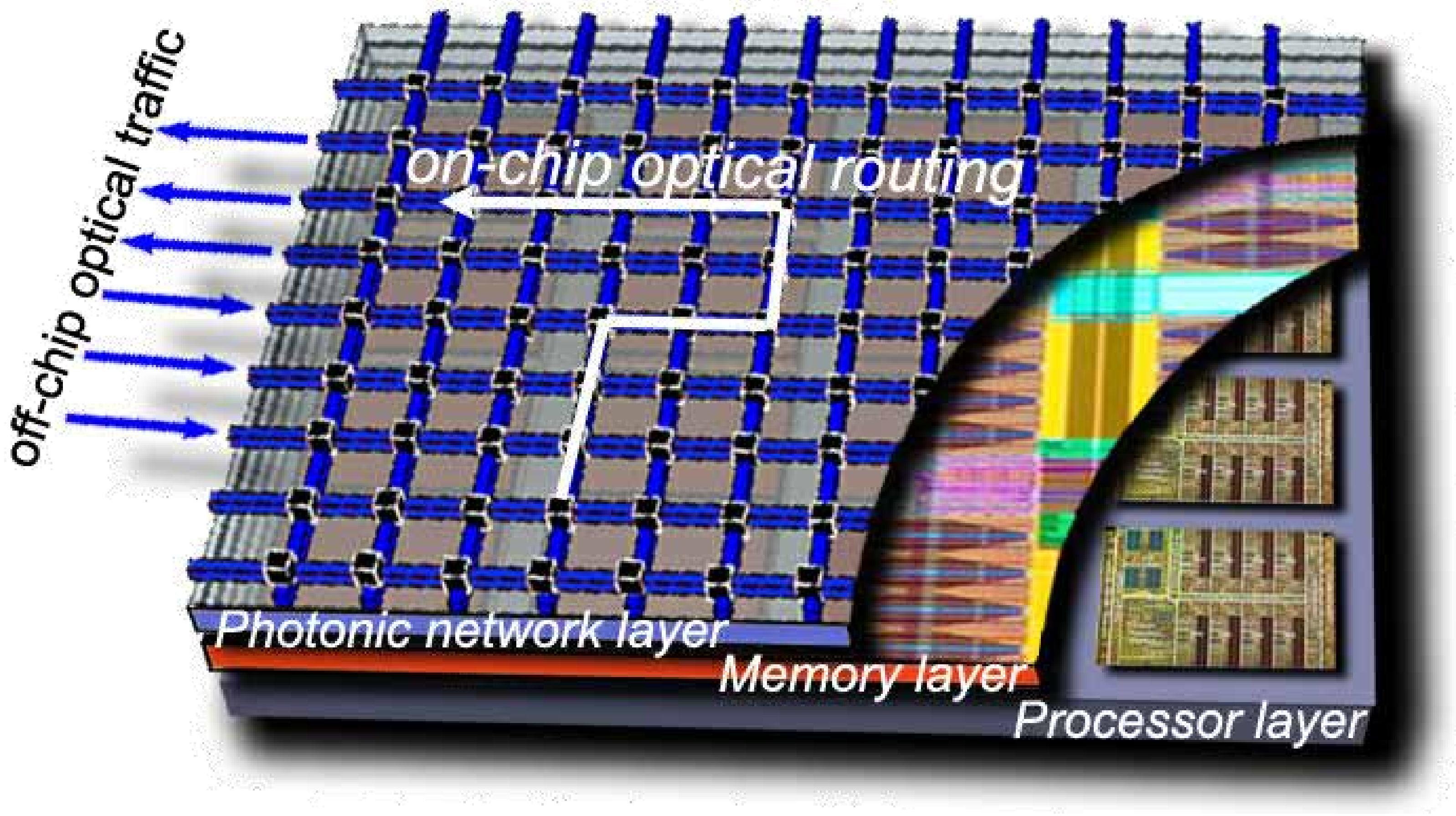
DNA data memory system (Harvard U., 2012)

2012: DNA system could store it in about 1mm cube (Science, Aug. 2012)

2000: NNI goal for ~2025
- all data from Library of Congress in a device of size of a 1cm sugar cube (President Clinton)
– it was labeled as too ambitious in 2000

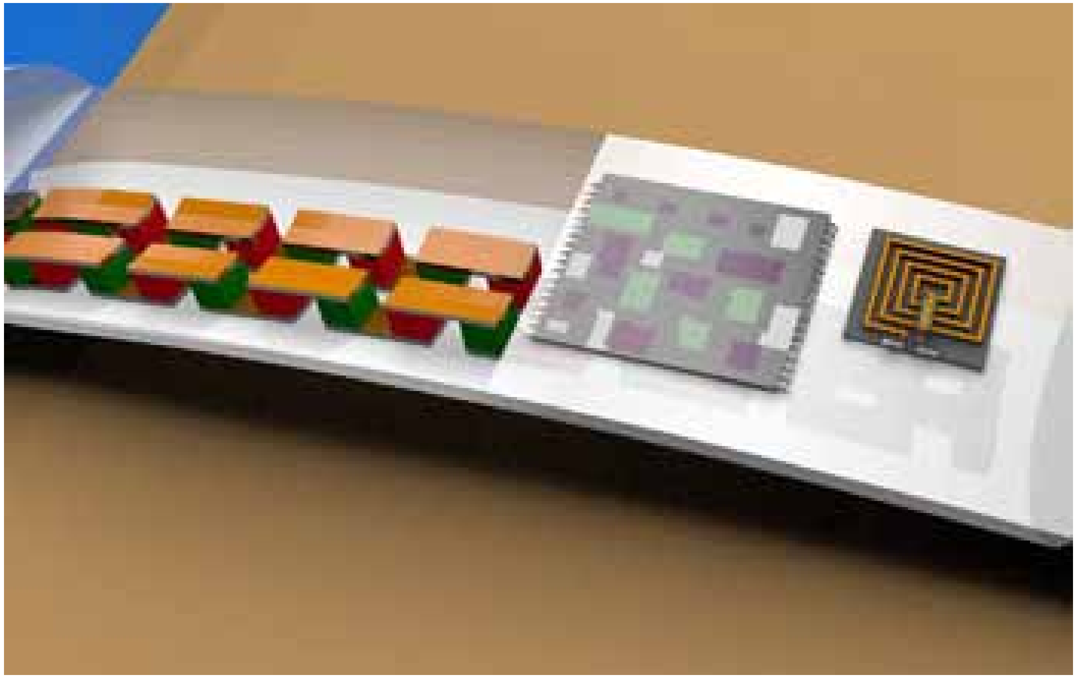


Silicon Nanophotonics - chip with three layers

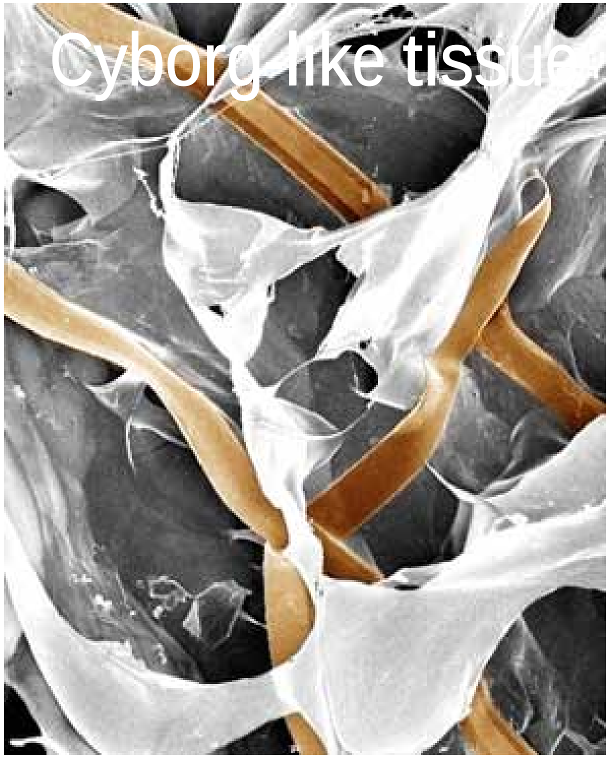


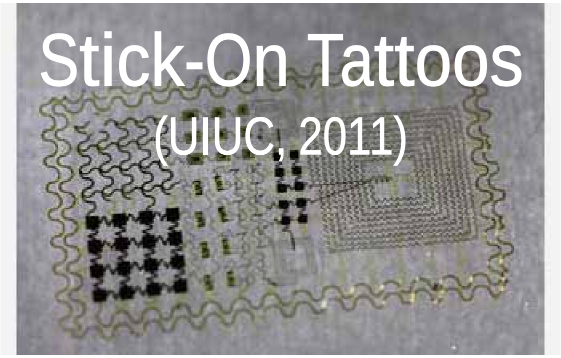
Yurii Vlasov, IBM

Nanosystems Engineering Research Center (NSF) @NCSU will use nanomaterials and nanodevices to develop self-powered health and environmental monitoring systems. Example of device could be worn on the wrist, like a watch. Search of connections between exposure to pollutants and chronic diseases.



Cyborg-like tissue monitors cells and organs
Nanoelectronic scaffolding supports living tissue





Lieber, Langer et al. (Harvard U., 2012)

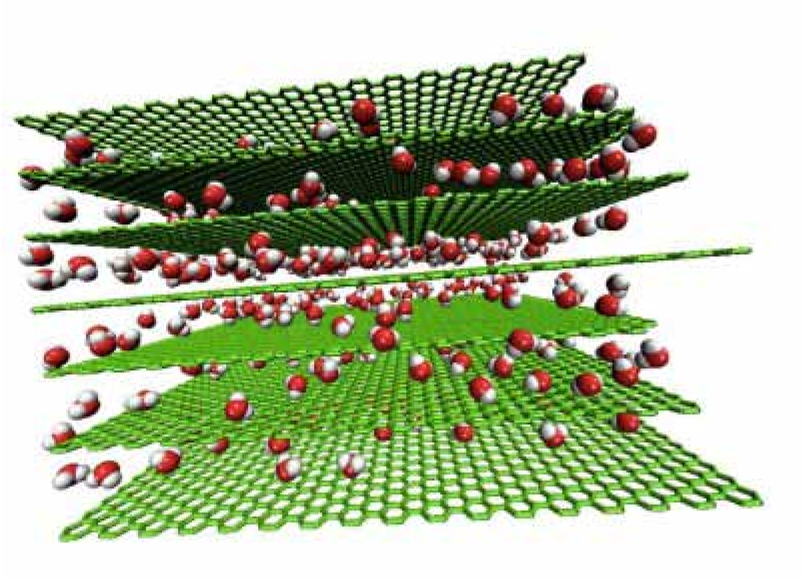
- The cyborg-like tissue merges nanoscale electronics with biological tissues into a mesh of transistors and cells, and supports cell growth while simultaneously monitoring the activities of those cells

- It could improve *in vitro* drug screening by allowing researchers to track how cells in a three-dimensional environment respond to drugs in real time

- It may also be a step toward prosthetics that communicate directly with the nervous system, (Nature Materials, Aug 2012)

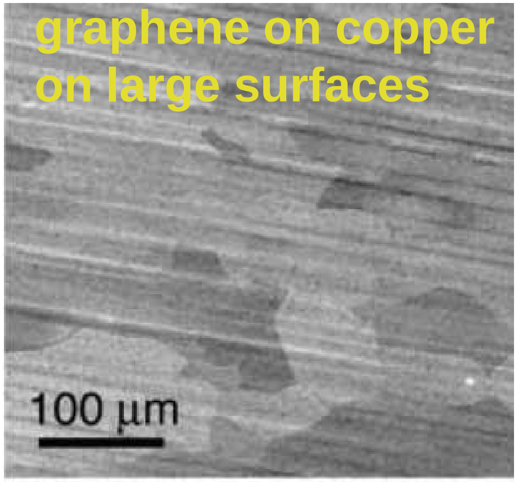
Graphite + water = high density energy storage
(G. Jiang, 2011)

Keeping graphene moist – in gel form – provides repulsive forces between the sheets and prevents re-stacking, making it ready for energy storage applications

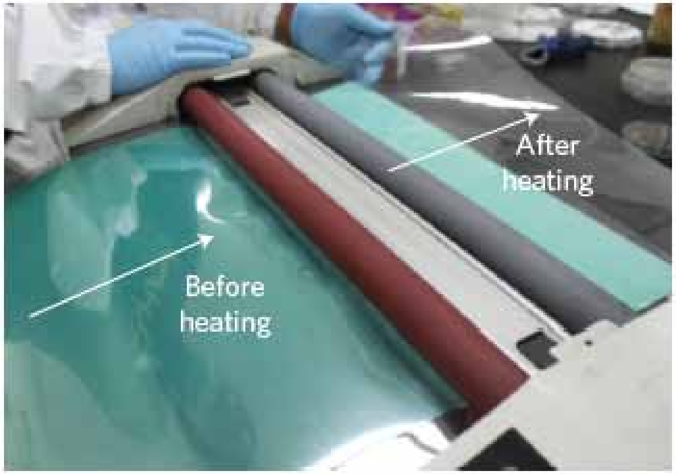


Advanced Nanomanufacturing

Roll-to-roll production of graphene for transparent conducting electrodes



U. Texas Austin



Korea/Japan/Singapore Collaboration

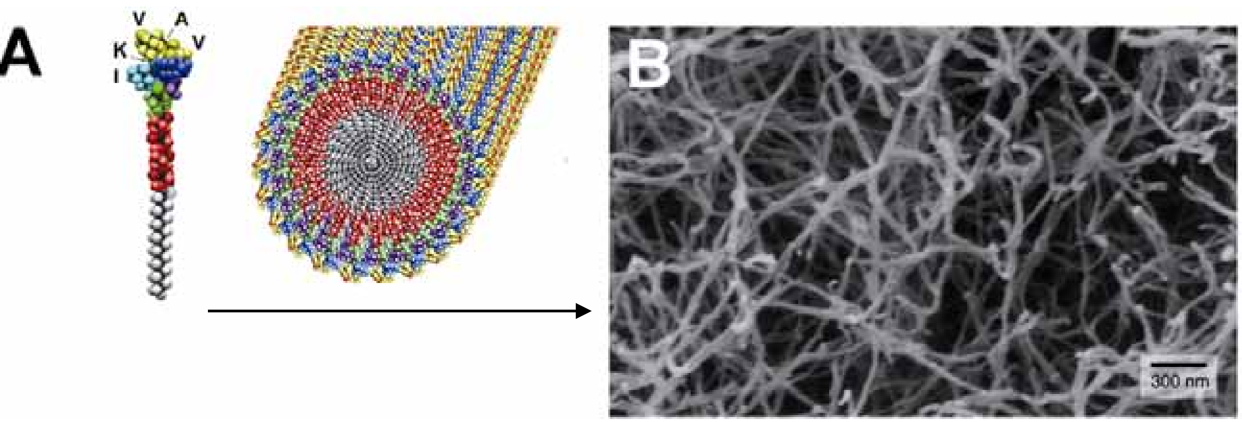
S. Bae, et al. *Nature Nanotech*. 2010

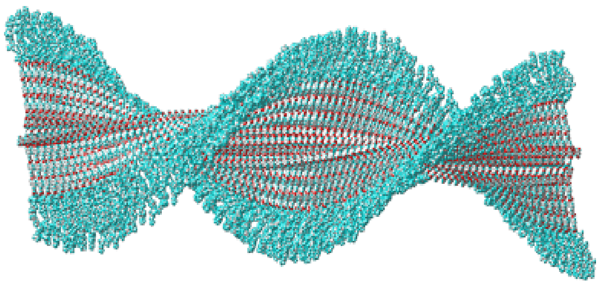
Example for hierarchical selfassembling - 4th NT generation (in research)

Example: Designing new molecules

with engineered structures and functionalities

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





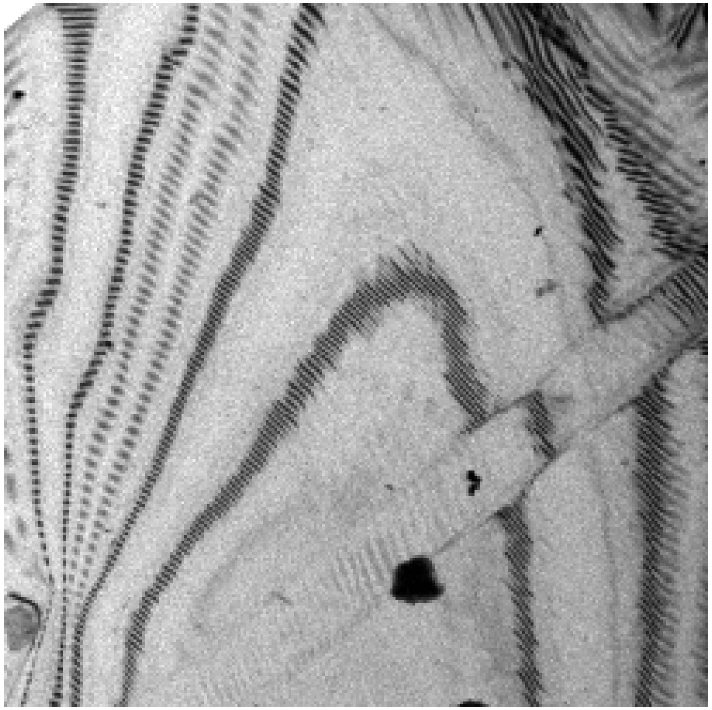
- *New nanomachines, robotics* - DNA architectures (Ned Seeman, Poly. Inst.)
- Designed molecules for *self-assembled porous walls* (Virgil Percec, U. PA)
- Self-assembly processing for *artificial cells* (Matt Tirrell, UCSB)
- Block co-polymers for *3-D structures on surfaces* (U. Mass, U. Wisconsin)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

(B) 2000-2010: Novel Methods and Tools

- *Femtosecond measurements* with atomic precision in domains of biological and engineering relevance
- *Sub-nanometer measurements* of molecular electron densities
- *Single-atom and single-molecule* characterization methods
- *Scanning probe tools for printing*, sub-50 nm "desktop fab"
- *Simulation* from basic principles has expanded to *assemblies of atoms 100 times larger than in 2000*
- New measurements: negative index of refraction in IR/visible wavelength radiation, Casimir forces, quantum confinement, nanofluidics, nanopatterning, teleportation of information between atoms, and biointeractions at the nanoscale. Each has become the foundation for new domains in science and engineering

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.

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

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

(C) 2000-2010 Infrastructure and R&D
- NNI illustrations -

- Infrastructure
  - Developed an *extensive infrastructure* of interdisciplinary research of
    ~ 100 large centers, networks and user facilities
  - *Educate and train > 10,000 students and teachers* per year
    ~ 1,000 new curricula in accredited research universities ;
    ~ 30 associate degree nanotechnology programs
  - *Established networks for ELSI and public awareness*

- R&D&I Results

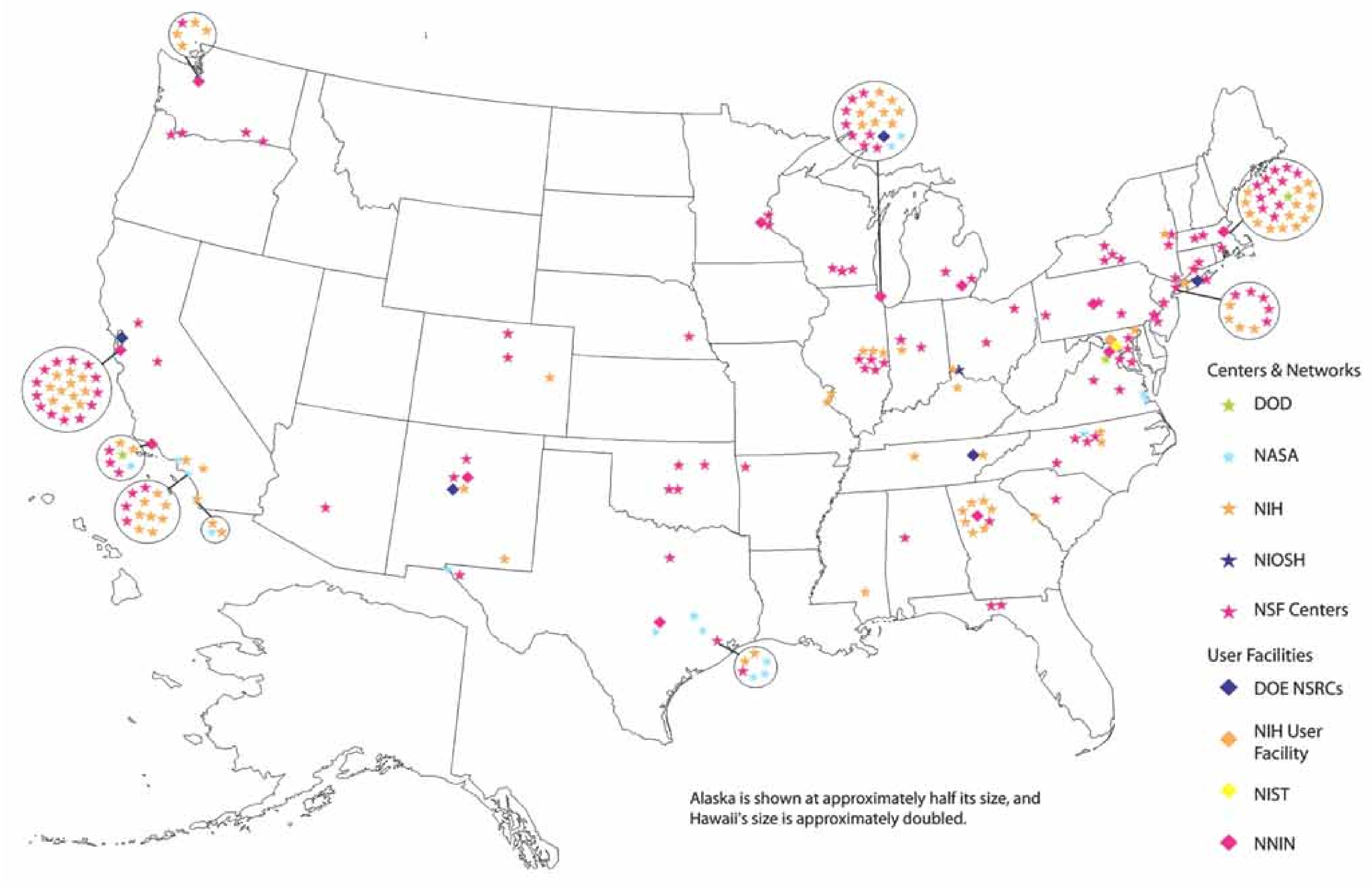
  With ~22% **of global government investments**, U.S. accounts for

  ~ **70% of startups** in nanotechnology worldwide

  > 2,500 U.S. nanotech companies with products in 2010, with

  $110B (~38% of the world) products incorporating nano parts

About 100 major NNI centers, networks, user facilities



MC Roco, 2012 11 04

National Nanomanufacturing Network (2006-)
Its core: Four Nanomanufacturing NSECs

- Center for Hierarchical Manufacturing (CHM)
  - U. Mass Amherst/UPR/MHC/Binghamton

CHM
Center for Hierarchical Manufacturing
University of Massachusetts Amherst

- Center for High-Rate Nanomanufacturing (CHN)
  - Northeastern/U. Mass Lowell/UNH

Center for High-rate Nanomanufacturing

- Center for Scalable and Integrated Nanomanufacturing (SINAM)
  - UC Berkeley/UCLA/UCSD/Stanford/UNC Charlotte

SINAM
CENTER FOR SCALABLE AND INTEGRATED NANOMANUFACTURING

- Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS)
  - UIUC/CalTech/NC A&T

Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems

National Nanomanufacturing Network

Open-access network
www.nanomanufacturing.org

Director: Mark Tuominen
beta.internano.org

NSF Centers with EHS relevance – Examples:

- Center for Biological and Environmental Nanotechnology at Rice University (manufactured nanoparticles at the wet/dry interface)
- Center for High-rate Nanomanufacturing at Northeastern University (occupational safety in nanomanufacturing)
- Nano/Bio Interface Center at University of Pennsylvania (interaction of nanomaterials and cells)
- NSEC on Templated Synthesis and Assembly at the Nanoscale at University of Wisconsin, Madison (effect of nanostructured polymers on EHS)
- Center for Integrated Nanomechanical Systems at University of California, Berkeley (detecting exposure to individual and portable nanomaterials)
- Center for Affordable Nanoengineering of Polymeric Biomedical Devices at the University of Ohio (nanoscale devices for monitoring and healing)
- Center for Hierarchical Manufacturing at University of Massachusetts, Amherst (occupational safety)
- CEINT Center for Environmental Implications of NanoTechnology at Duke University
- UC-CEIN Center for Environmental Implications of Nanotechnology at University of California Los Angeles

NETWORK FOR COMPUTATIONAL NANOTECHNOLOGY

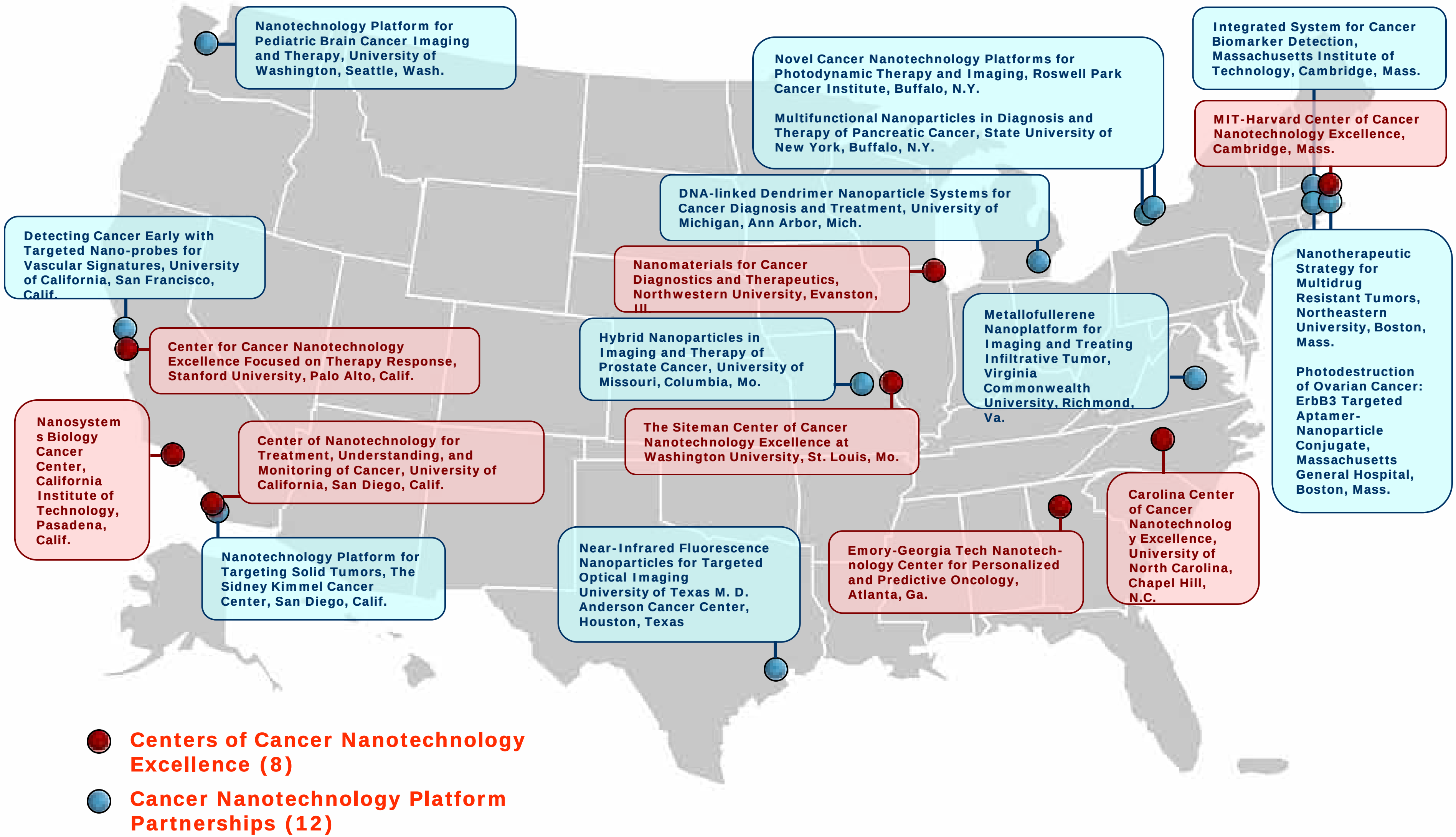
nanoHUB.org is a resource for the global Nanotechnology Community.
The map below indicates a red-peg for every nanoHUB user on the planet

http://www.nanoHUB.org **est**. 190,000 users / 2012 NSF ~ $20 / user

Support global eco-systems via COLLABORATION

Five DOE Nanoscale Science Research Centers (NSRCs)

NCI Nanotechnology Alliance – Center and Platform Awards



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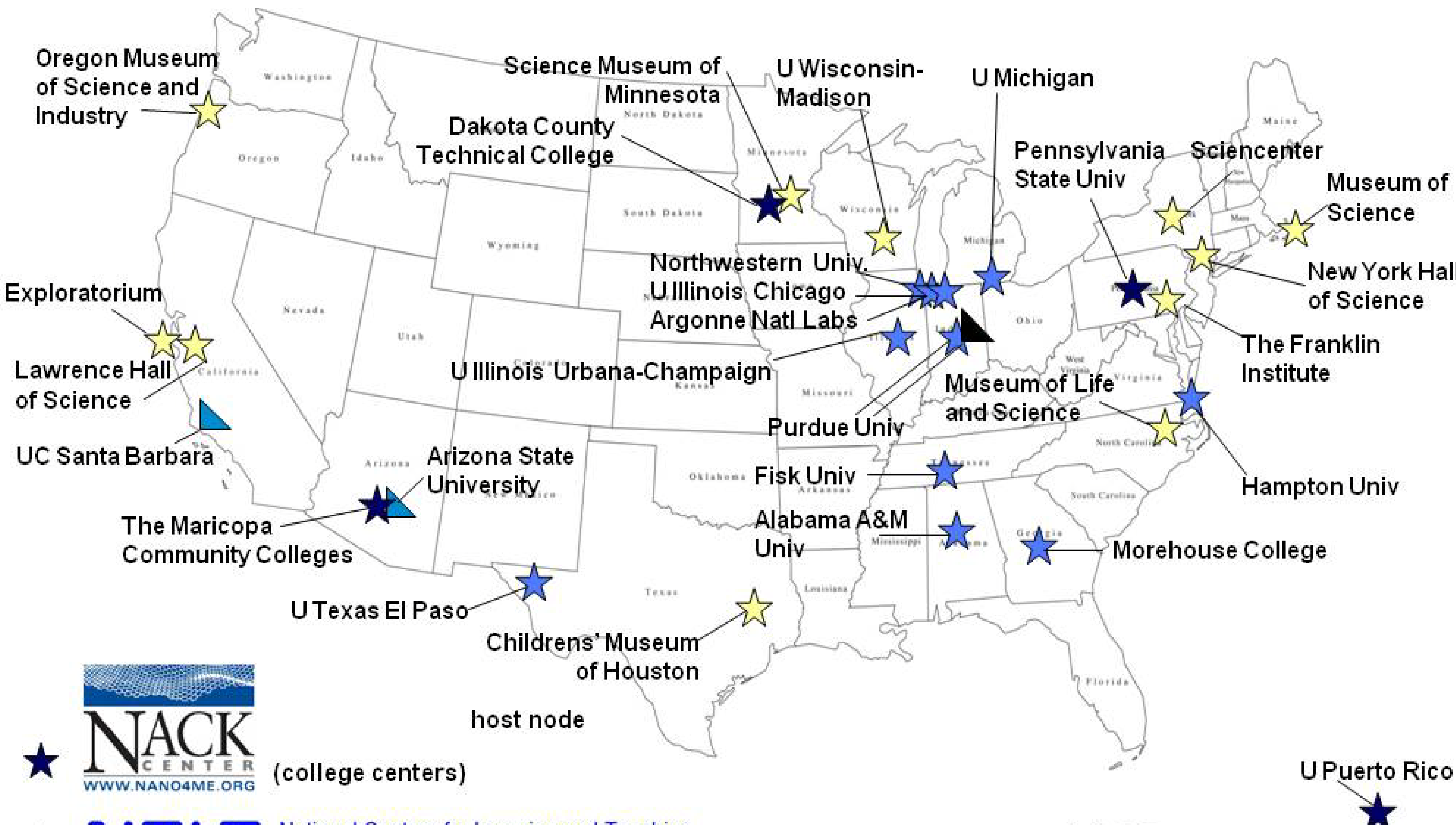
Key NSF/NNI education networks in 2010



NACK CENTER WWW.NANO4ME.ORG (college centers)

NCLT National Centers for Learning and Teaching in Nanoscale Science and Engineering (core partners)

nanoHUB (host node)

NISE network NANOSCALE INFORMAL SCIENCE EDUCATION (regional hubs / museums)

CNS The Centers for Nanotechnology in Society

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

MC Roco, 2012 11 04

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

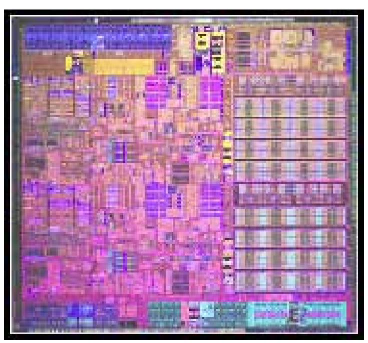
(D) 2000-2010: Ten highly promising products incorporating nanotechnology

- *Catalysts*
- *Transistors and memory devices*
- *Structural applications (coatings, hard materials, CMP)*
- *Biomedical applications (detection, implants,.)*
- *Treating cancer and chronic diseases*
- *Energy storage (batteries), conversion and utilization*
- *Water filtration*
- *Video displays*
- *Optical lithography and other nanopatterning methods*
- *Environmental applications*

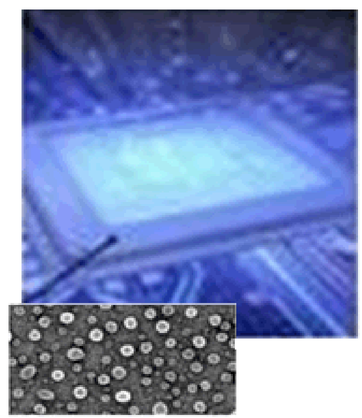
Leading to new industries, some with safety concerns: cosmetics, food, disinfectants,..

After 2010 nanosystems: nano-radio, tissue eng., fluidics, etc

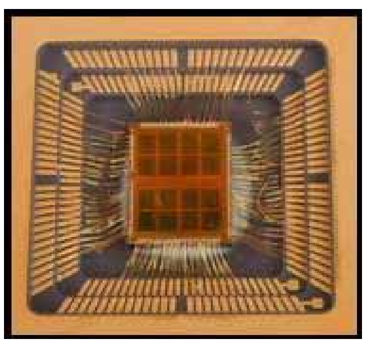
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



32 nm CMOS processor technology by Intel (2009)

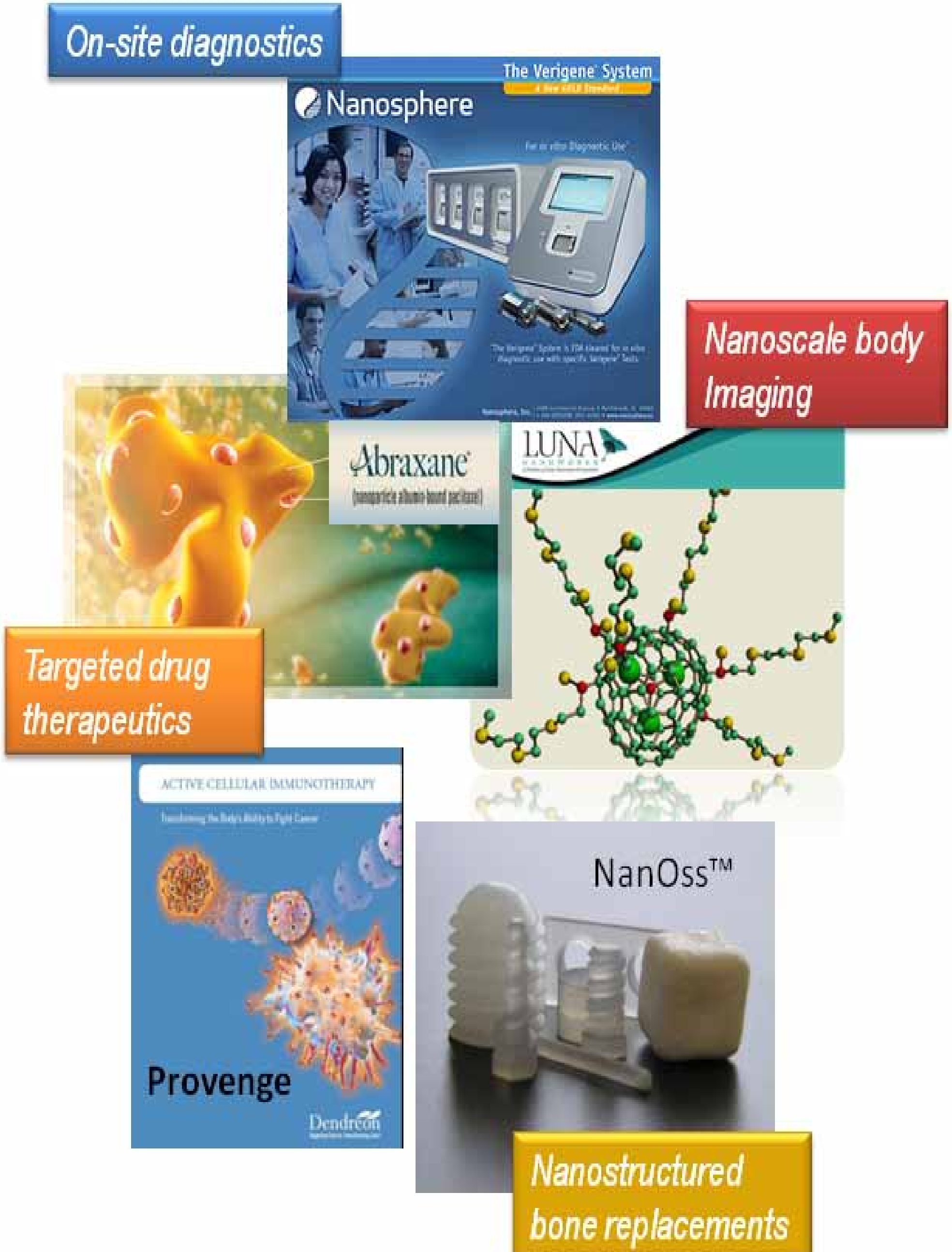


90 nm thin-film storage (TFS) flash flexmemory by Freescale (2010)



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

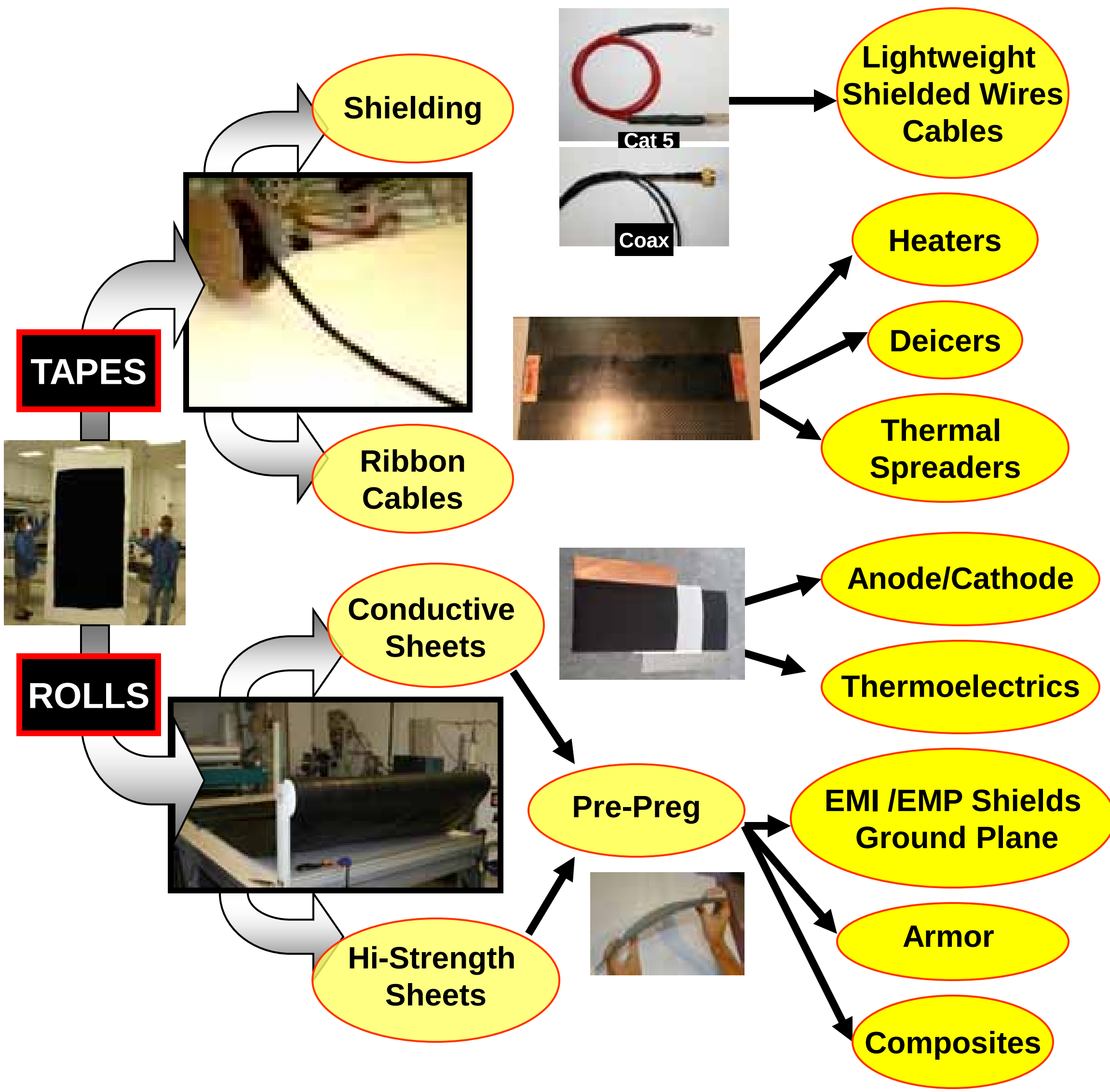
Nano2 Report, 2010, p. XII

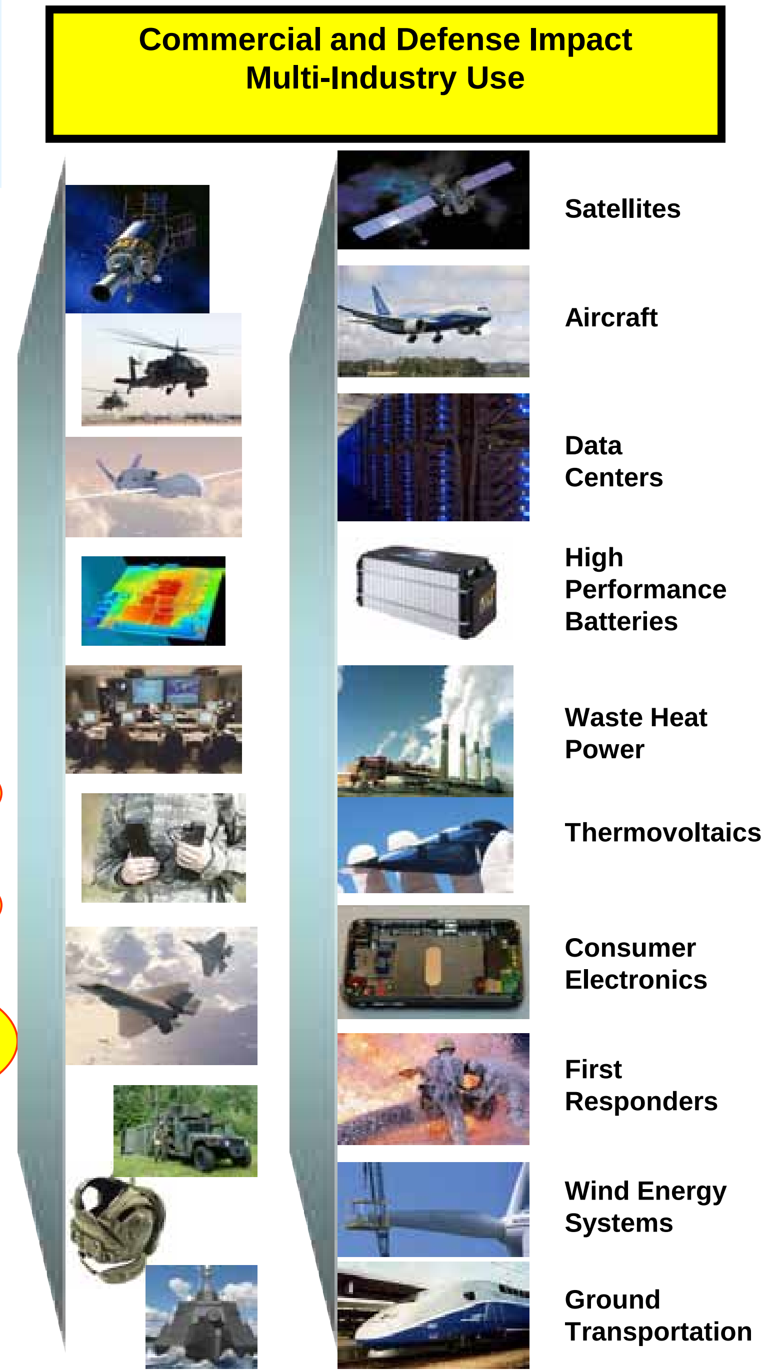


Examples of nanotechnology incorporated into commercial healthcare products, in production in 2010

Nano2 Report, 2010, p. XIV

Example of production platform: Expanded CNT sheet





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

Example of research platform: Nanoelectronics Research Initiative (SIA, NSF, NIST)

Nanoelectronics • Architectures
MIND
MIDWEST INSTITUTE FOR NANOELECTRONICS DISCOVERY

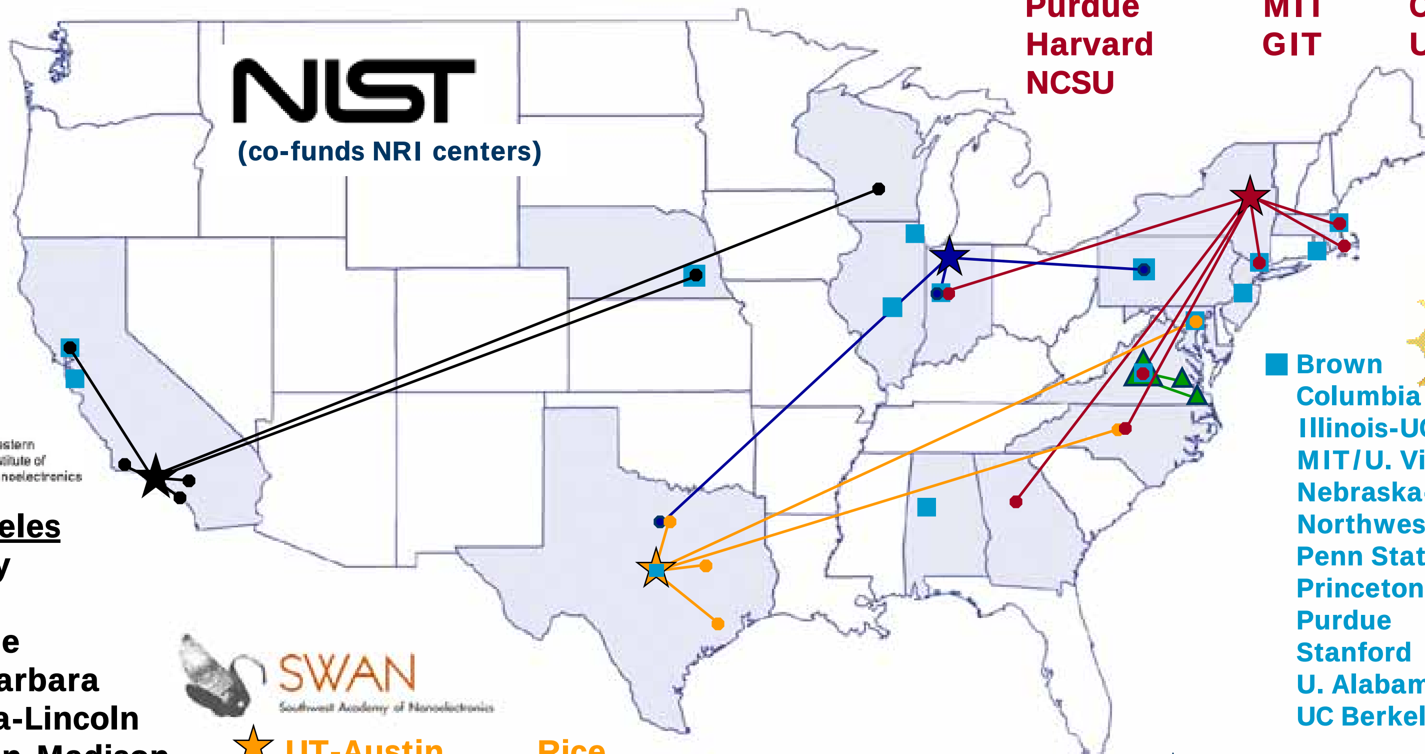
★ **Notre Dame**
Penn State
Purdue
UT-Dallas

INDEX
INSTITUTE FOR NANOELECTRONICS DISCOVERY AND EXPLORATION

★ **SUNY-Albany**
Purdue
Harvard
NCSU
MIT
GIT
Columbia
U. Virginia

NIST
(co-funds NRI centers)

NSF
∨ **Awards made in 2011 for collaborative group research (NNI Signature Initiative)**



WIN Western Institute of Nanoelectronics

★ **UC Los Angeles**
UC Berkeley
UC Irvine
UC Riverside
UC Santa Barbara
U. Nebraska-Lincoln
U. Wisconsin-Madison

SWAN Southwest Academy of Nanoelectronics

☆ **UT-Austin**
UT-Dallas
U. Maryland
Rice
Texas A&M
NCSU

NSF
■ **Brown**
Columbia
Illinois-UC
MIT/U. Virginia
Nebraska-Lincoln
Northwestern
Penn State
Princeton / UT-Austin
Purdue
Stanford
U. Alabama
UC Berkeley

▲ **Virginia Nanoelectronics Center (ViNC)**
University of Virginia
Old Dominion University
College of William & Mary

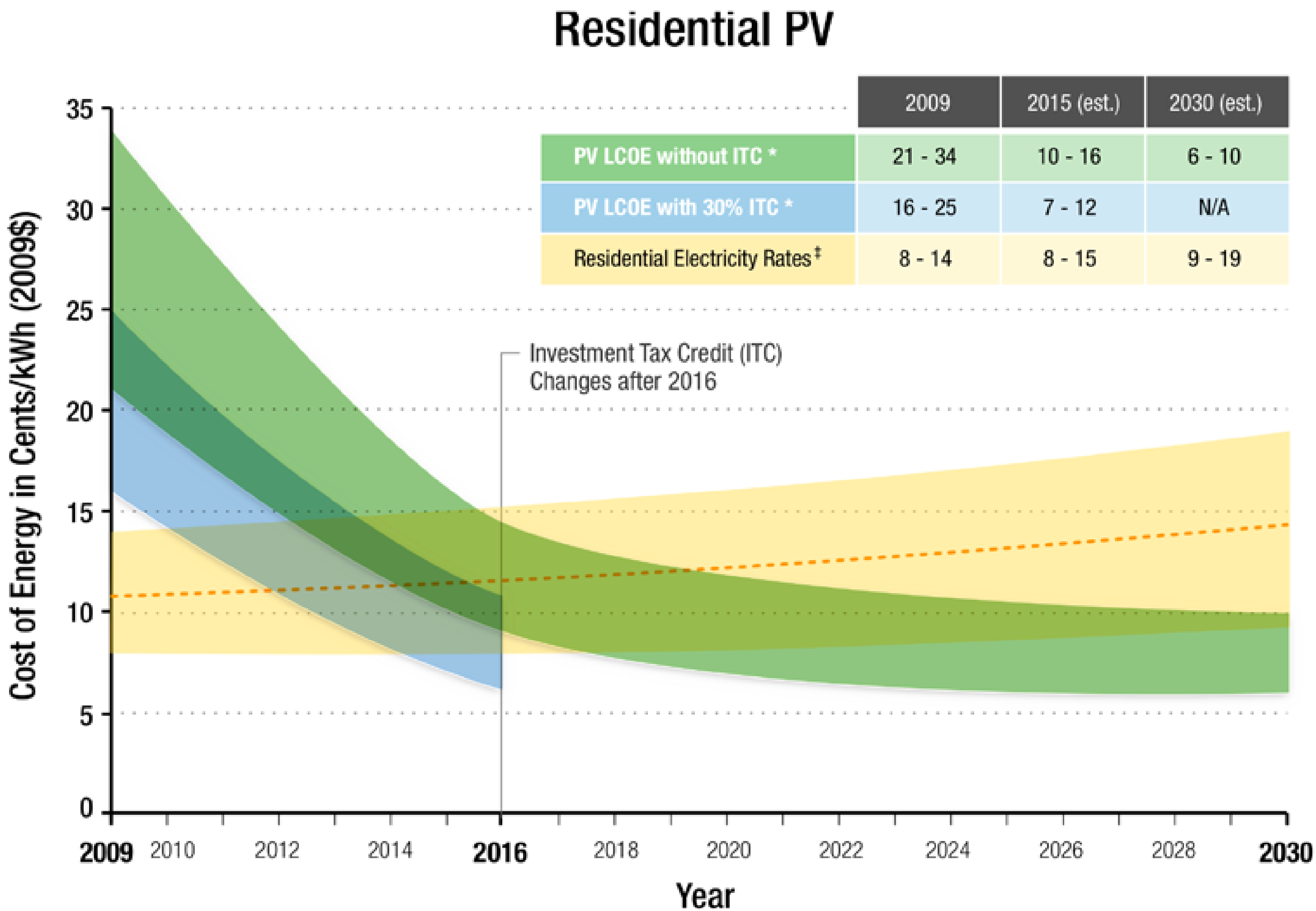
Partnerships NSF, NIST, SIA, SRC with over 30 Universities in 16 States

(E) 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

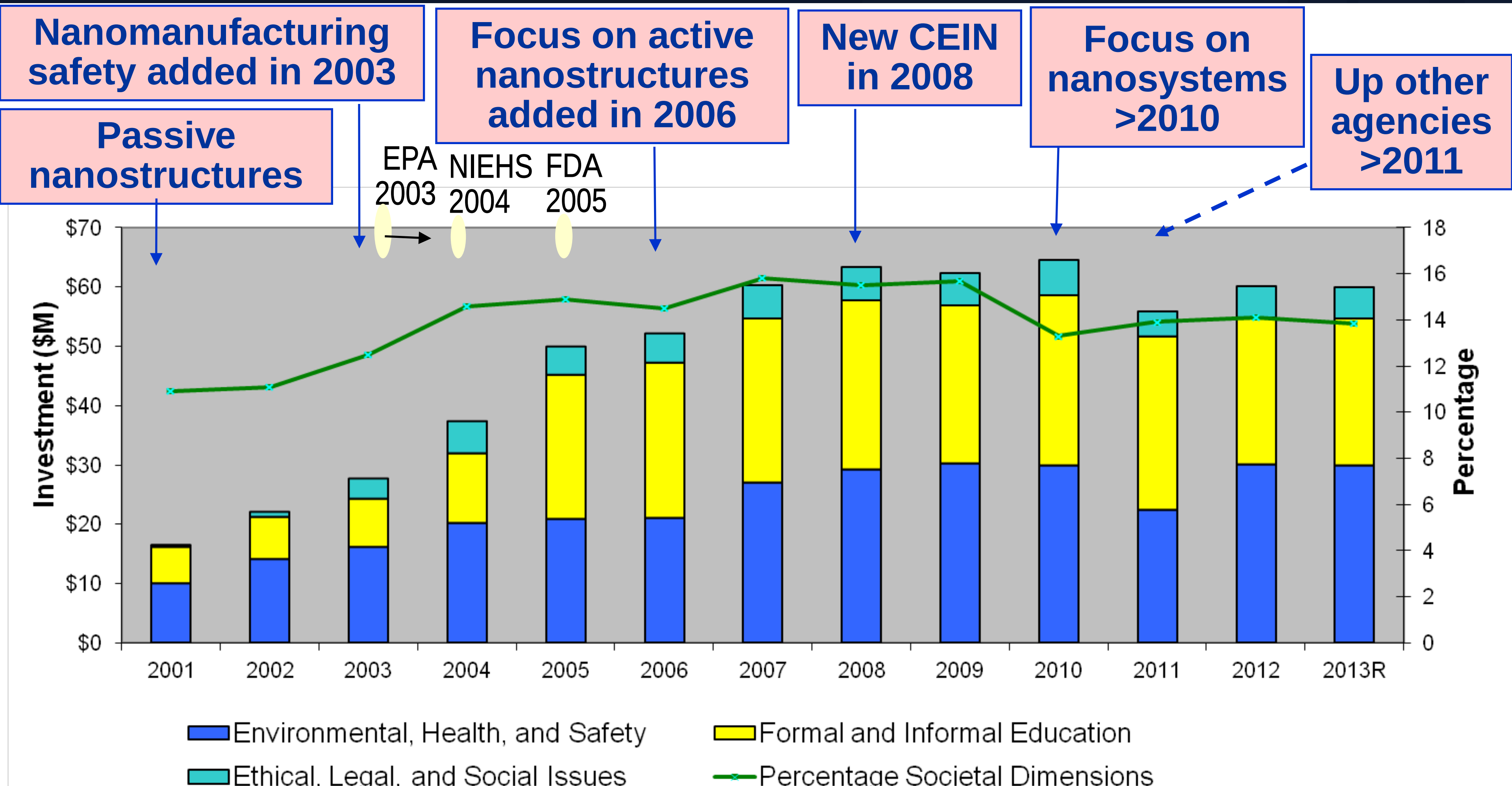
Goal: U.S. grid parity by 2015 for photovoltaic technologies

Levelized cost of energy (LCOE)



Based on DOE, 2010

NSF Investment in Nanotechnology Implications for Safety and Society



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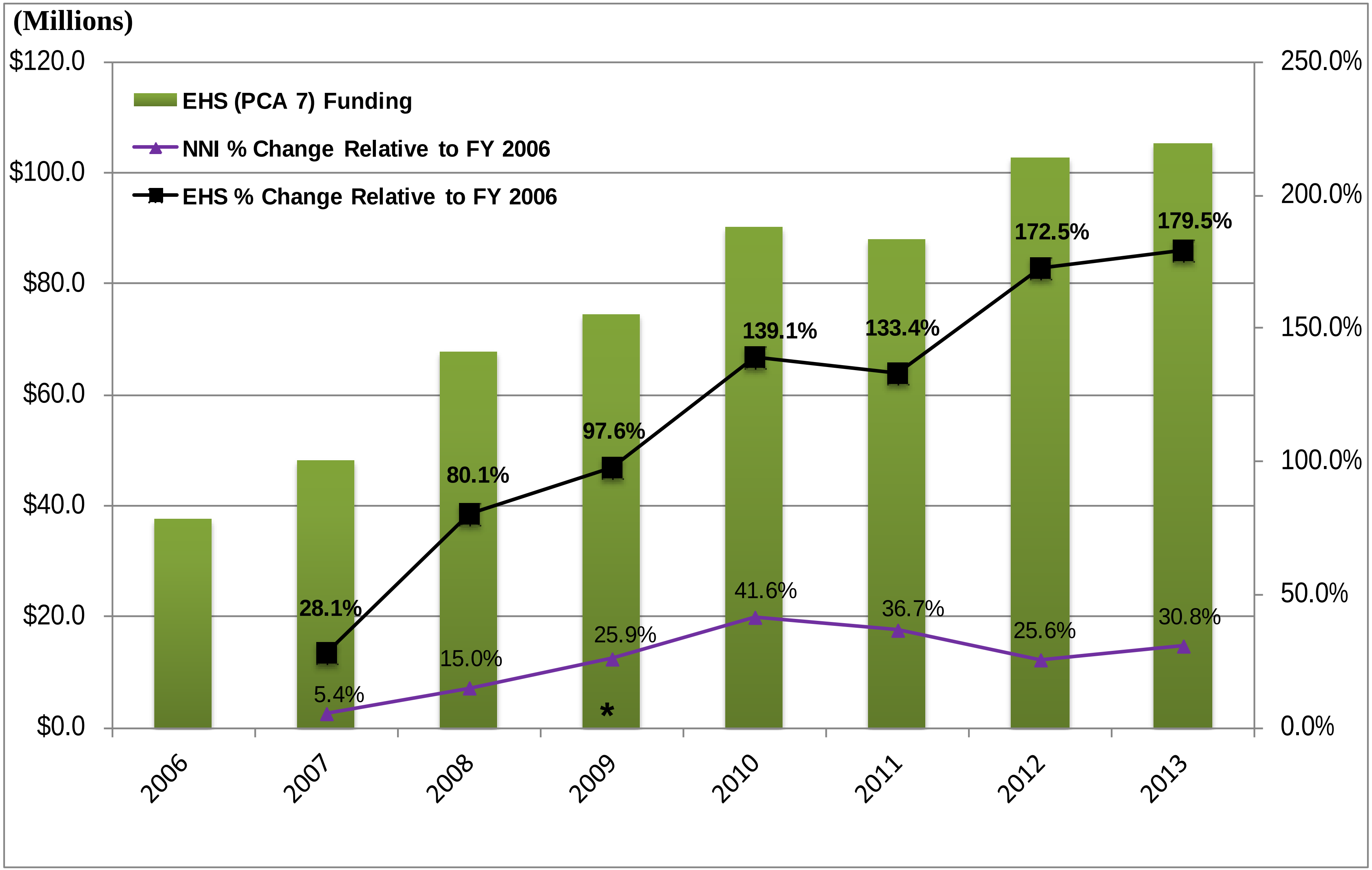
NNI funding for nanotechnology-related EHS research* has grown faster than the NNI as a whole

by fiscal year, in $ millions (FY 2012 is estimated; FY 2013 is requested); *2009 does **NOT** include ARRA funding

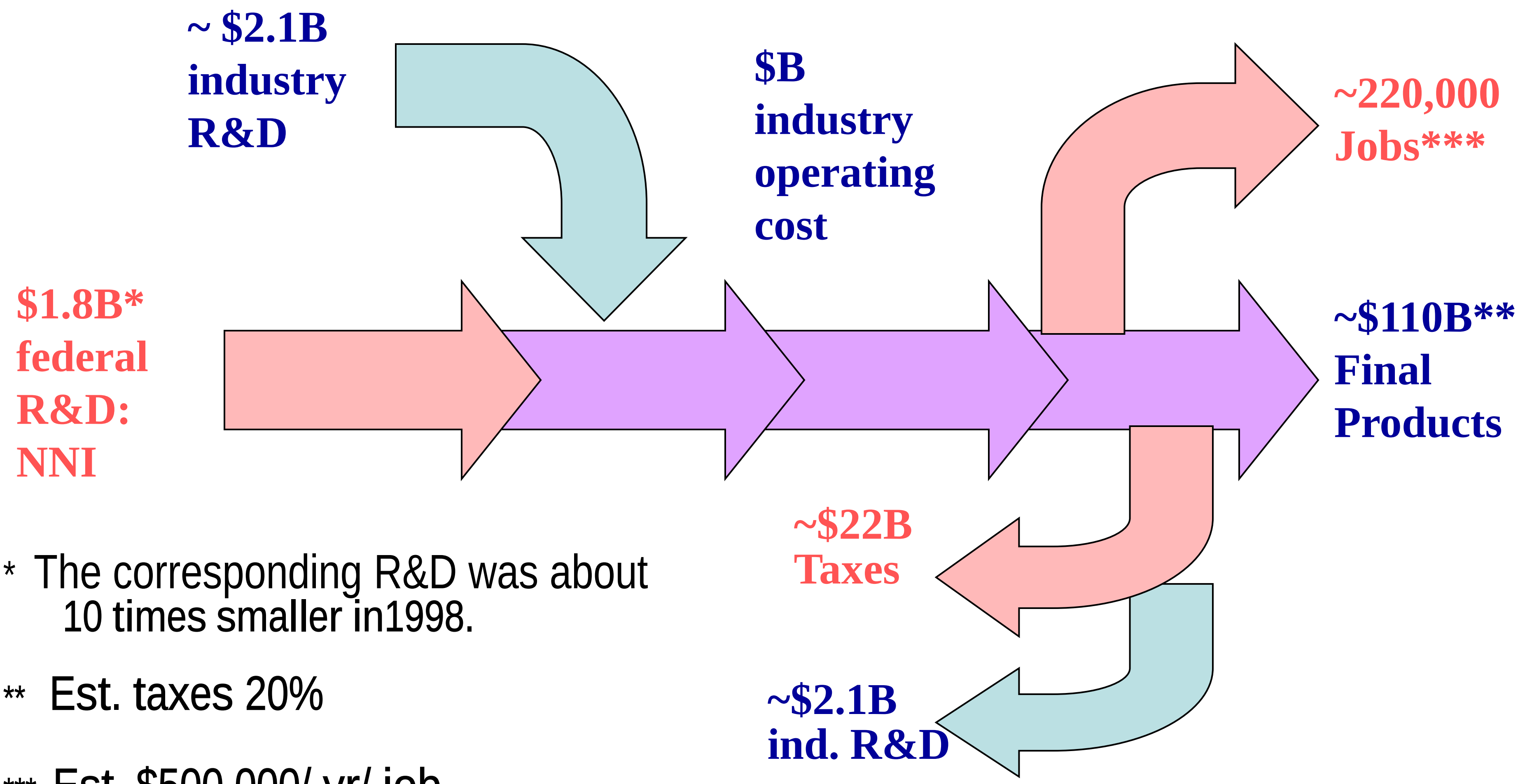


University-Industry-government partnerships (Public-private hybrids)

- 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

Return on Annual Federal Investment in Nanotechnology R&D (2010)



* The corresponding R&D was about 10 times smaller in1998.

** Est. taxes 20%

*** Est. $500,000/ yr/ job

Expert review (international WTEC study): 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

Better than expected after ten years

ü **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

ü **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 ..

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

Nanotechnology in 2011, still in an earlier formative phase of development

- Characterization of nanomodules is using micro parameters and not internal structure
- Measurements and simulations of a domain of biological or engineering relevance cannot be done with atomic precision and time resolution of chemical reactions
- Manufacturing Processes – empirical, synthesis by trial and error, some control only for one chemical component and in steady state
- Nanotechnology products are using only rudimentary nanostructures (dispersions in catalysts, layers in electronics) incorporated in existing products or systems
- Knowledge for risk governance – in formation

FY 2011 NS&E Priorities Research Areas (1)

The long-term objective is systematic understanding, control and restructuring of matter at the nanoscale for societal benefit

A. Scientific challenges

- Theory at the nanoscale
  Ex: transition from quantum to classical physics, collective behavior; simultaneous nanoscale phenomena
- Non-equilibrium processes
- Designing new molecules with engineered functions
- New architectures for assemblies of nanocomponents
- The emergent behavior of nanosystems

FY 2011 NS&E Priorities Research Areas (2)

B. Development of nanotechnology

- Tools for measuring and restructuring
  with atomic precision
  and time resolution of chemical reactions
- Understanding and use of quantum phenomena
- Understanding and use of multi-scale selfassembling
- Nanobiotechnology – sub-cellular and systems approach
- Nanomanufacturing hybrid, on site
- Systems nanotechnology

FY 2011 NS&E Priorities Research Areas (3)

C. Integration of nanotechnology in application areas

- Nanomanufacturing for sustainable environment
- Replacing electron charge as the information carrier in electronics (Ex: NRI)
- Energy conversion, water filtration / desalinization
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for communication, nanosystem design
- Converging science, engineering and technology

From FY 2011 NSF priority research areas (4)

D. Societal dimensions of nanotechnology

- Understanding and sustainable ENV, including research for natural / incidental / manufactured nanomaterials
- Earlier formal and informal education
- Social issues and public engagement

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

NNI "signature initiatives"
2012-2013

Sustainable Nanomanufacturing

Nanoelectronics for 2020 and Beyond

Nanotechnology for Solar Energy

Nanotechnology Knowledge Infrastructure

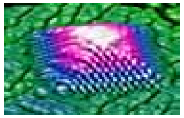
Nanotechnology for Sensors

Defining Convergence

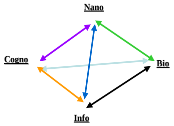
NSF/WTEC, www.wtec.org/nano2/ (2012)

Convergence is the evolutionary interaction to achieve mutual compatibility, synergism and integration of seemingly different disciplines, technologies and communities to create added-value for shared goals

Successive levels of convergence



Nanotechnology – integrate knowledge of material world



NBIC – integrate foundational and emerging technologies

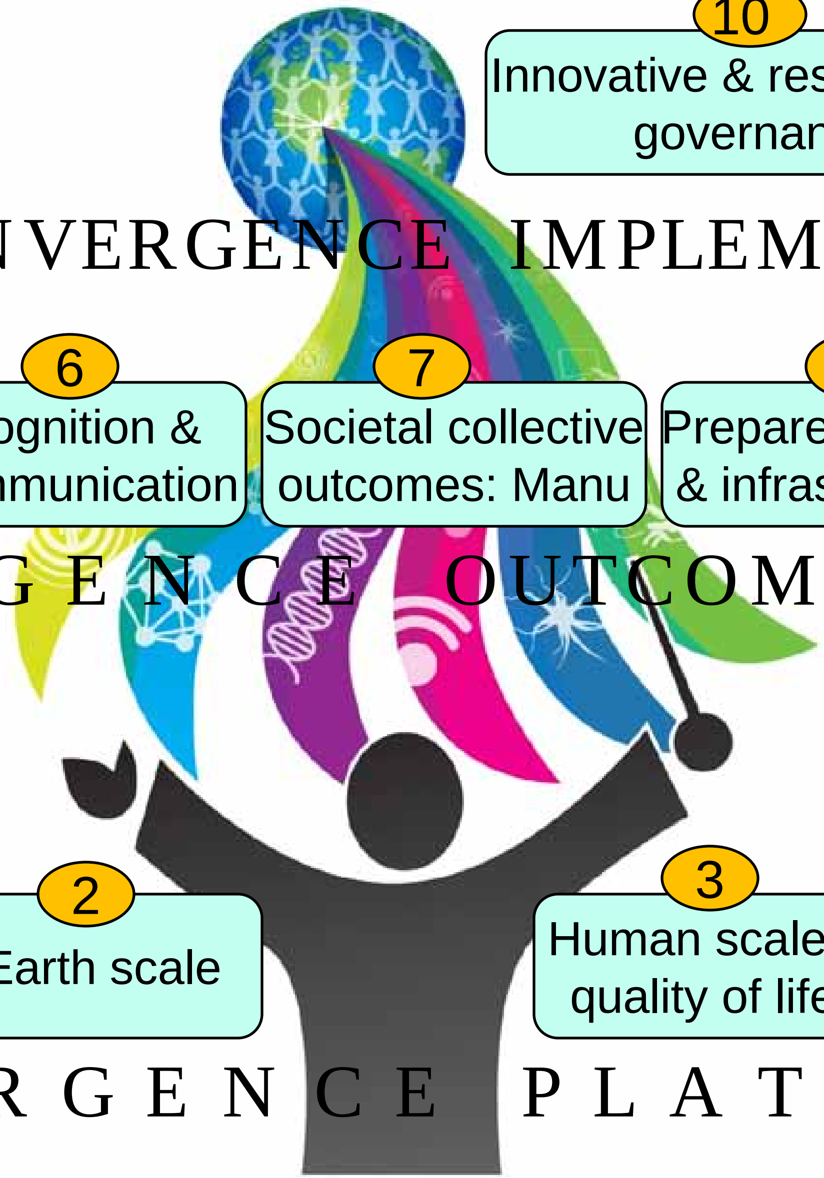
NBIC2 (beyond NBIC) – integration of essential convergence platforms in knowledge, technology and society

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)

Converging Technologies for Societal Benefit

Report presentation: Dec 11 2012 (Board Room 1235, NSF)



10 Innovative & responsible governance

CONVERGENCE IMPLEMENTATION

5 Human health & Physical potential

6 Cognition & communication

7 Societal collective outcomes: Manu

8 Prepare people & infrastructure

9 Sustainable development

CONVERGENCE OUTCOMES DOMAINS

1 Foundational Tools - NBIC

2 Earth scale

3 Human scale & quality of life

4 System approach & synergism

CONVERGENCE PLATFORMS

MC Roco, 2012 11 04

nano2

2010-2020: Key areas of S&T emphasis

- Integration of nanocomponents at the nanoscale in nanosystems of larger scales, for fundamentally new products
- Better experimental and simulation control of self-assembly, quantum behavior, creation of new molecules, transport processes, interaction of nanostructures with external fields
- Understanding of biological processes and of nano-bio interfaces with abiotic materials, and their biomedical applications
- Nanotechnology solutions for sustainable development
- Governance for responsible innovation and public-private partnerships; oversight of nanotechnology EHS, ELSI, multi stakeholder, public and international participation. Sustained support for education, workforce preparation, and infrastructure.

The next ten years

- Preparing for **mass application of nanotechnology by 2020**, with shift to more complex generations of nanotechnology products and increased connection to biology. Address risks (EHS, long-term DNA, nanobiology) and public participation

- **Greater emphasis on innovation and commercialization,** with incentives for greater use of public/private partnerships

- **Focus on return to society and serving human dimensions** (health, cognition, human-machine interface, productivity high-added value nanomanufacturing, sustainability)

- *Nanotechnology governance will be institutionalized* , with increased globalization and a co-funding mechanism

Closing remarks

- Nanotechnology for a sustainable society is **one of the most important topic in S&T today**: sustainability determine the planetary boundary for human development, and nanotechnology offer best intrinsic general purpose technology solutions

- "Converging knowledge and technologies" approach: all sustainability facets, sustainability and other areas, applications and implications

- SNO may contribute to societal governance and advancing converging approach

Several background references

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"Nanotechnology Research Directions for Societal Needs in 2020"
Springer (Roco, Mirkin and Hersam 2011)

"Nanotechnology: From Discovery to Innovation and Socioeconomic Projects" AIChE/CEP Roco, May 2011)