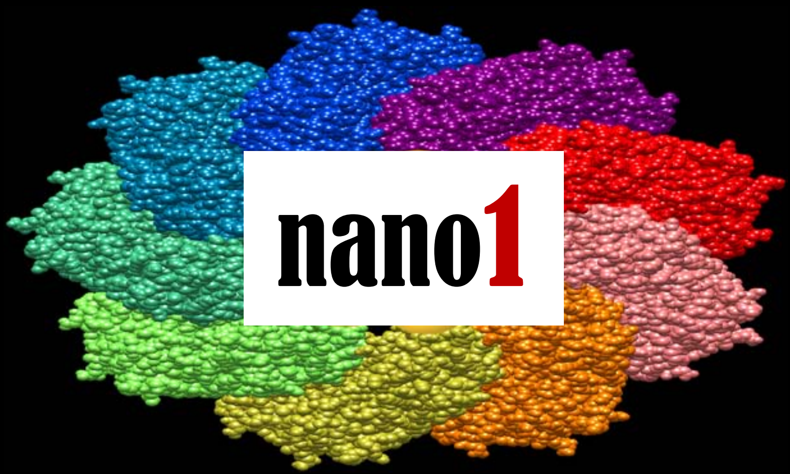
2000



2010

2020

Long-view Nanotechnology Research Directions: 2000-2020

Mihail Roco
National Science Foundation and National Nanotechnology Initiative

Romanian Academy, January 19, 2010

<u>Context</u>: Emergence of new technologies
Nanotechnology is a prime example

- Knowledge generation quasi-exponential growth
  There is an accelerating & non -uniform process of discoveries and innovations leading to emerging technologies

- Societal needs of radically new technologies
  Demographics (more crowded, aging, non-uniform) & developmen with limited natural resources (sustainability constrain)

- Emerging technologies governance
  - *Integration of new tools and separated disciplines,*
  - *General purpose integrators:*
    <u>nanotechnology, IT, and complex systems</u>

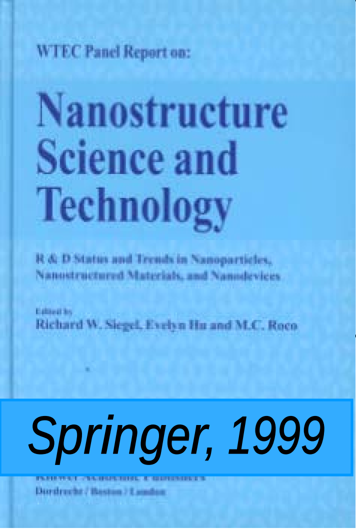
Examples of emerging technologies and corresponding U.S. long-term S&T projects

Justified mainly by societal/application factors

- 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)
- IT Research (top-down born & managed; application driven)

Justified mainly by science and technology potential, competitive

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



Benchmark with experts in over 20 countries in 1997-1999

"Nanostructure Science and Technology"

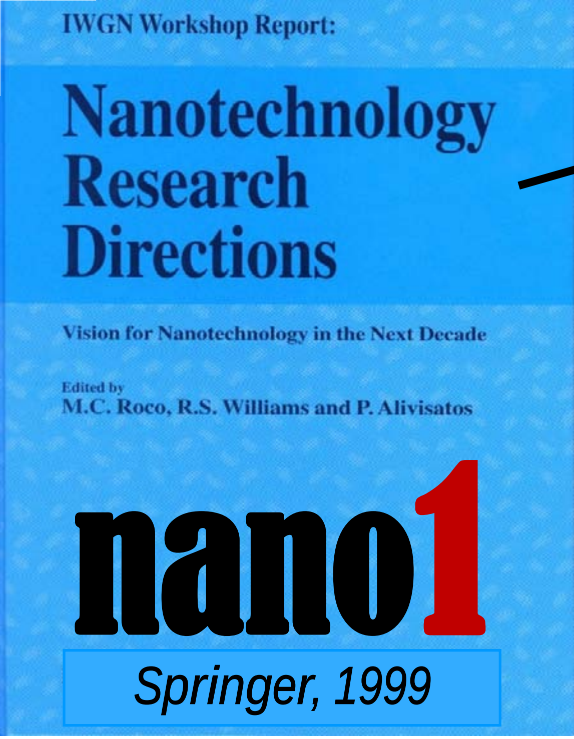
NNI preparatory Report, Springer, 1999

Nanotechnology Definition for the R&D program

Working at the atomic, molecular and supramolecular levels, in the length scale of ~ 1 nm (a small molecule) to ~ 100 nm range, in order to understand, create and use materials, devices and systems with specific, fundamentally new properties and functions because of their small structure

NNI definition encourages new R&D that were not possible before:

- ***the ability to control and restructure matter at nanoscale***
- ***collective effects → new phenomena → novel applications***
- ***integration along length scales, systems and applications***



"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

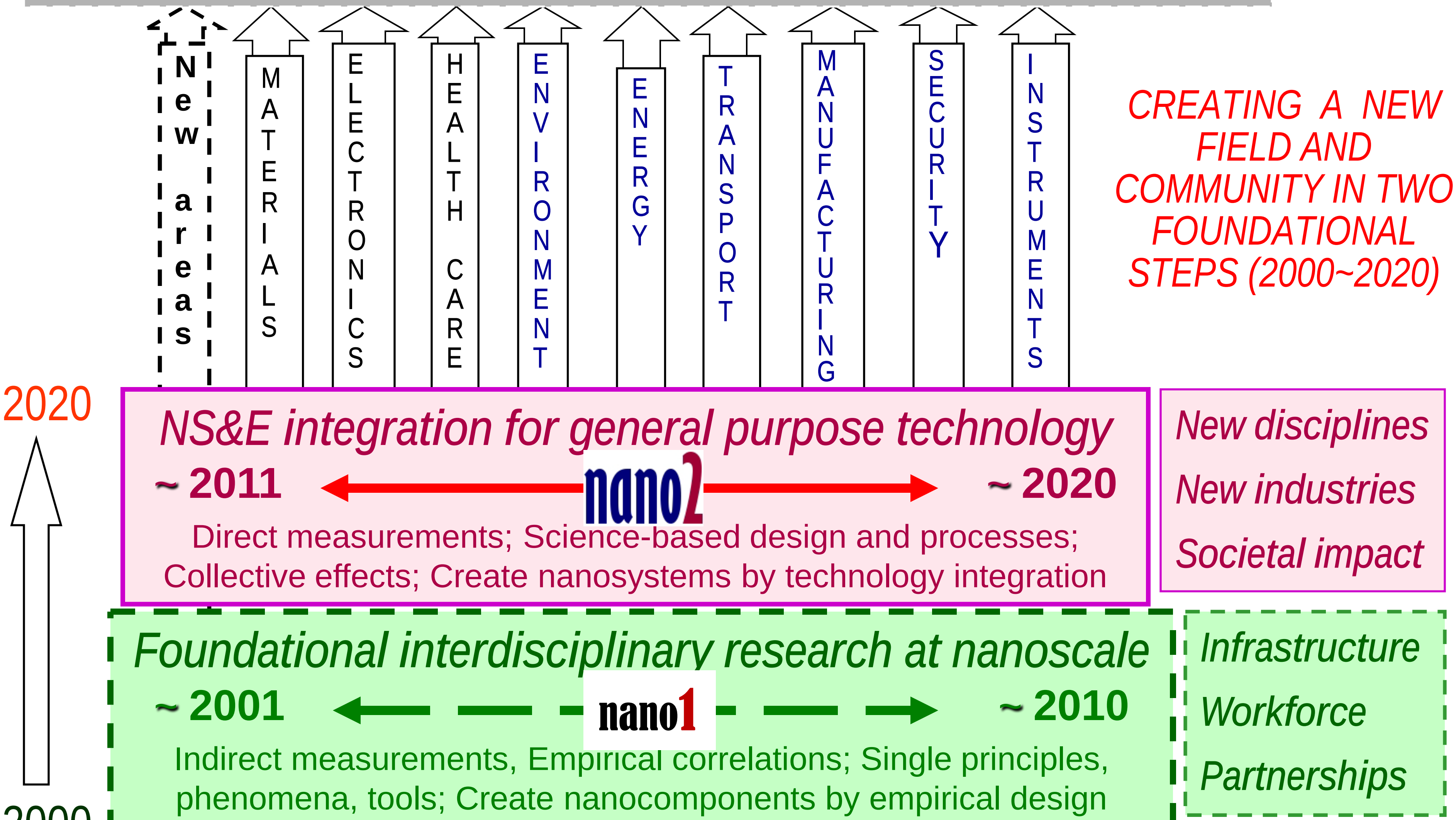
MC Roco, U.S. White House, March 11 1999

The long-term view drives NNI
2000-2020

- NNI was designed as a science project after two years of planning without dedicated funding in 1997-1999:
  - Long-term view ("Nanotechnology Research Directions")
  - Definitions and international benchmarking ("Nanostructure S&T")
  - Science and Engineering Priorities and Grand Challenges ("NNI")
  - Societal implications ("NSF Report", 2000)
  - Plan for government agencies ("National plans and budgets")
  - Public engagement brochure ("Reshaping the word", 1999)

- Combine four time scales in planning (2001-2005)
  - Vision - 10-20yrs, Strategic plan – 3 yrs, Annual budget - 1yr, and Management decisions - 1 month;
  - at four levels: program, agency, national executive, legislative

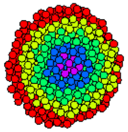
Mass Application of Nanotechnology after ~ 2020



Nano2 Report, 2010, p. XXXVII

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

Timeline for beginning of industrial prototyping and nanotechnology commercialization

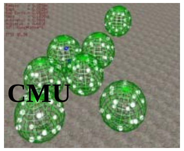


2000

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

Increased Complexity, Dynamics, Transdisciplinarity

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

Goals

- Global progress made in nanotechnology 2000 - 2010
- Vision and research directions by 2020?
- How to re-define nanotechnology as a S&E megatrend in the next decade (2010-2020) with new goals
- How to institutionalize advances in nanotechnology R&D

nano2

Nano 2020 Report

Panel of U.S. experts

Input from 250 leading nanotechnologists from 35 countries; Dan Dascalu rep. Romania

5 brainstorming workshops

Peer review

Public comment

Open source

2000-2008
Estimates show an average growth rate of key nanotechnology indicators of 23 - 35%

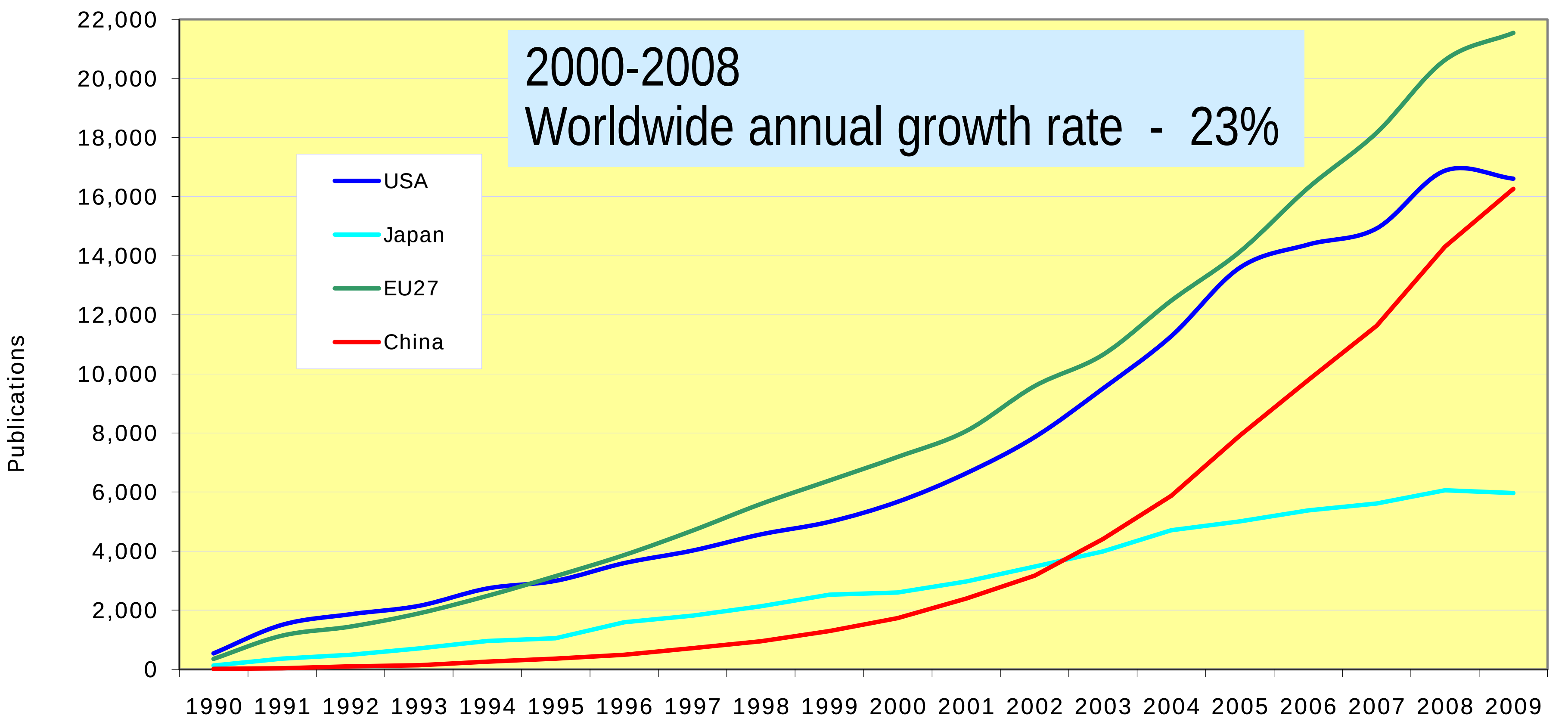
World /US/	People -primary workforce	SCI papers	Patents applicat-ions	Final Products Market	R&D Funding public + private	Venture Capital
2000 *(actual)*	~ 60,000 /25,000/	18,085 /5,342/	1,197 /405/	~ $30 B /$13 B/	~ $1.2 B /$0.37 B/	~ $0.21 B /$0.17 B/
2008 *(actual)*	~ 400,000 /150,000/	65,000 /15,000/	12,776 /3,729/	~ $200 B /$80 B/	~ $14 B /$3.7 B/	~ $1.4 B /$1.17 B/
2000 - 2008 average growth	~ 25%	~ 23%	~ 35%	~ 25%	~ 35%	~ 30%
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*					

Nano2 Report, 2010, p. XXXIII

MC Roco, Jan 19 2011

Nanotechnology publications in the Science Citation Index (SCI) 1990 - 2009

Data was generated from online search in Web of Science using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen, Dang and Roco, 2010)

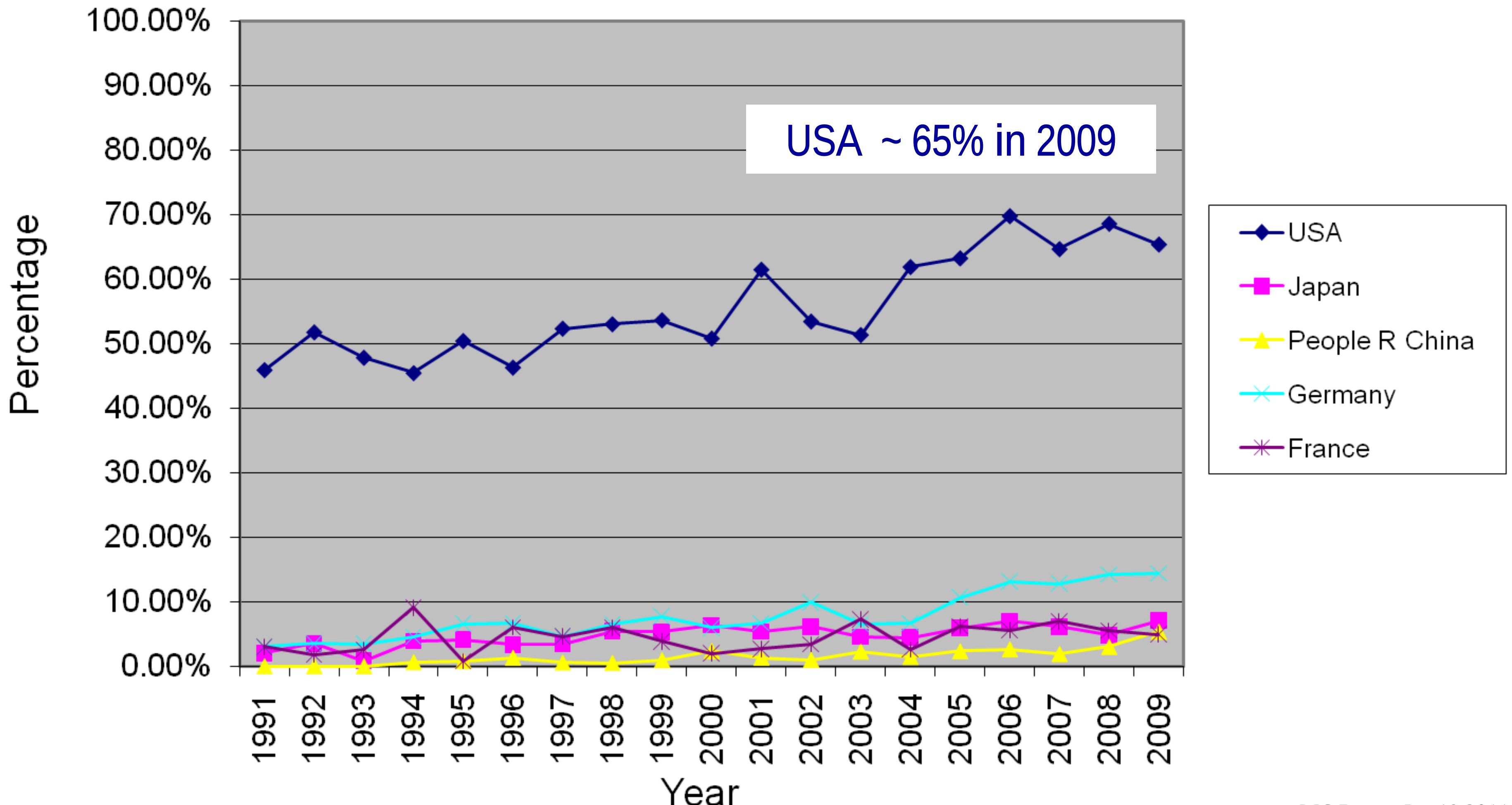


Rapid, uneven growth per countries

MC Roco, Jan 19 2011

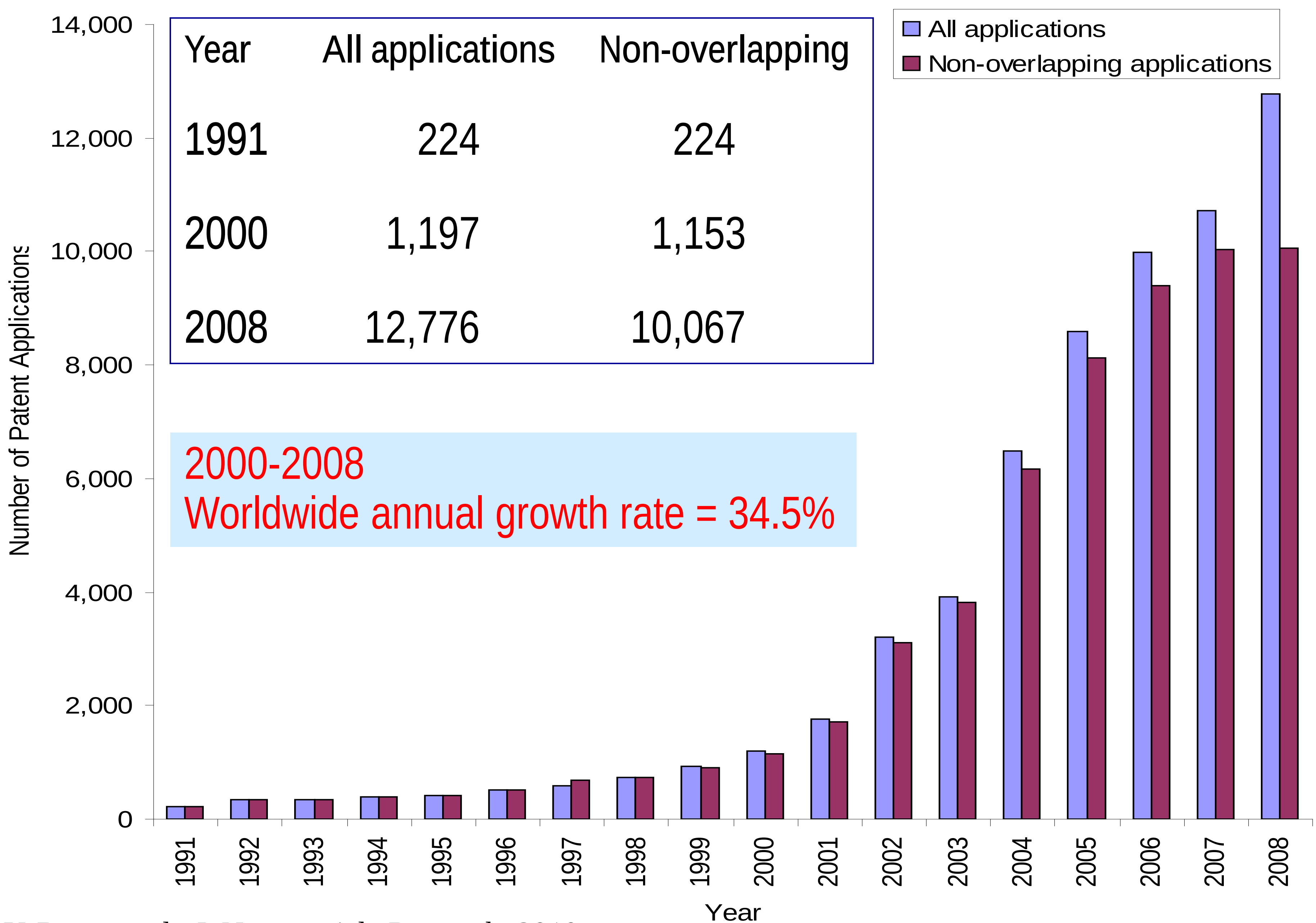
Percent contribution by country to nanotechnology publications in Science, Nature, and Proc. NAS

Title-abstract search (Chen, Dang and Roco, 2010)



MC Roco, Jan 19 2011

WORDWIDE NUMBER OF NANOTECHNOLOGY PATENT APPLICATIONS



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

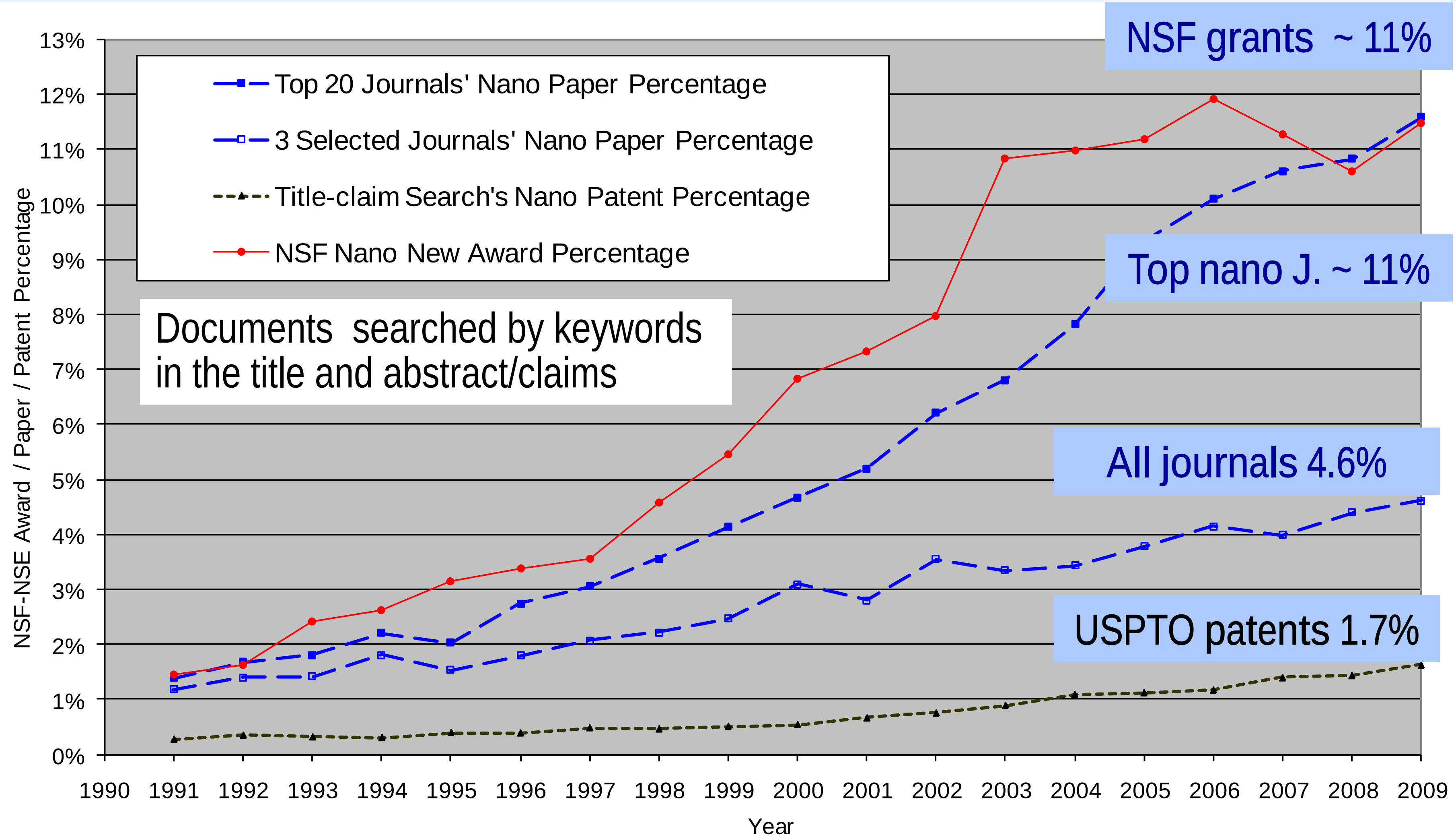
2000-2008
Worldwide annual growth rate = 34.5%

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

MC Roco, Jan 19 2011

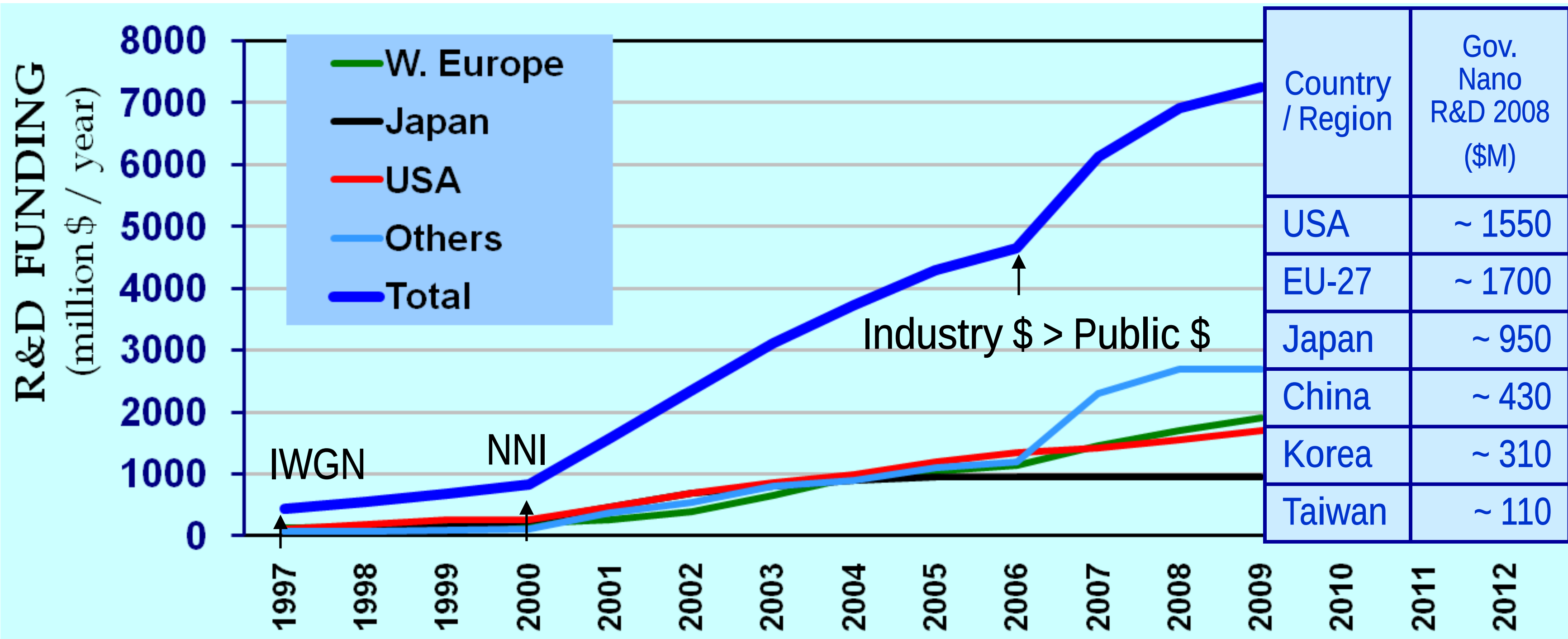
Percentage of nanotechnology content in NSF awards, ISO papers and USPTO patents (1991-2009)

(update after Encyclopedia Nanoscience, Roco, 2008)



Similar, delayed penetration curves: for 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

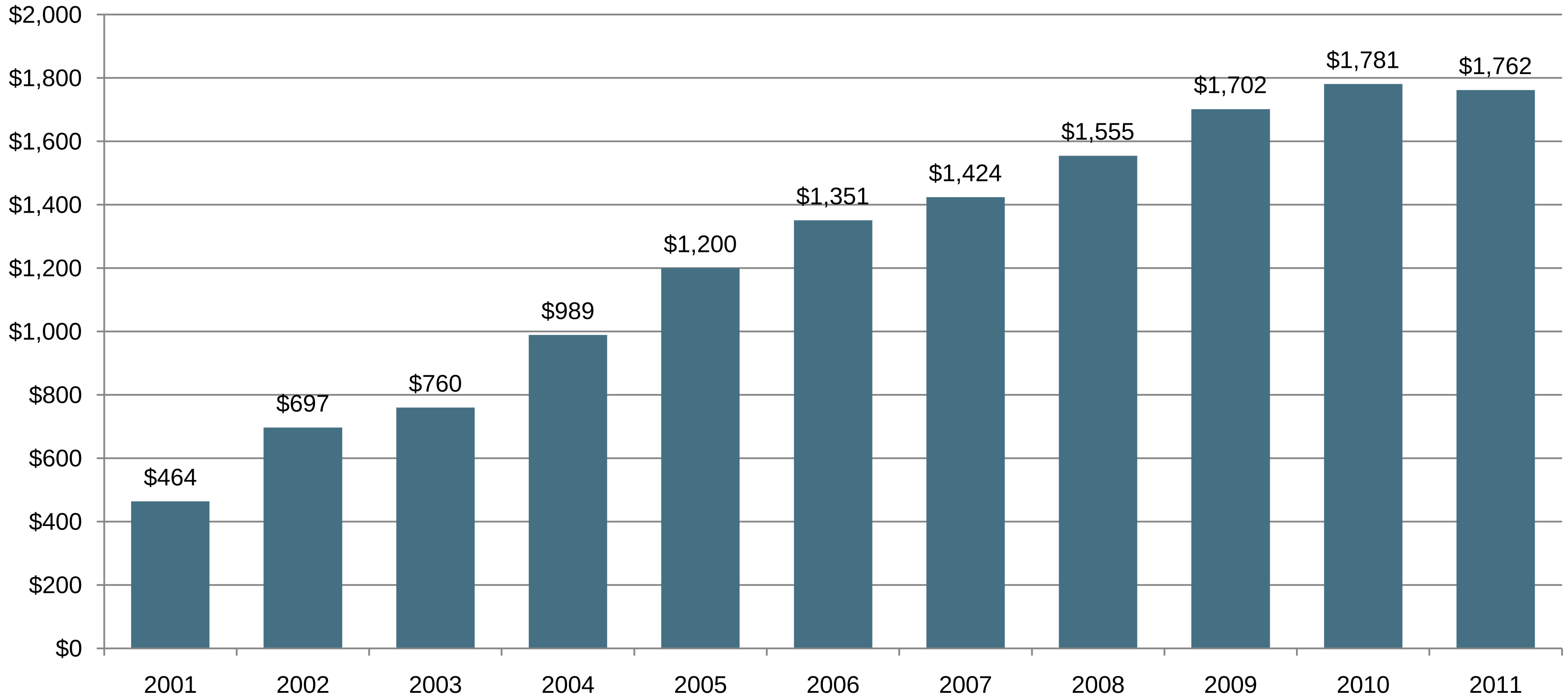
Rapid, uneven growth per countries

MC Roco, Jan 19 2011

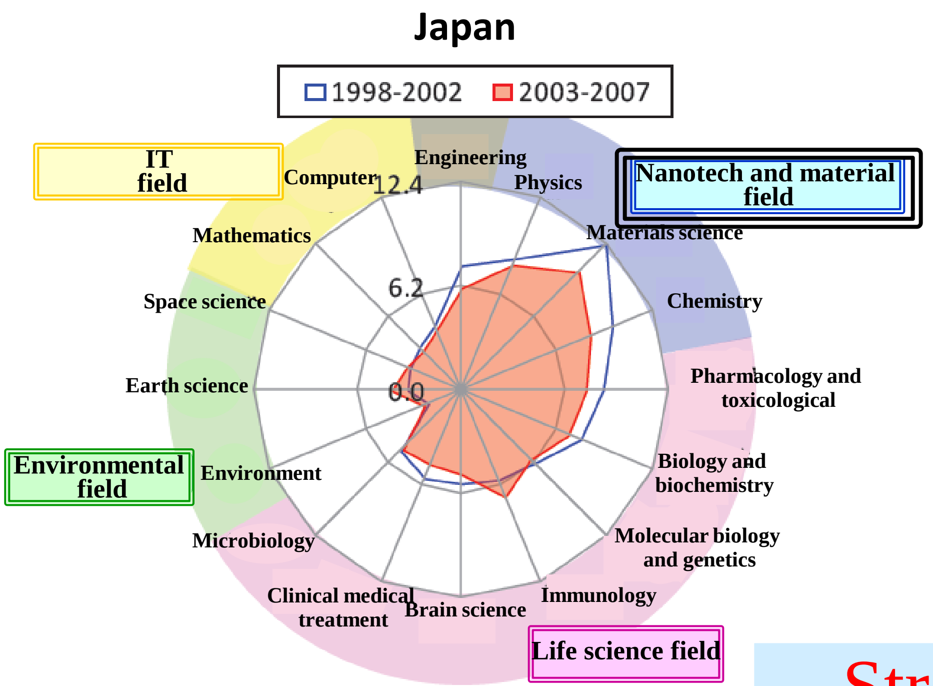
2001-
2010

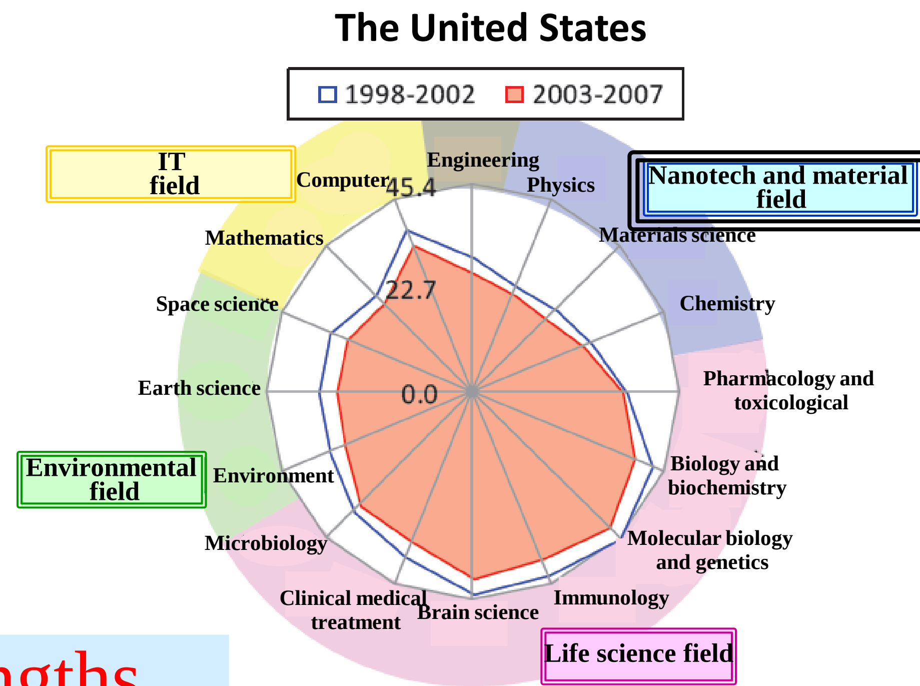
NNI budget information

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

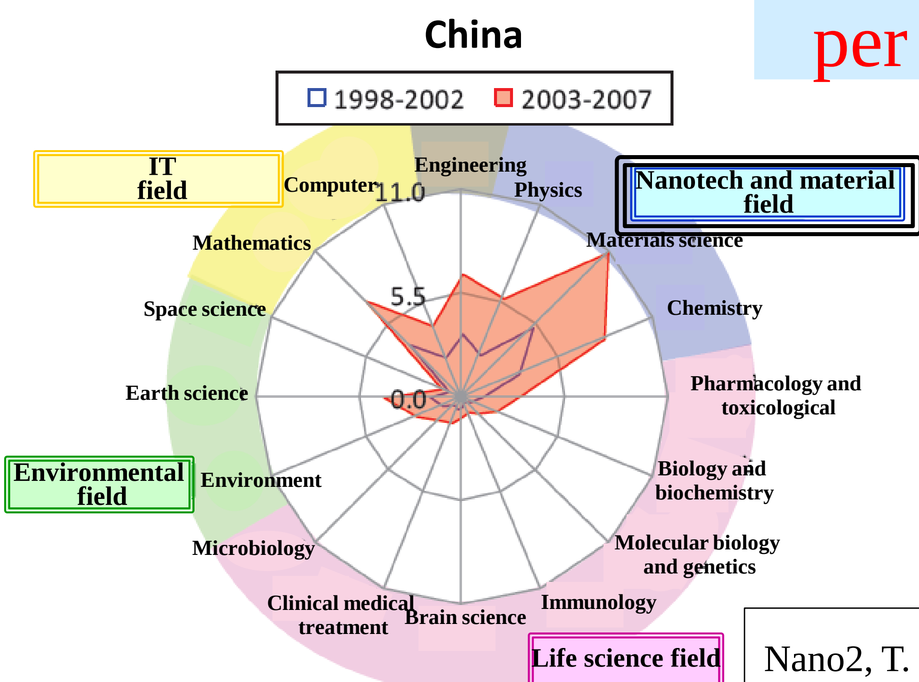


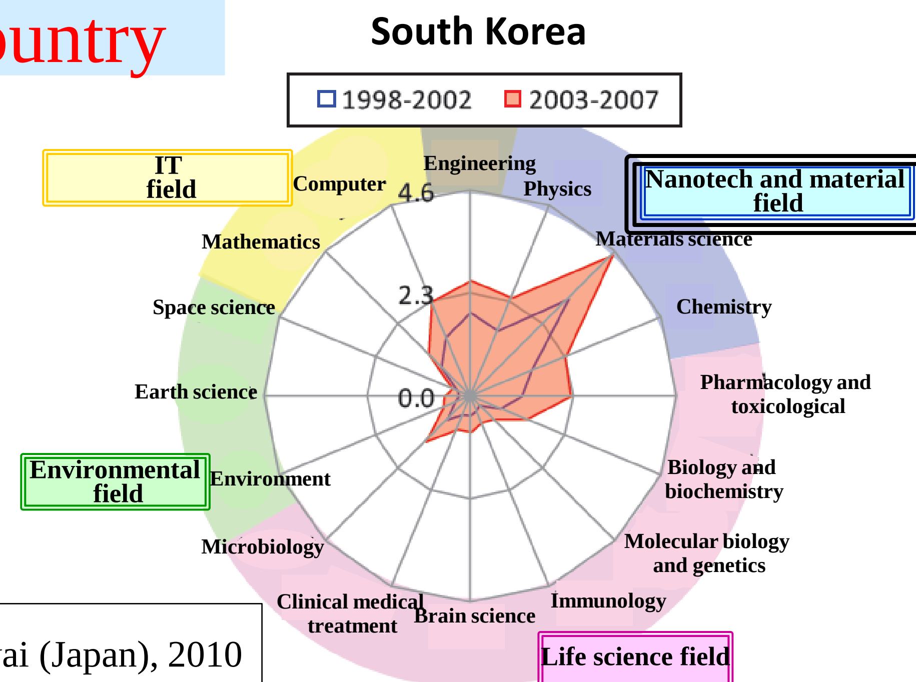
*** All numbers shown above are actual spending, except 2010, which is estimated spending for the current year and 2011 , which is requested amount for next year**
(FY ‘09 figure shown here does *not* include ~$500 million in additional ARRA funding).
**** 2011 figure shown here does *not* include DOD earmarks included in previous yrs. ($117 M ‘09)**





Strengths per country

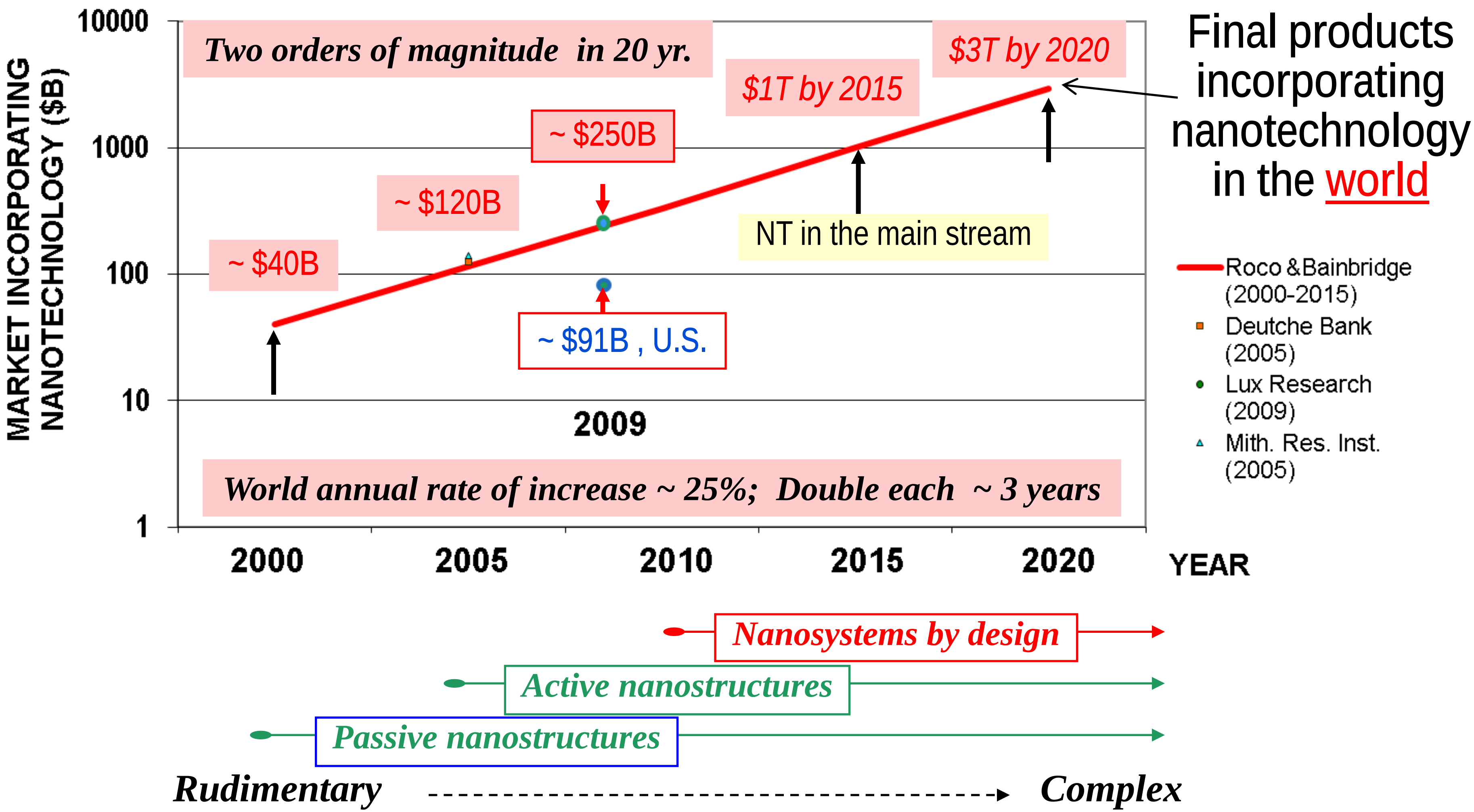




Nano2, T. Kawai (Japan), 2010

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

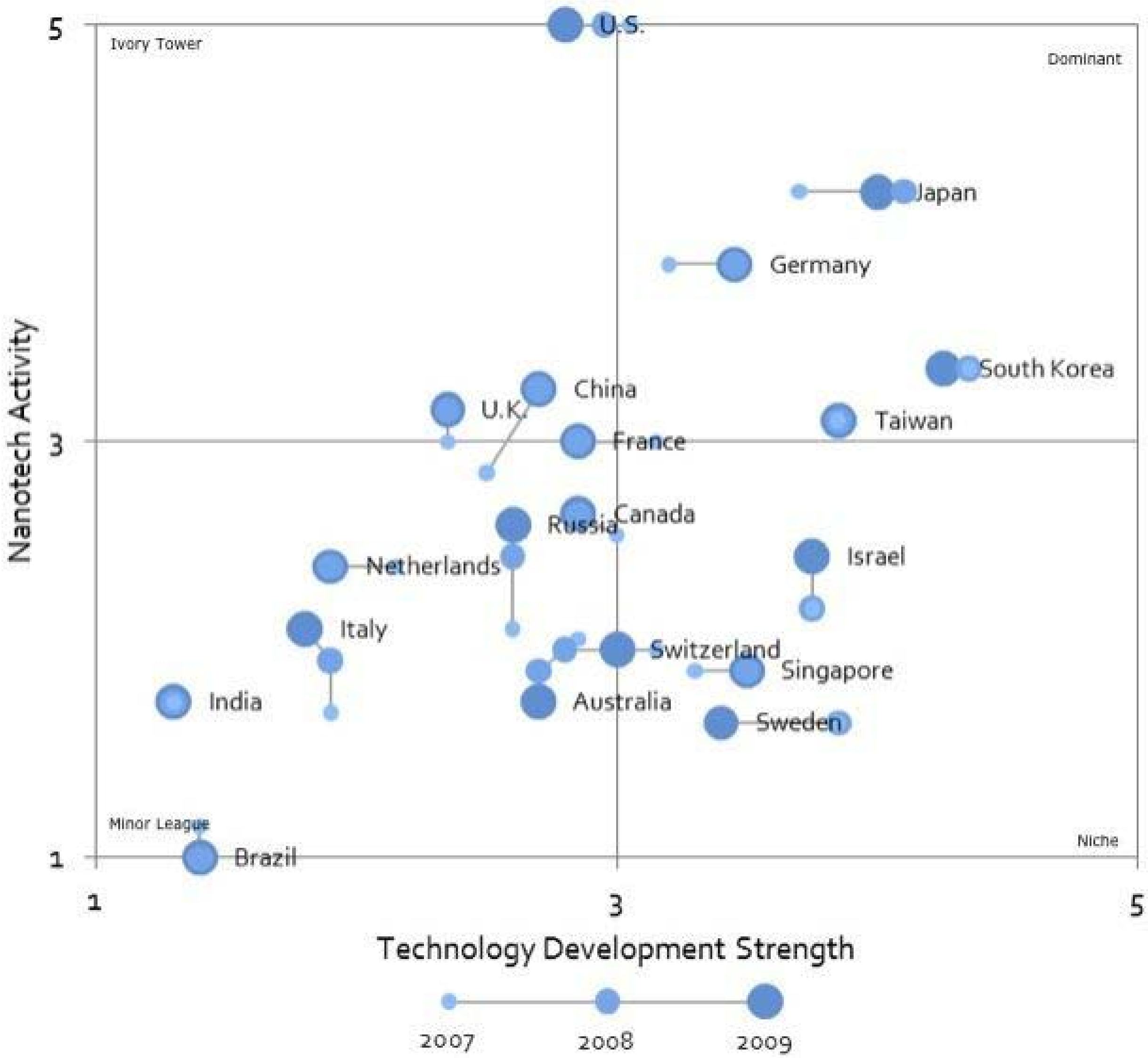
(Estimation made in 2000 after international study in > 20 countries)



Reference: Roco and Bainbridge, Springer, 2001

MC Roco, Jan 19 2010

Ranking the nations on nanotechnology: rapid changes in ability to assimilate it



by David Hwang, Lux Research, August 2010

2000-2010 Outcomes

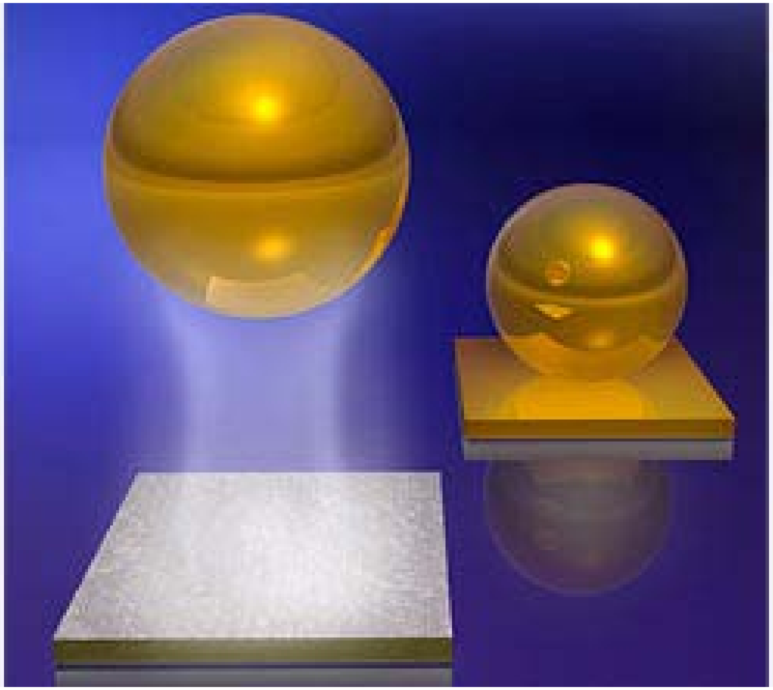
- Remarkable scientific discoveries than span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of 1D - 4D nanostructured **building blocks for devices and systems**

- 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

Discovery of Nanoscale Repulsion

Federico Capasso, Harvard University



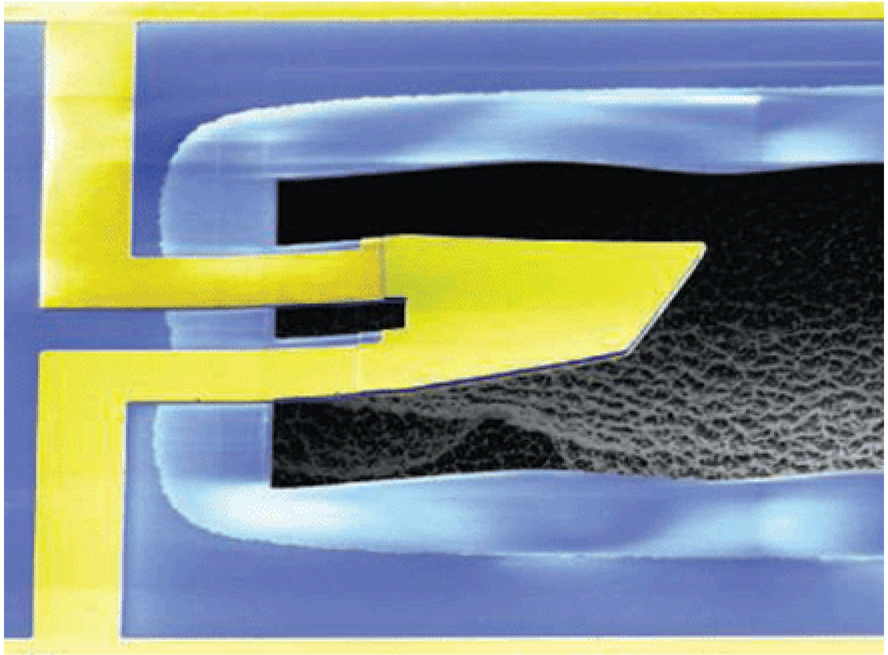
A repulsive force arising at nanoscale was identified similar to attractive repulsive Casimir-Lifshitz forces.

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

The First Quantum Machine

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



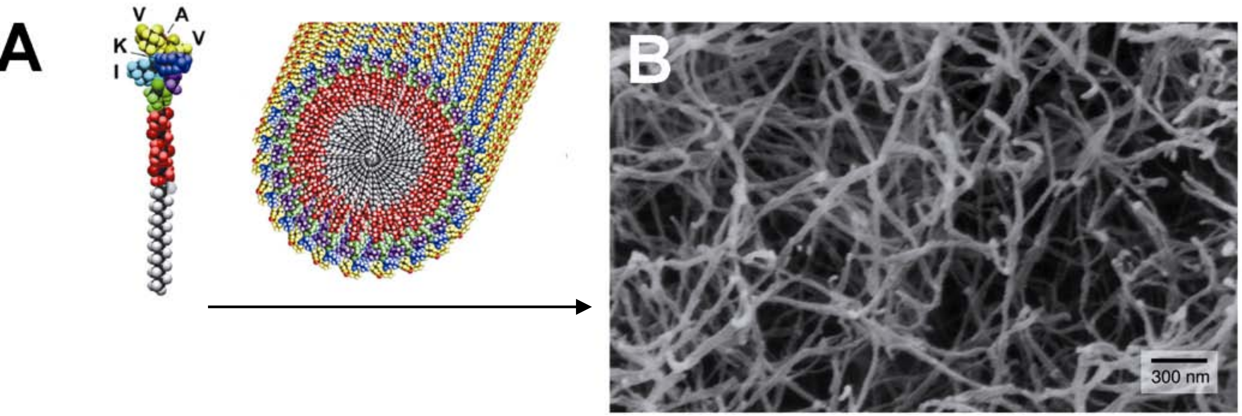
The simplest quantum states of motion with a vibrating device was measured (the board of aluminum is as long as a hair is wide)

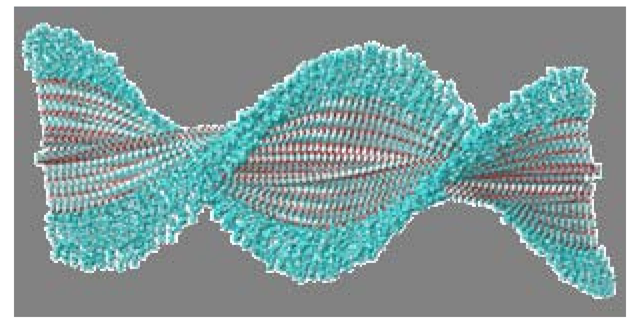
Aaron O'Connell and Andrew Cleland, UCSB, 2010

Example 4th generation (in research)

Designing molecules for hierarchical selfassembling

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

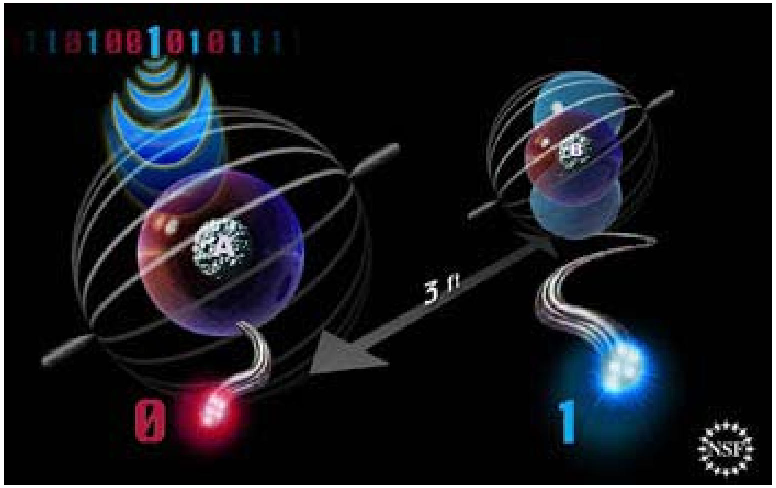




- New nanomachines, robotics - DNA architectures (Ned Seeman, Poly. Inst.)
- Designed molecules for self-assembled porous walls (Virgil Percec, U. PA)
- Self-assembly processing for artificial cells (Matt Tirrell, UCSB)
- Block co-polymers for 3-D structures on surfaces (U. Mass, U. Wisconsin)

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

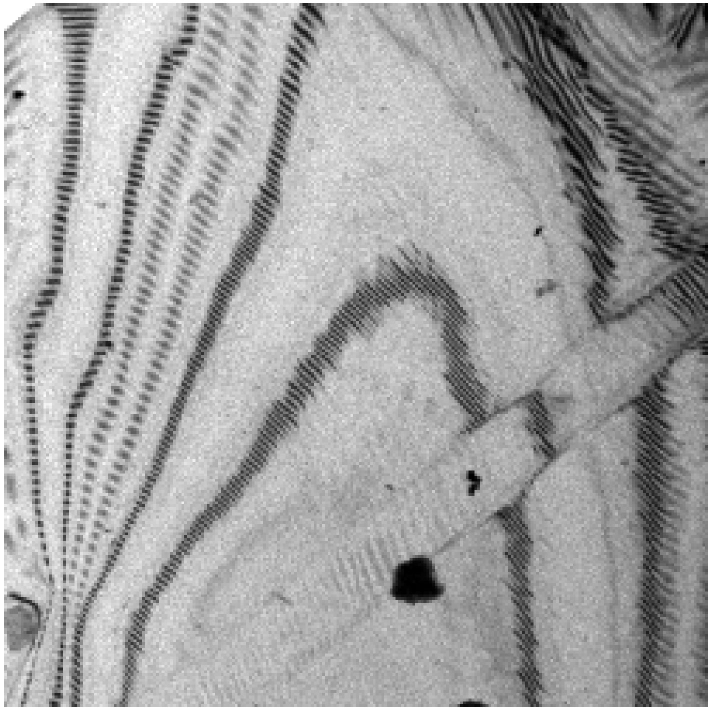
Experiments have attempted to teleport states tens of thousands of times per second. But only about 5 times in every billion attempts do they get the simultaneous signal at the beam splitter telling them they can proceed to the final step.

2000-2010: 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
- Simulation from basic principles has expanded to **assemblies of atoms 100 times larger** than in 2000
- Measure: 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/

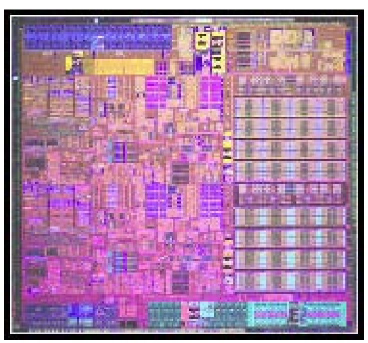
Use of ultra short laser flashes to observe fundamental motion and chemical reactions in real-time (timescale of a femtosecond, 10^{-15}s), with 3D real-space atomic resolution.

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

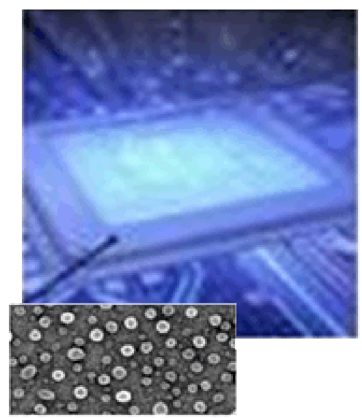
2000-2010: Examples of innovations

- Discovery of spin torque transfer (the ability to switch the magnetization of nanomagnet using a spin polarized current), which has significant implications for memory, logic, sensors, and nano-oscillators. **A new class of devices** has been enabled
- Scanning probe tools for printing one molecule or nanostructure high on surfaces over large areas with sub-50 nm resolution have become reality in research and commercial settings. This has set the stage for developing true “desktop fab” capabilities that allow researchers and companies to rapidly prototype and evaluate nanostructured materials or devices at point of use

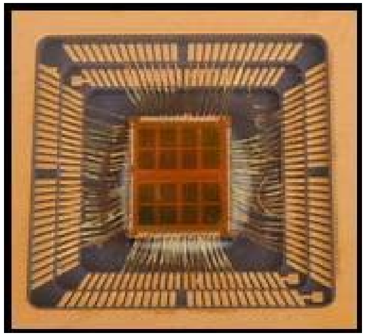
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



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)

From: Nano2 Report, 2010, p. XII

2000-2010: Safe Development

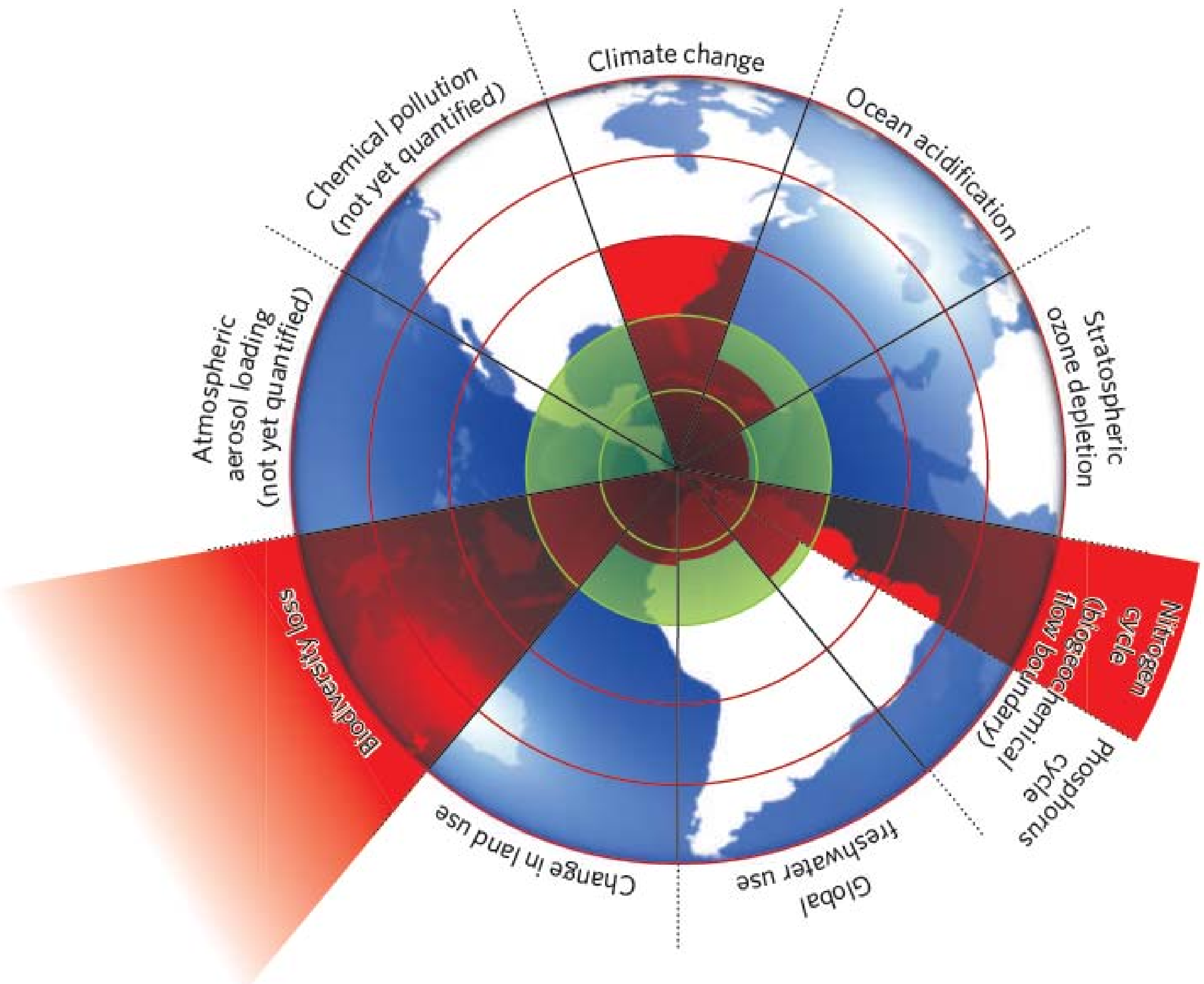
There is greater recognition of the essential areas of nanotechnology-related EHS and ELSI issues

- Building physico-chemical-biological understanding
- Regulatory challenges for specific nanomaterials
- Experiment governance methods under conditions of uncertainty and knowledge gaps
  - risk assessment frameworks
  - life cycle analysis based on expert judgment
  - use of voluntary codes, and
  - incorporation of safety considerations into the design and production stages of new nano-enabled products

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 improved hydrogen 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

Sustainable nanotechnology solutions for clean environment; energy, water, food, mineral resources supplies; green manufacturing, habitat, transportation, climate change, biodiversity



Current critical planetary boundaries are biodiversity, nitrogen cycle, climate change

(Rockström et al. 2009)

Nano2 Report, 2010, p. 147

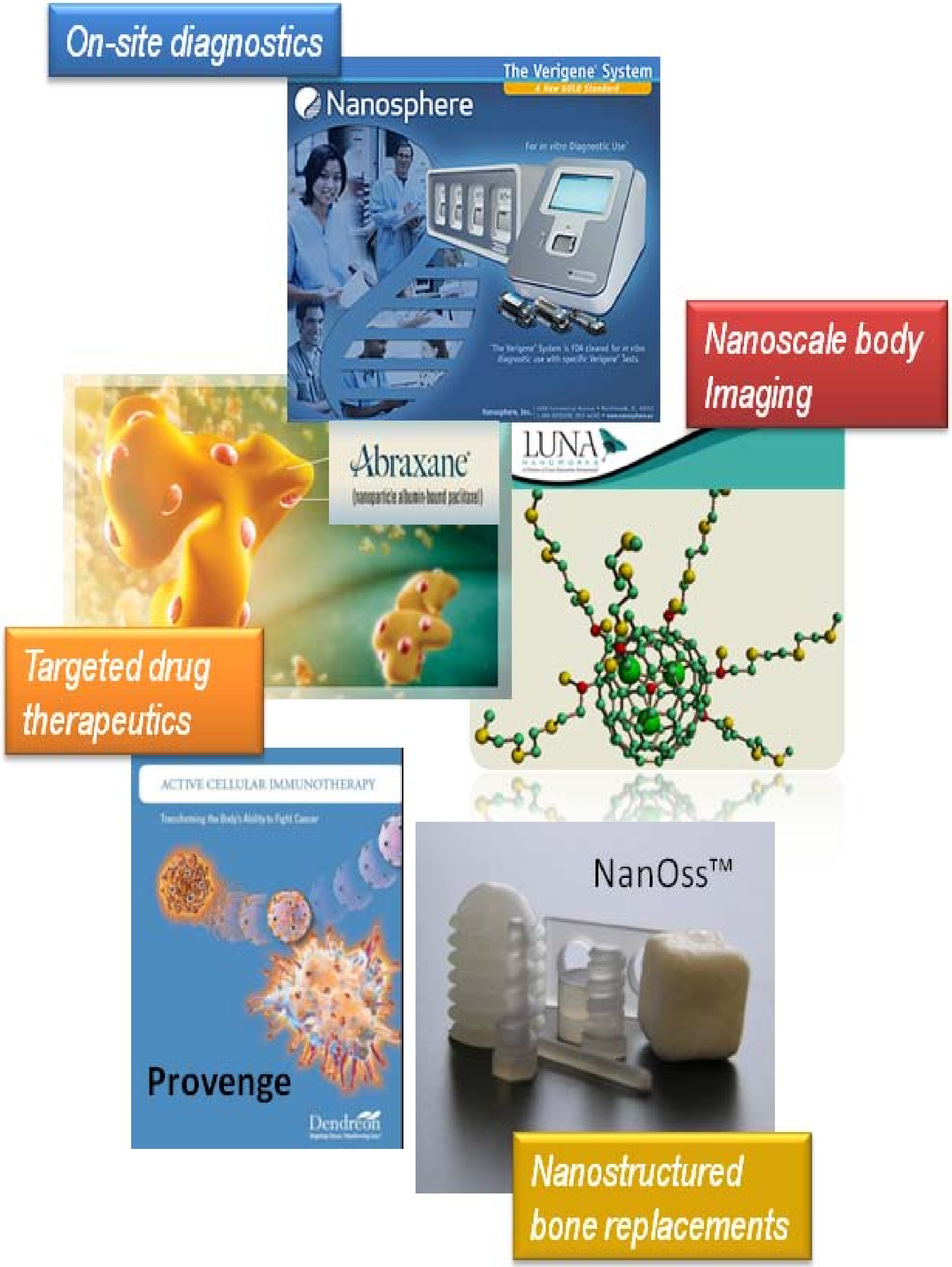
2000-2010: Towards nanotechnology applications

- Current applications are based upon relatively simple "passive" (steady function) nanostructures used as components to improve products (e.g., nanoparticle-reinforced polymers). However, **since 2005, more sophisticated products with "active" nanostructures** and devices have been introduced (e.g., point-of-care molecular diagnostic tools and life-saving targeted drug therapeutics).
- Entirely new classes of materials have been discovered and developed: from one-dimensional nanowires and quantum dots of various compositions to polyvalent noble metal nanostructures, graphene, metamaterials, nanowire superlattices, and many other nanocomposites. **A periodic table of nanostructures is emerging**

2000-2010: Towards nanotechnology applications - examples -

Nanoscale medicine has made significant breakthroughs in the laboratory, advanced rapidly in clinical trials, and made inroads in biocompatible materials, diagnostics, and treatments.

Ex: **Abraxane i**s commercialized for treating different forms of cancer. The first point-of-care nano-enabled medical diagnostic tools such as the **Verigene System** are now being used to rapidly diagnose disease. **Over 50 cancer-targeting drugs based on nanotechnology are in clinical trial** in the U.S. alone. Nanotechnology solutions are enabling companies such as **Pacific Biosciences and Illumina** to offer products that are on track to meet the **$1000 genome challenge**

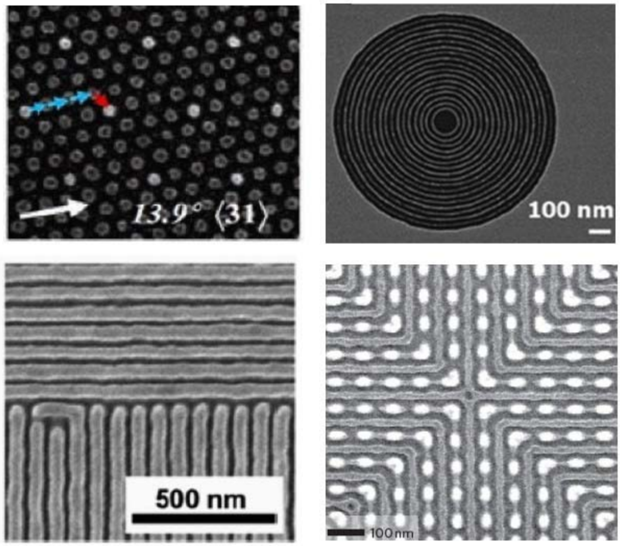


Nano2 Report, 2010, p. XIV

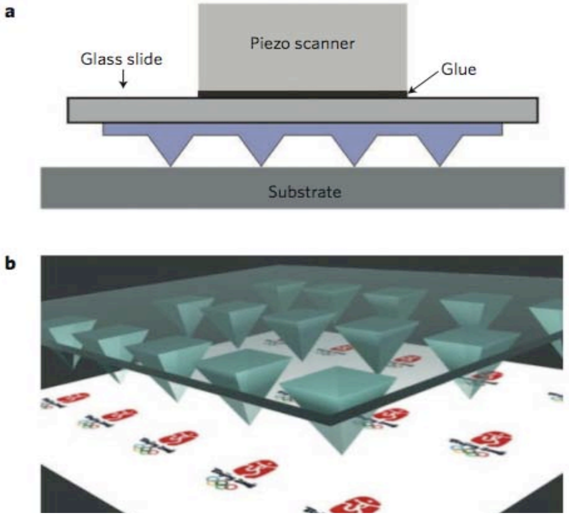
Examples of nanotechnology incorporated into commercial healthcare products, in production in 2010

2000-2010: Towards nanotechnology applications - examples -

- Patterning on surfaces: a versatile library has been invented of surface patterning methods including directed selfassembling, optical and "dip-pen" nanolithography, nanoimprint lithography, and roll-to-roll processes for manufacturing graphene and other nanosheets

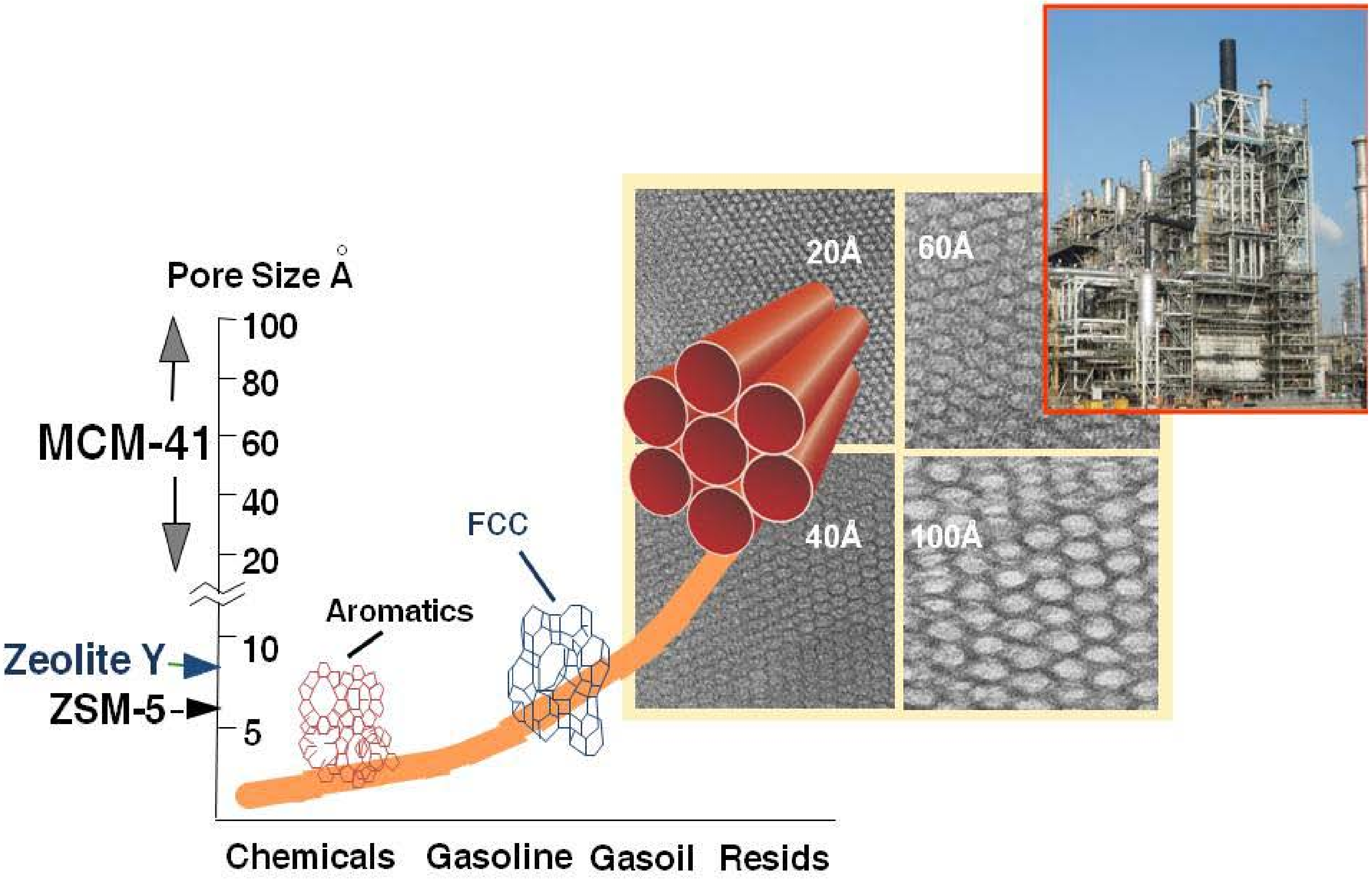


Diblock copymer directed selfassembling



Polymer-pen array lithography

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

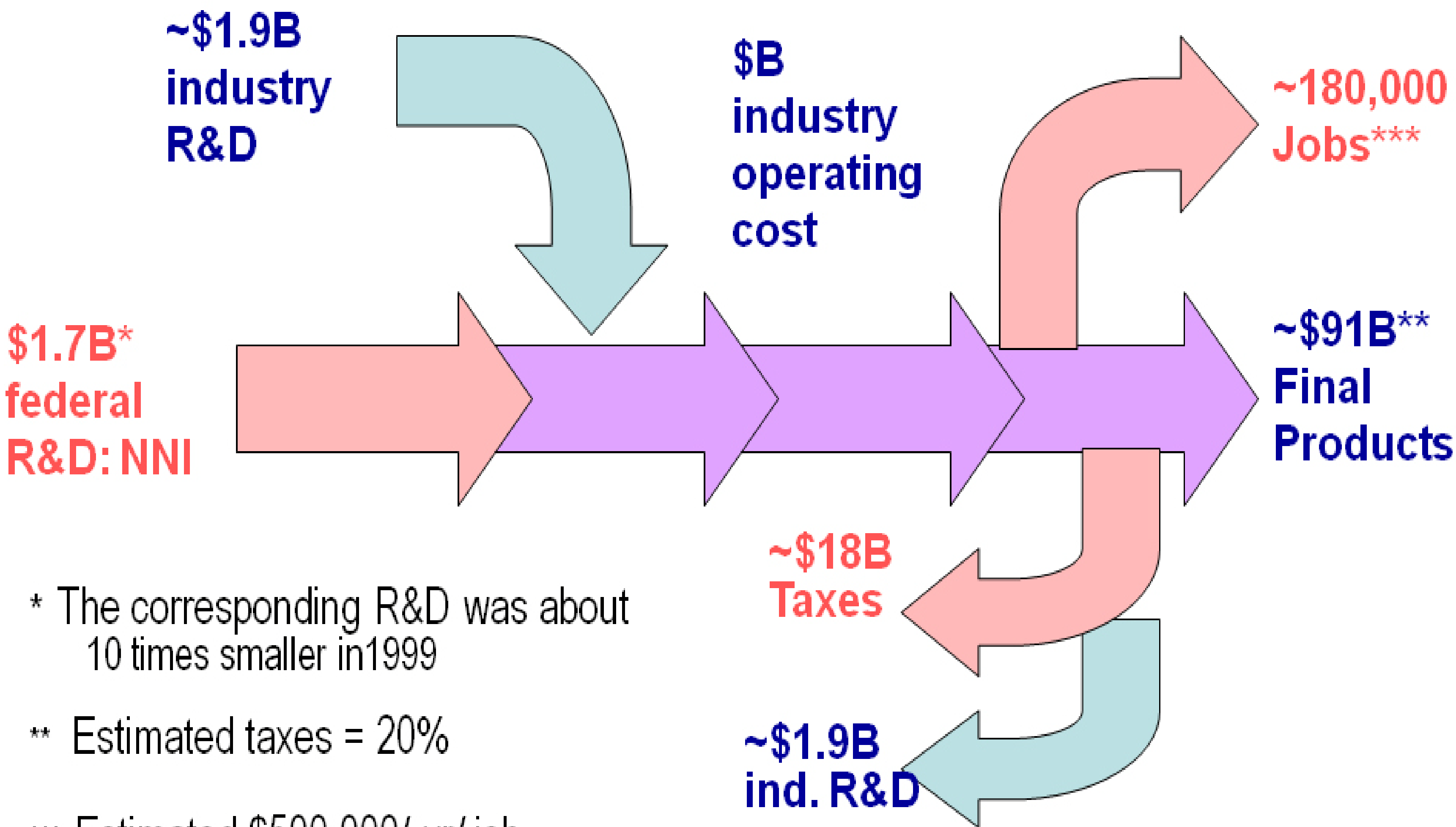
Ten highly promising products incorporating nanotechnology in 2010

- 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

With safety concerns: cosmetics, food, disinfectants,..

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

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



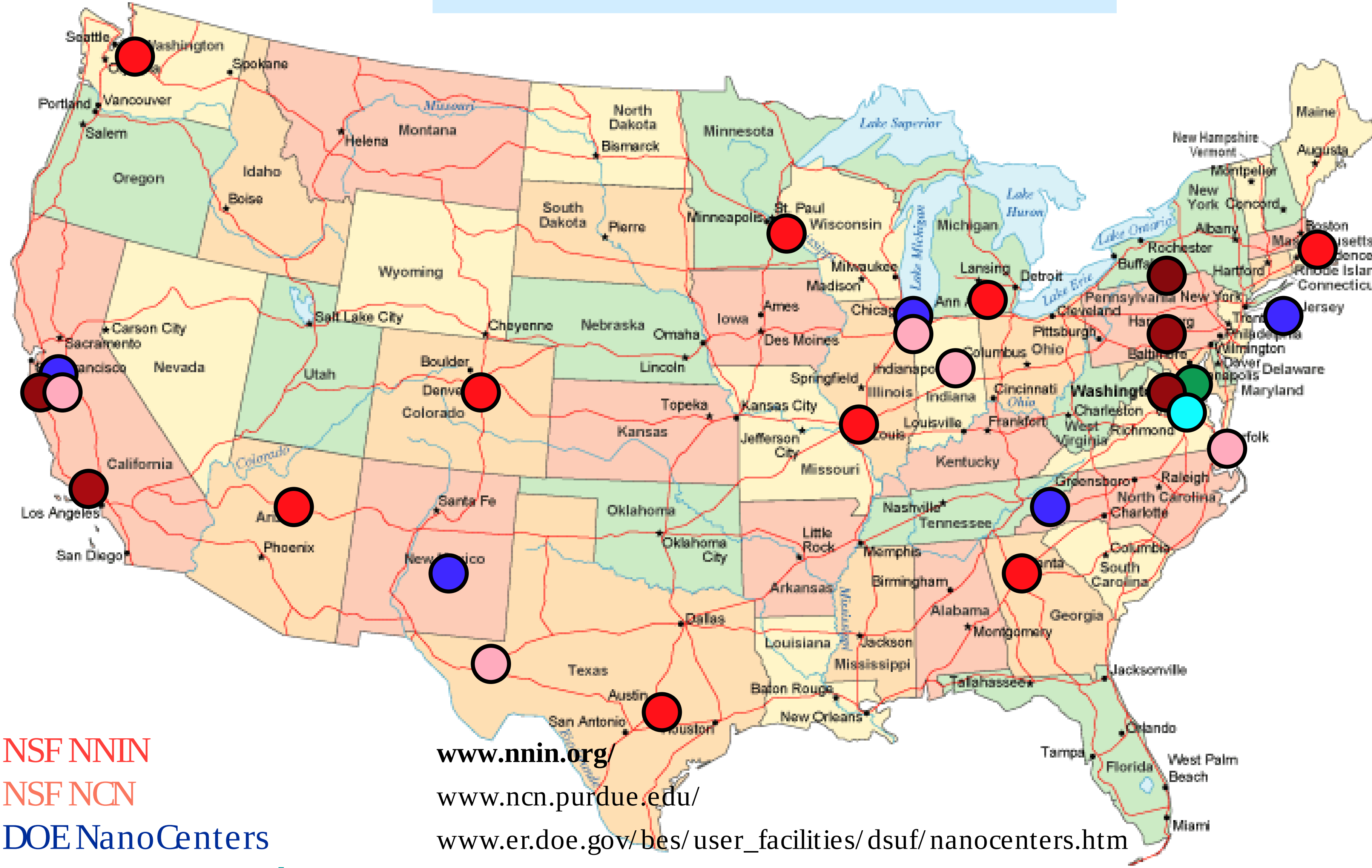
* The corresponding R&D was about 10 times smaller in1999

** Estimated taxes = 20%

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

U.S. Infrastructure

NNI R&D User Facilities



NSF NNIN — **www.nnin.org/**

NSF NCN — www.ncn.purdue.edu/

DOE NanoCenters — www.er.doe.gov/bes/user_facilities/dsuf/nanocenters.htm

NIST CNST NanoFab — www.cnst.nist.gov/nanofab/nanofab.html

NIH NCI NCL — **ncl.cancer.gov/**

Nano2 Report, 2010, p. XVIII

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

Nano2 Report, 2010, p. 360

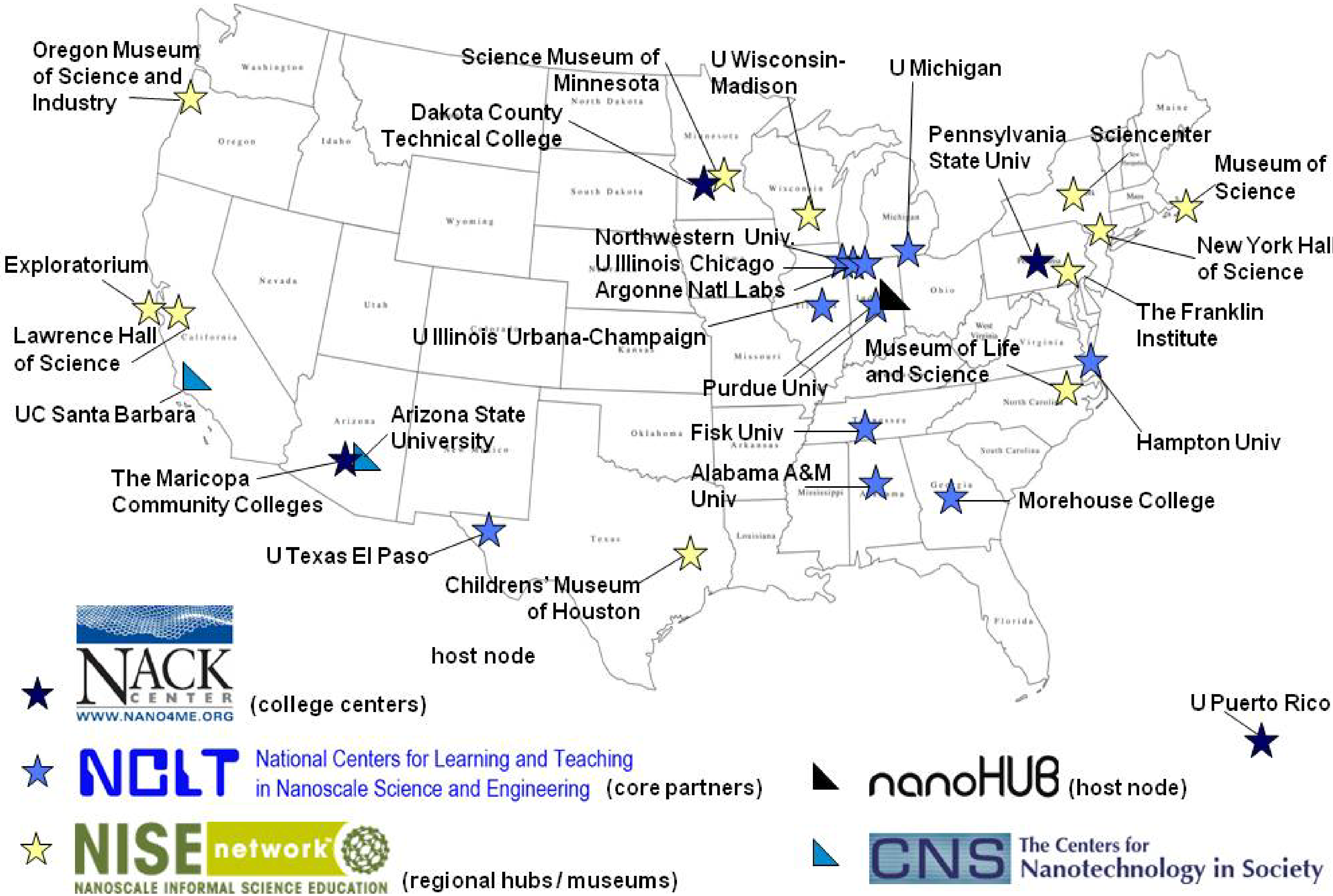
NSE education

“A five-year goal of the NNI is to ensure that 50% of U.S. research institutions’ faculty and students have access to the full range of nanoscale research facilities, and student access to education in nanoscale science and engineering is enabled in at least 25% of the research universities.”

Mihail C. Roco, NSF, 2001

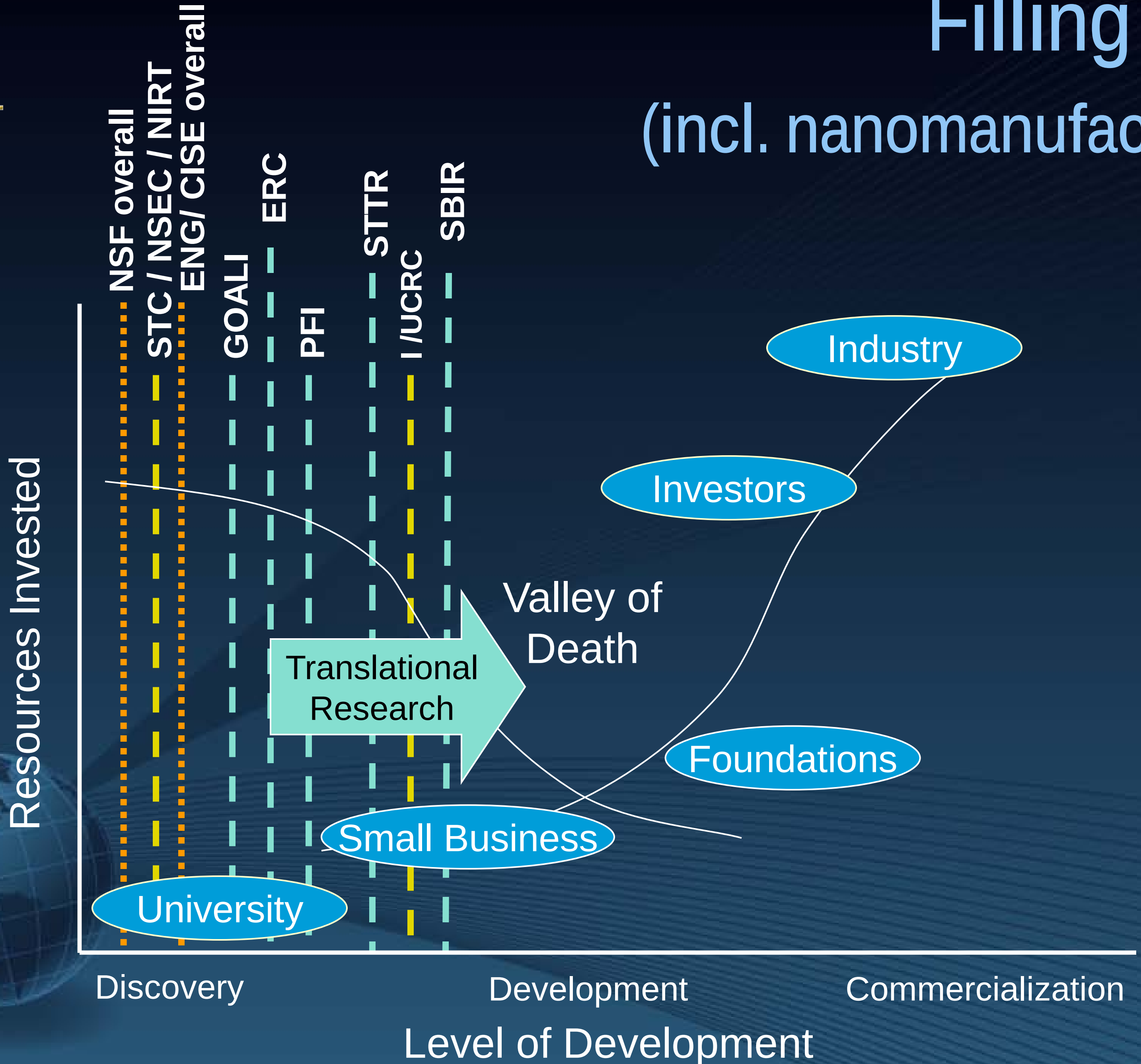
http://www.nano.gov/html/edu/home_edu.html

Key NNI education networks in 2010



Nano2 Report, 2010, p. XVIII

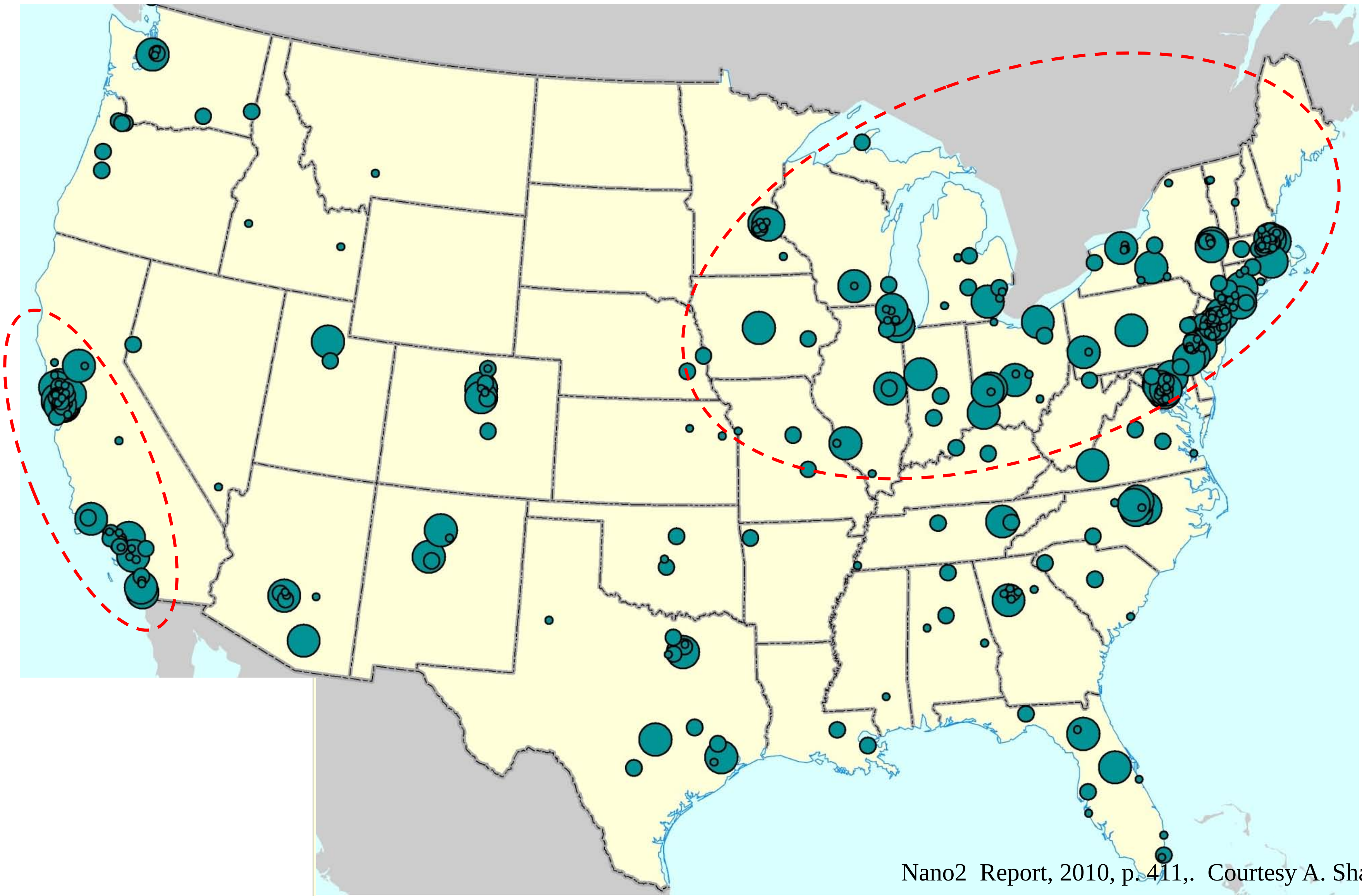
Filling Gaps
(incl. nanomanufacturing)



Corporate entry into nanotechnology by city in 2008

(establishments with nano publications or patents for cities with 10 or more establishments)

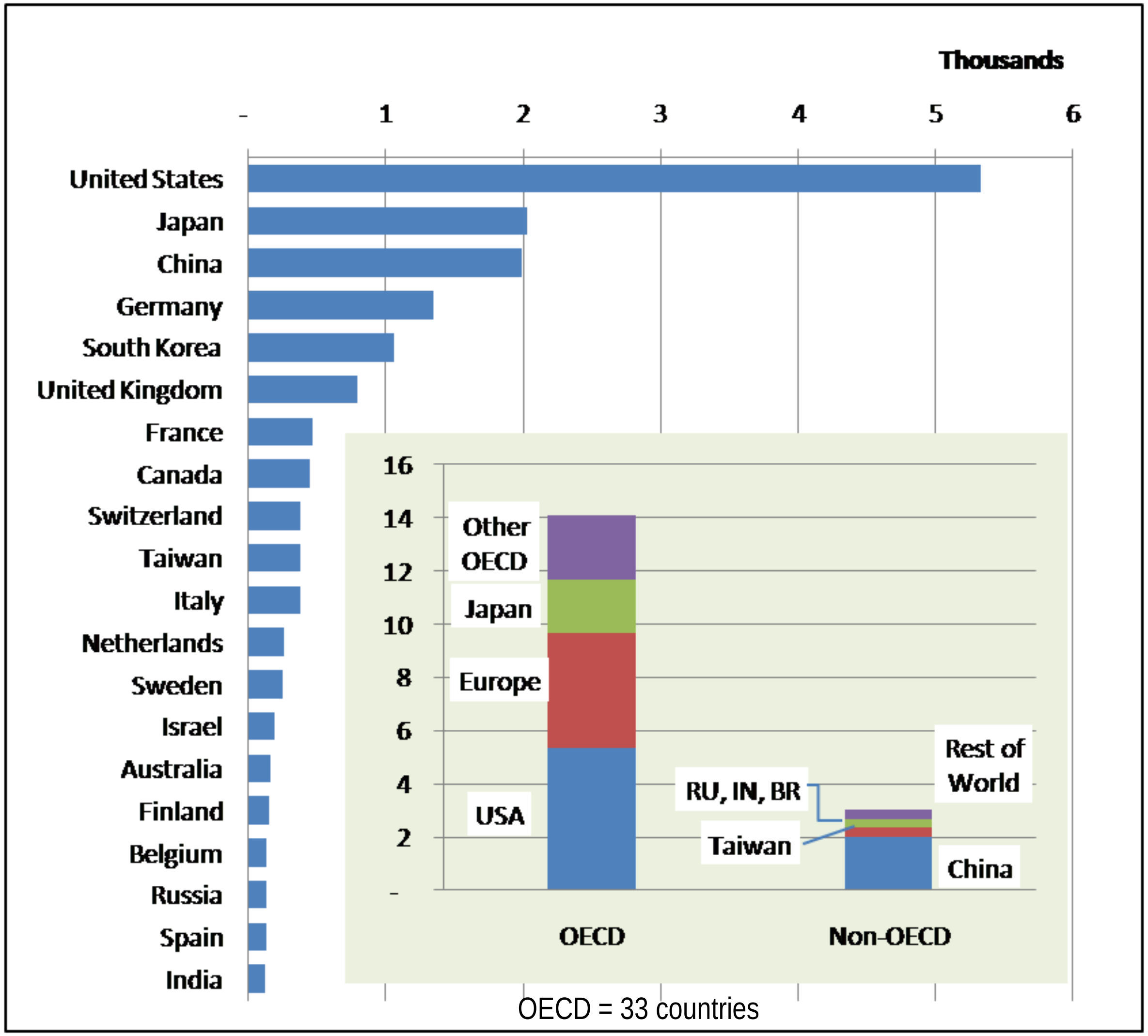
US: 5,440 co. with papers/patents/products (31% of the world; 44% of nano patents)



Nano2 Report, 2010, p. 411,. Courtesy A. Shapira

Transformative governance

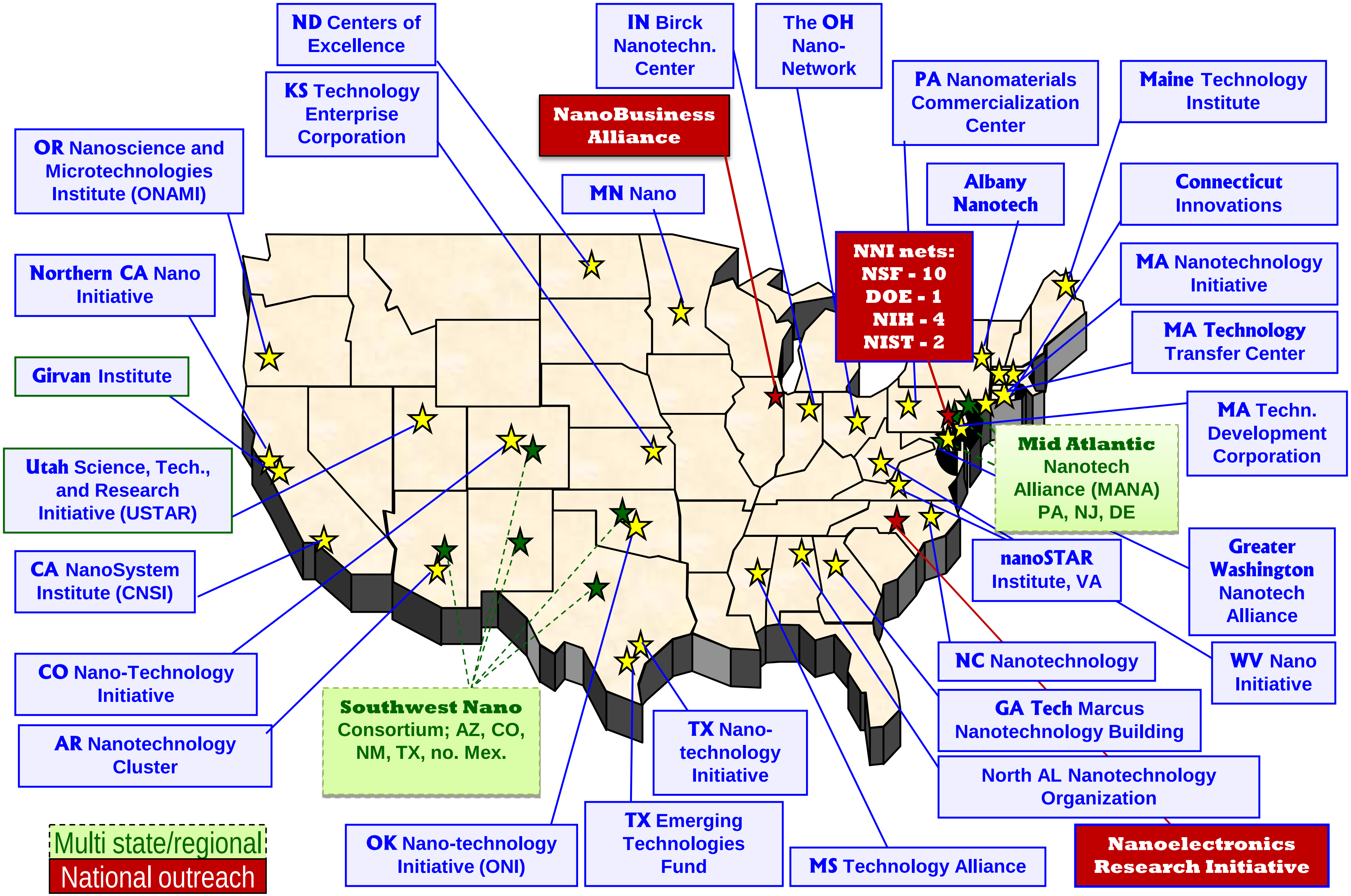
Ex.: Corporate Entry in leading countries (has products, articles and/or patents), 1990-2009



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

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

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



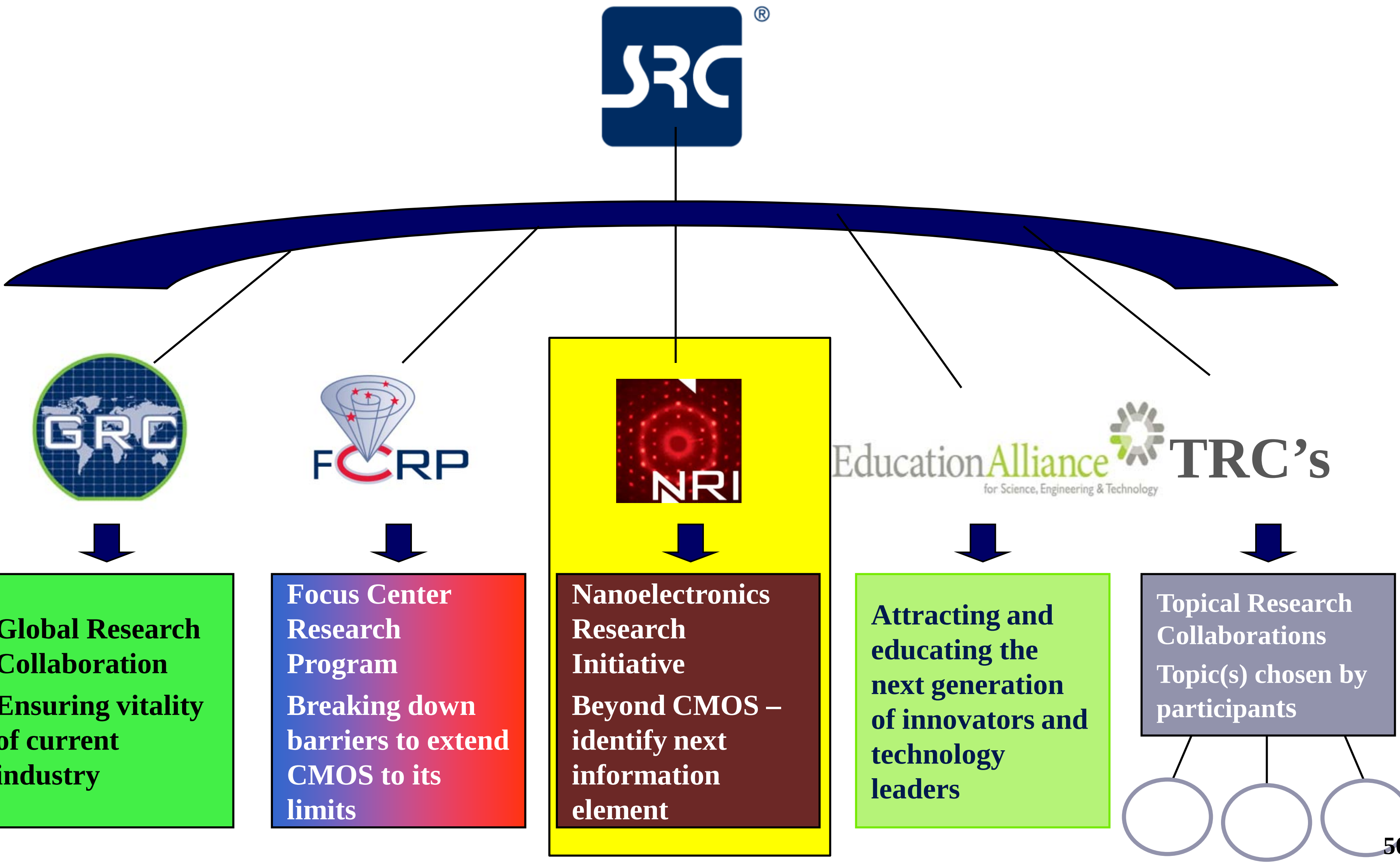
MC Roco, Nov 10 2010

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

Example of emerging technology organization:
Semiconductor Research Corporation



Changes of the vision in the last ten years

Nanotechnology governance *has evolved considerably* :

- The viability and societal importance of nanotechnology has been confirmed, while extreme predictions have receded
- An international community has been established
- Greater recognition to nanotechnology EHS and ELSI after 2004
- The 2001 vision of international collaboration – reality after the first International Dialogue on Responsible Development of Nanotechnology (Arlington, 2004)
- Nanotechnology has become a model for governance issues (transformative/responsible/inclusive/visionary) of other emerging technologies. Increasing role of innovation

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:** energy received momentum only after 5 years, nanotechnology for water filtration and desalination only limited; delay on nanotechnology for climate research (because of insufficient support from beneficiary stakeholders?)

- **Public awareness remains low**, at about 30%. Challenge for public participation

On target in 2010, even if doubted in 2000

- The growth rates of papers and inventions (23-35%) is quasi exponential at rates higher than the average in all fields (about 5-10%)
- Nanotechnology stimulated interdisciplinary research and education, creating a multidisciplinary projects, organizations, and communities
- Estimation that nanotechnology R&D investment in US will grow by about 30% annual growth rate (government and private sector, vertical and horizontal development) in 2000-2008; International coordination and collaboration

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

- Discoveries in several S&E fields

  plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, quantum information system

- The formation / strength of the international community,

  including in nanotechnology EHS and ELSI; governance studies

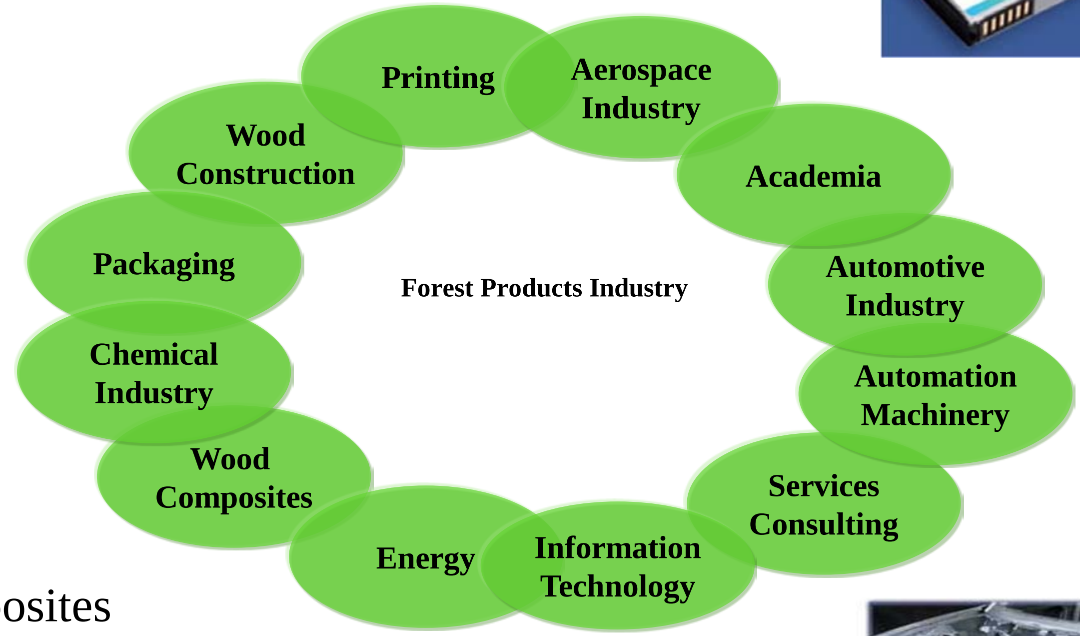
Main lessons learned after ten years

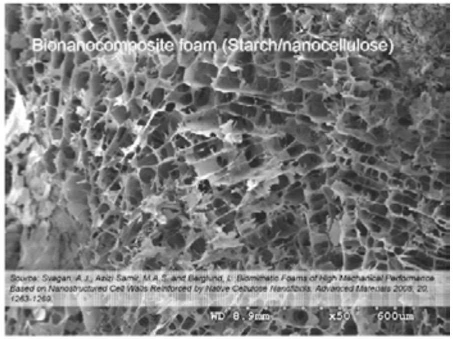
- Need continued, focused investment on **theory, direct measuring and simulation** at the nanoscale. Nanotechnology still in the formative phase
- Besides nanostructured metals, polymers and ceramics, **classical industries can provide excellent opportunities**, such as in: textiles, wood and paper, 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

Cellulose Nanotechnology Applications

Opportunity to replace fossil based materials from renewable resources (wood)

- Batteries
- Super-Capacitors
- Bio Plastics
- Nano Coatings
- Reinforced Polymers
- Smart Sensors
- High Efficiency Filters
- Photonic Devices
- Nano Membranes
- Light Weight Nano Composites
- Biomedical Tissue
- E-Ink
- Nano-Adhesives





Other less explored areas: Minerals; Oil industry; Food and agriculture

Nanotechnology in 2010 - 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

nano2

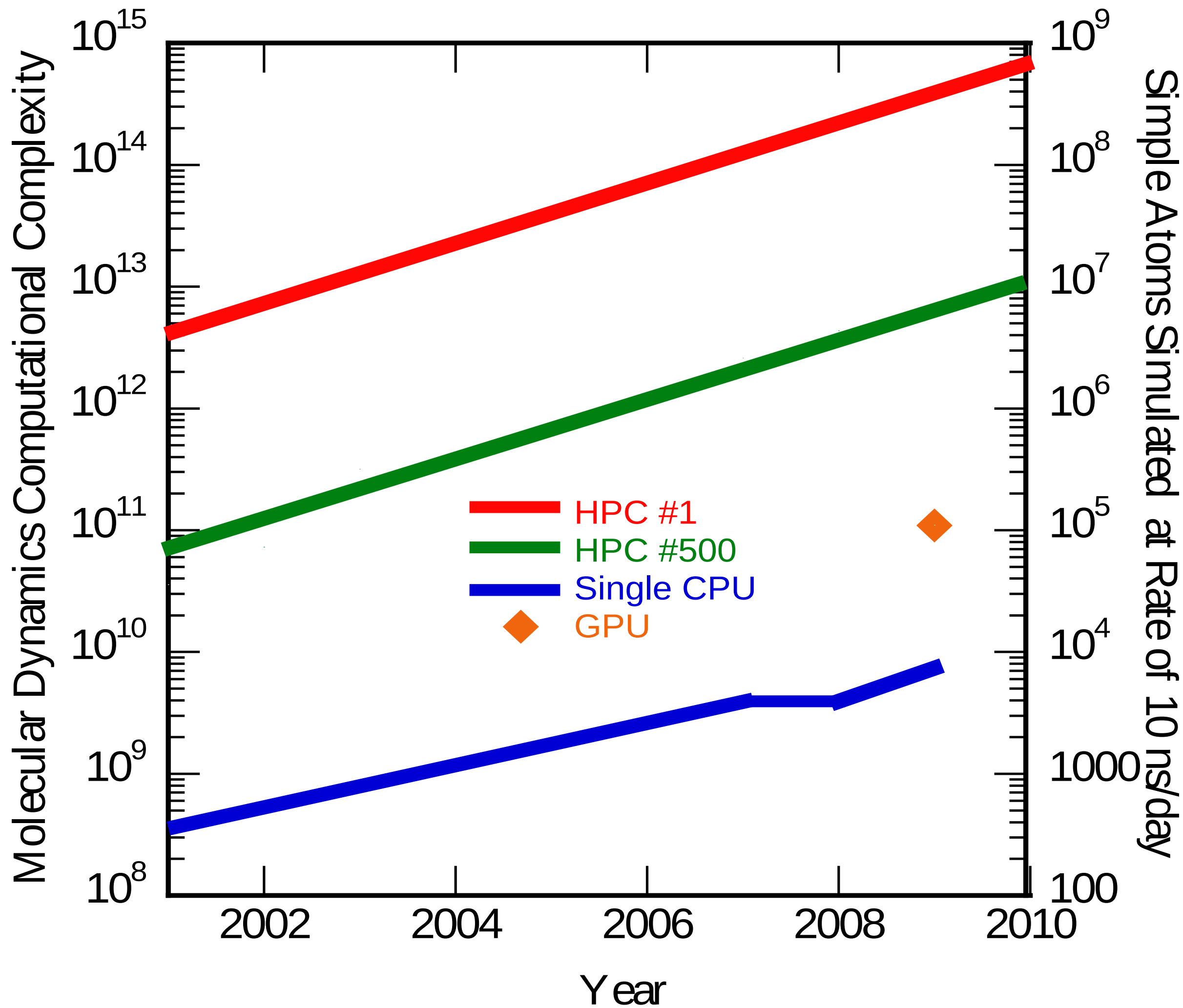
Twelve trends to 2020

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>

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

Scientific challenges

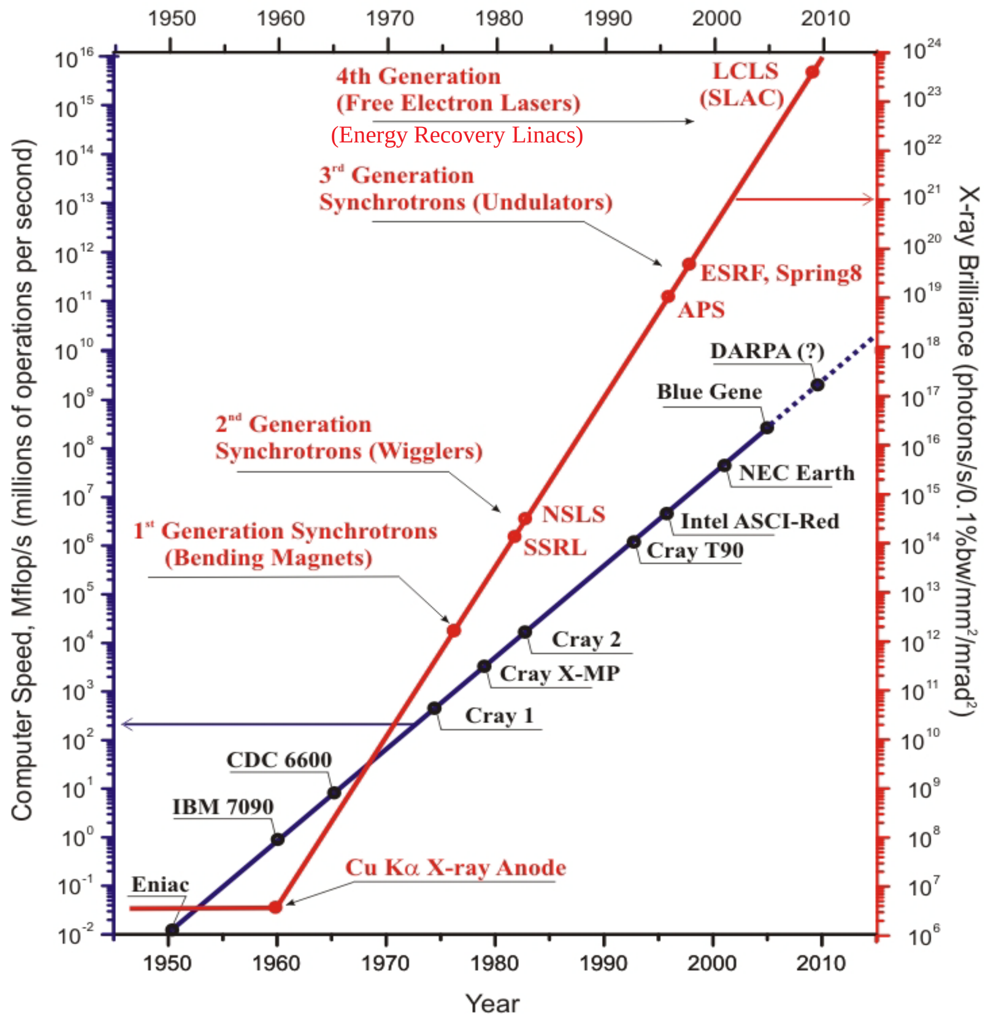
- New theories at nanoscale
  Ex: transition from quantum to classical physics, collective behavior, for simultaneous phenomena
- Non-equilibrium processes
- Understanding and use of quantum phenomena
- Understanding and use of multi-scale selfassembling
- Nanobiotechnology – sub-cellular and systems approach
- Designing new molecules with engineered functions
- New architectures for assemblies of nanocomponents
- The emergent behavior of nanosystems

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):

<u>2 orders of magnitude</u> in last decade (~100 times)



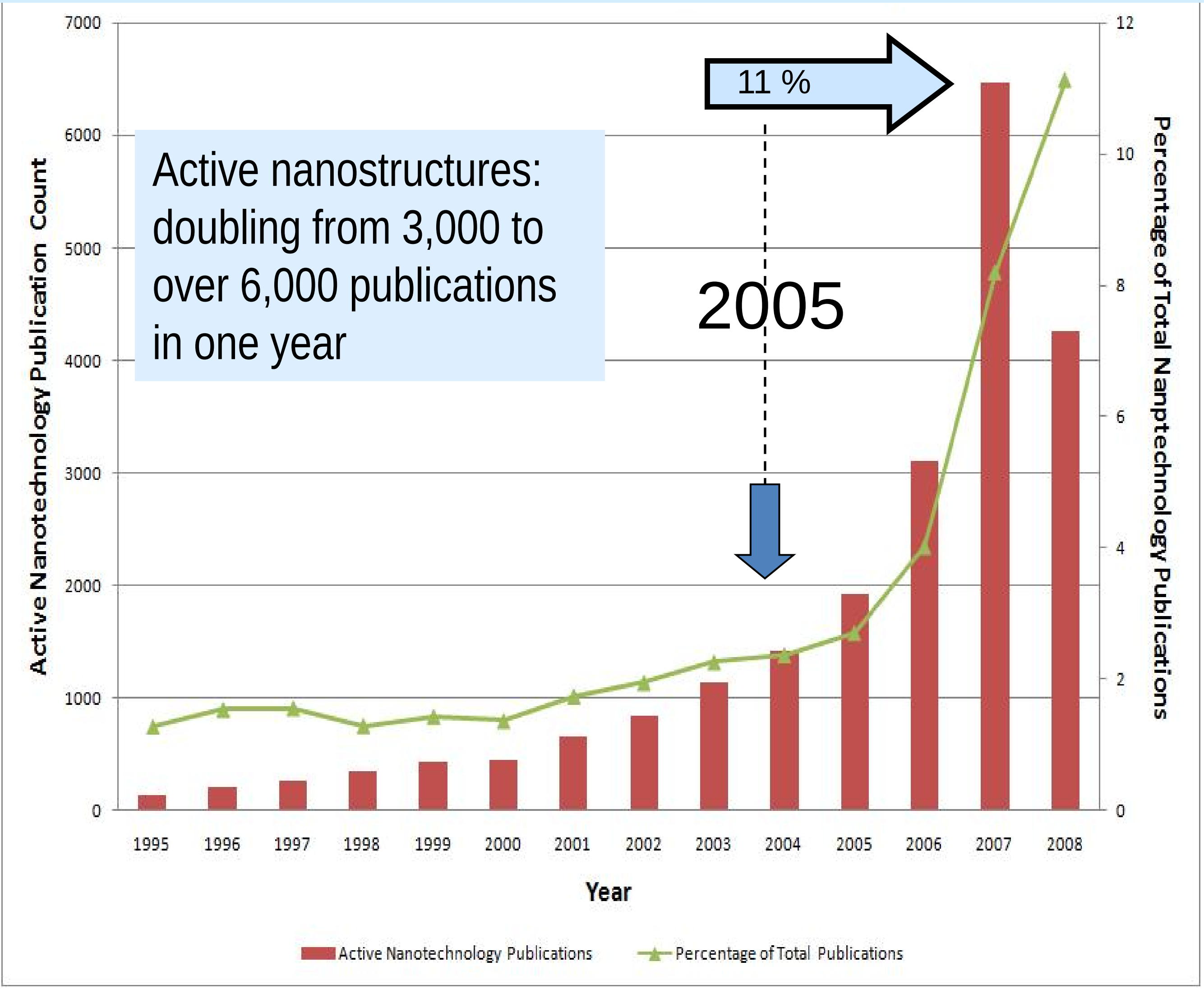
X-ray source brilliance (red):

estimated <u>3.6 orders of magnitude</u>

To increase ~ 5,000 times in next decade

Nano2 Report, 2010, p. 41

3. Shift from "passive " to "active" nanostructures (>2005) and systems (>2010)



Ex.:

Targeted drugs and chemicals

NEMS

Self-healing materials

Remote actuated (e.g., magnetic, electrical, light and wireless tagged nanotech)

Environmentally responsive

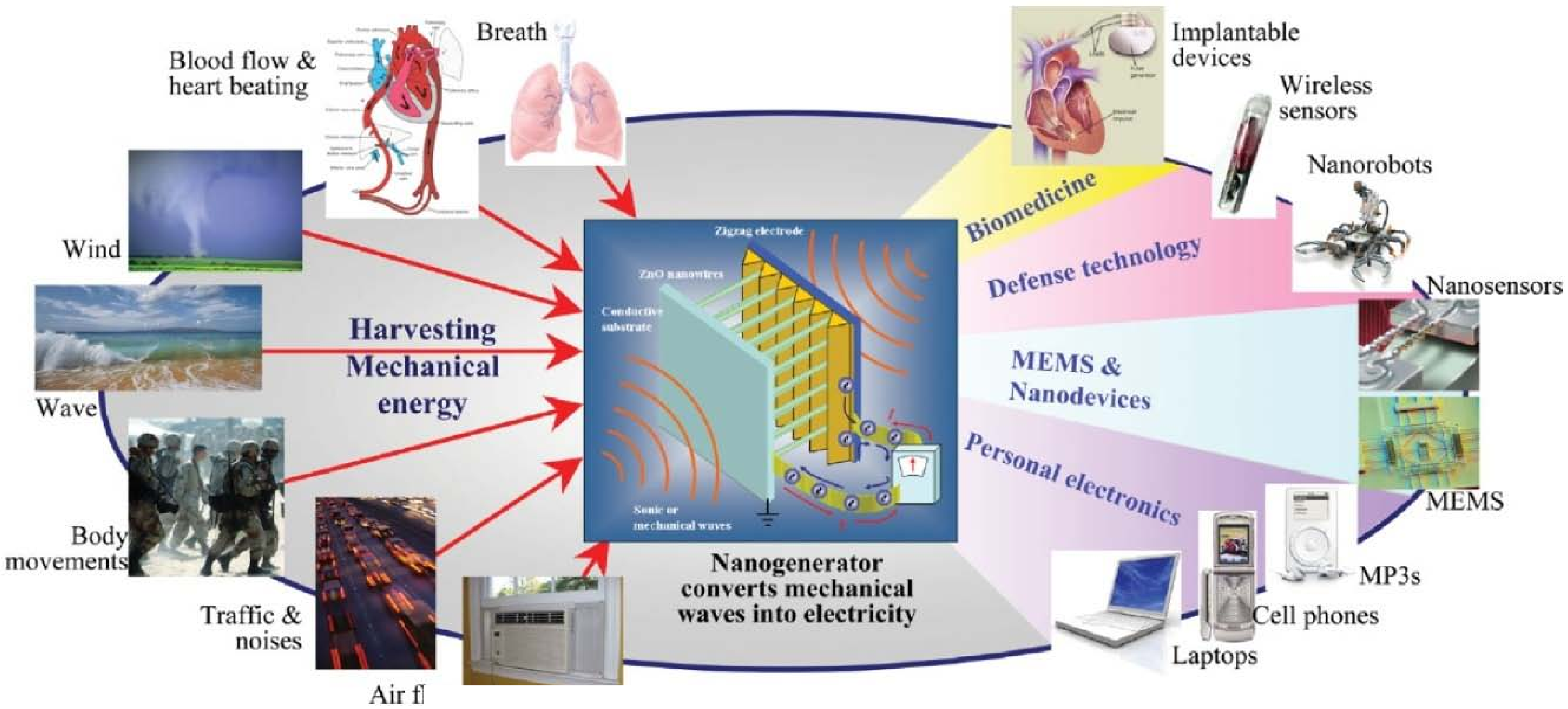
Energy storage devices

Semiconductors, molecular electronics

Nano2 Report, 2010, based on V. Subramanian et al., J. Nanoparticle Research, 2010

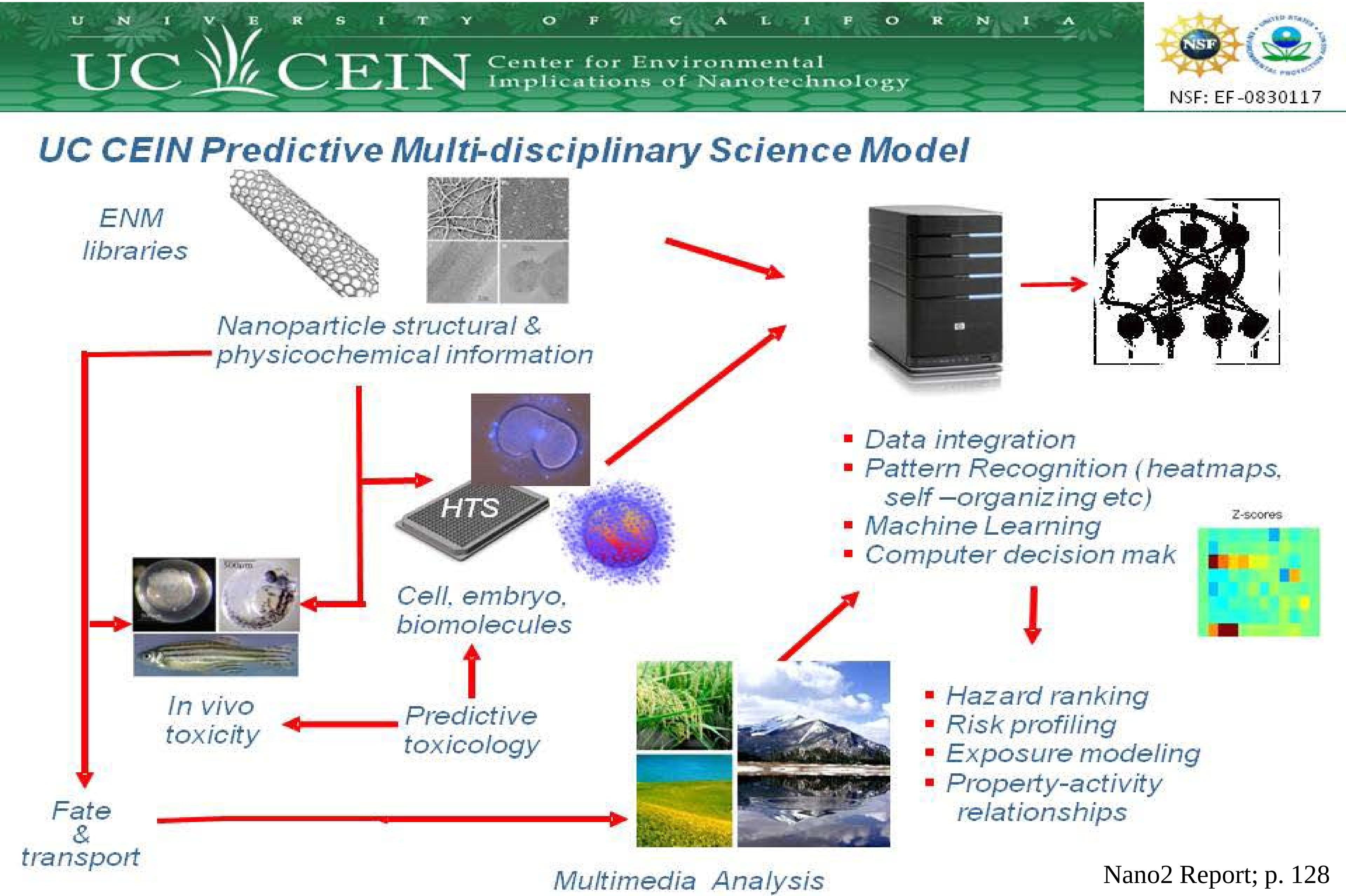
4. Ex: Self-powered nanosystems

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



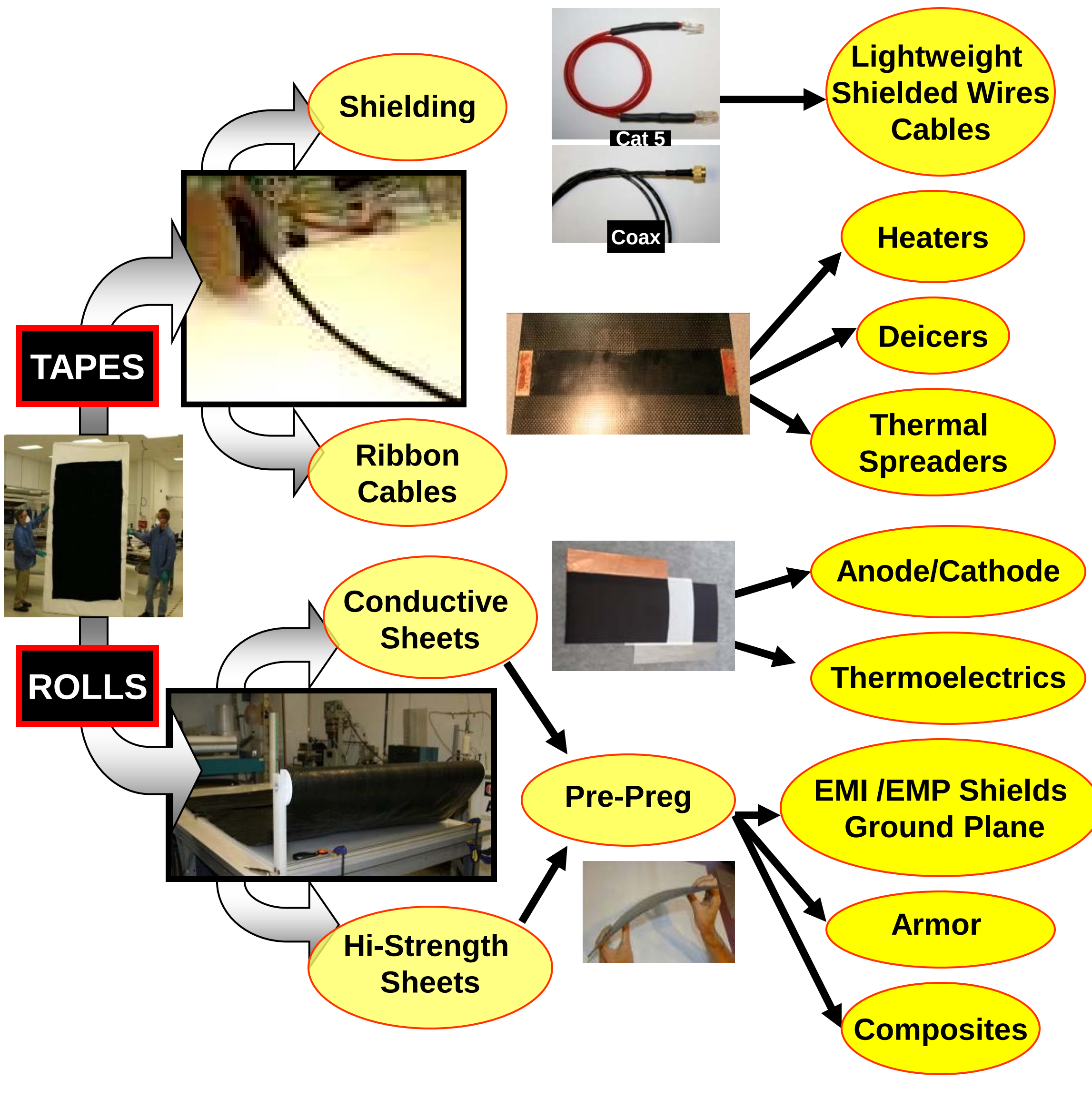
Reference: Z. L. Wang, Adv. Funct. Mater., 2008

UC CEIN predictive model for hazard ranking and risk profiling



Nano2 Report; p. 128

Expanded CNT sheet production with broad impact



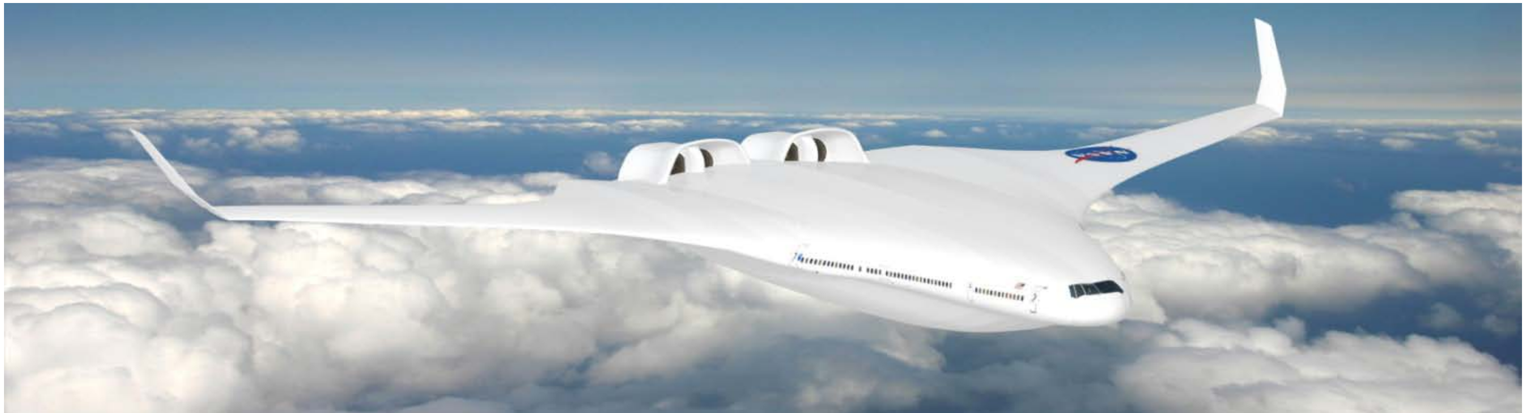
Nano2 Report, 2010, p. XLVI. Courtesy R. Ridgley

Nanotechnology for Aerospace

Future aircraft designs include nanocomposite materials for ultra-lightweight multifunctional airframes; “morphing” airframe and propulsion structures in wing-body that can change their shape; resistance to ice accretion; with carbon nanotube wires; networks of nanotechnology based sensors for reduced emissions and noise and improved safety

Design by NASA and MIT for a 354 passenger commercial aircraft that would be available for commercial use in 2030-2035 and would enable a reduction in aircraft fuel consumption by 54% over a Boeing 777 baseline aircraft

Nano2 Report, 2010, cover page. Courtesy of NASA and MIT

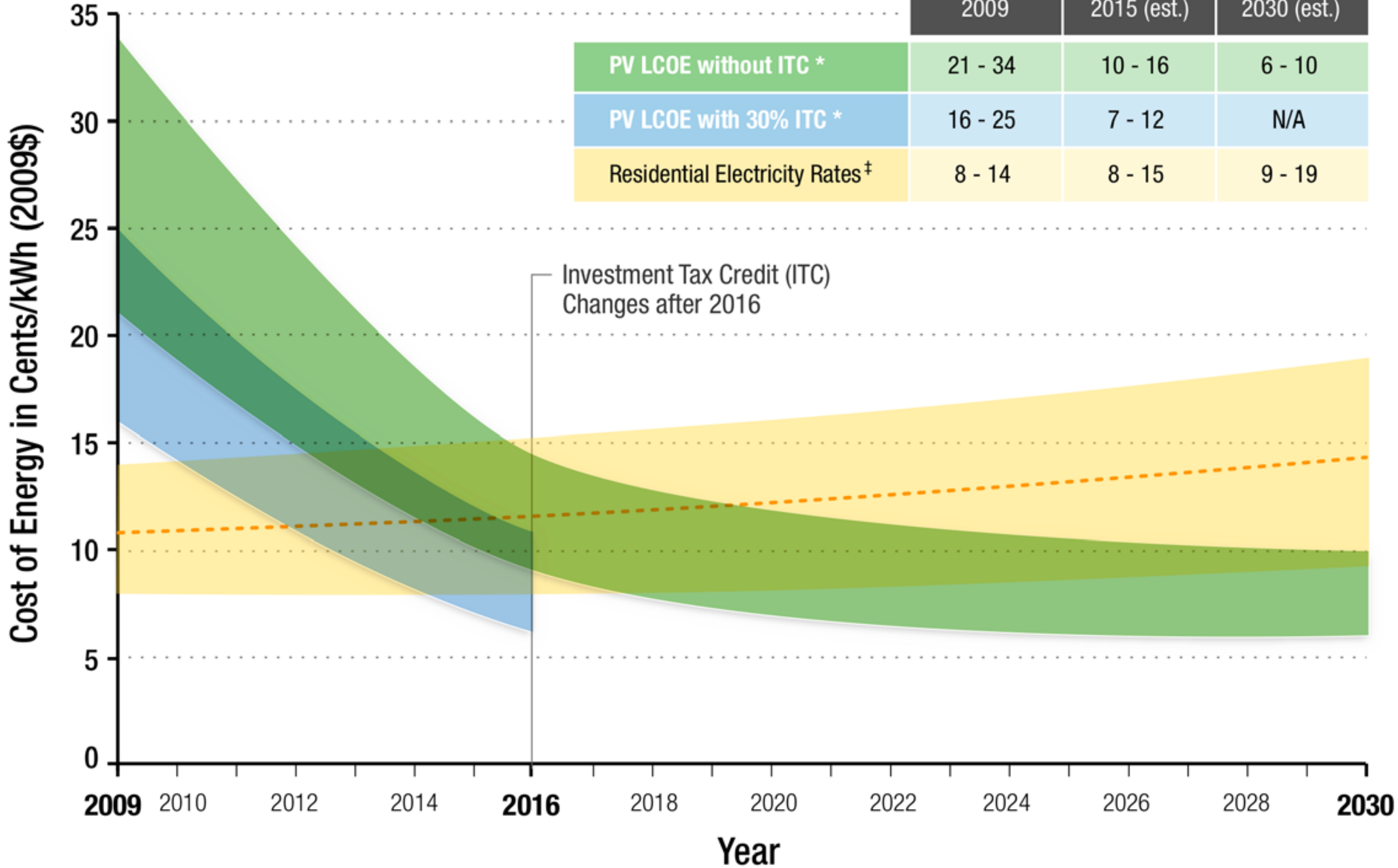


Goal: U.S. grid parity by 2015 for photovoltaic technologies

Levelized cost of energy (LCOE)

Residential PV

	2009	2015 (est.)	2030 (est.)
PV LCOE without ITC *	21 - 34	10 - 16	6 - 10
PV LCOE with 30% ITC *	16 - 25	7 - 12	N/A
Residential Electricity Rates ‡	8 - 14	8 - 15	9 - 19



Courtesy DOE, 2010

2010-2020: Key areas of emphasis

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

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)

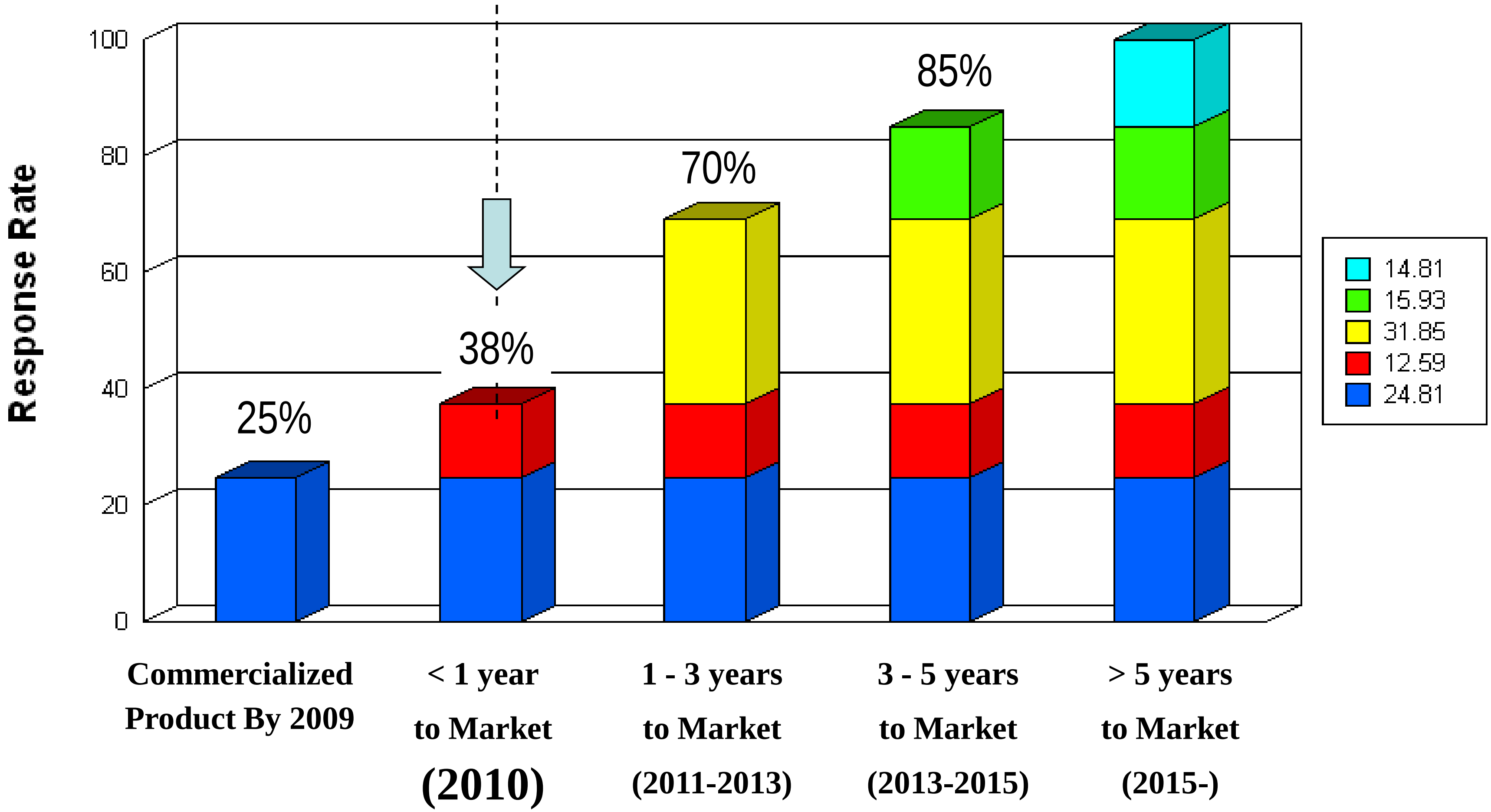
MC Roco, Jan 19 2011

2010-2020: Increasing R&D intensity and return

- Research into the systematic control of matter at the nanoscale will accelerate in the first part of the next decade (2011-2015)
- Nanotechnology by 2020 seamlessly integrated with most technologies and applications, driven by economics and by the strong potential for achieving previously unavailable solutions
- Support for **fundamental research** and infrastructure - essential
- Support **focused R&D programs** for frontiers and bottlenecks
- **Realize nanomaterials and nanosystems by design**
- High potential of nanotechnology to support **sustainable development** in water, energy, minerals, and other resources

A shift to new nano enabled commercial products after 2010

Survey of 270 manufacturing companies

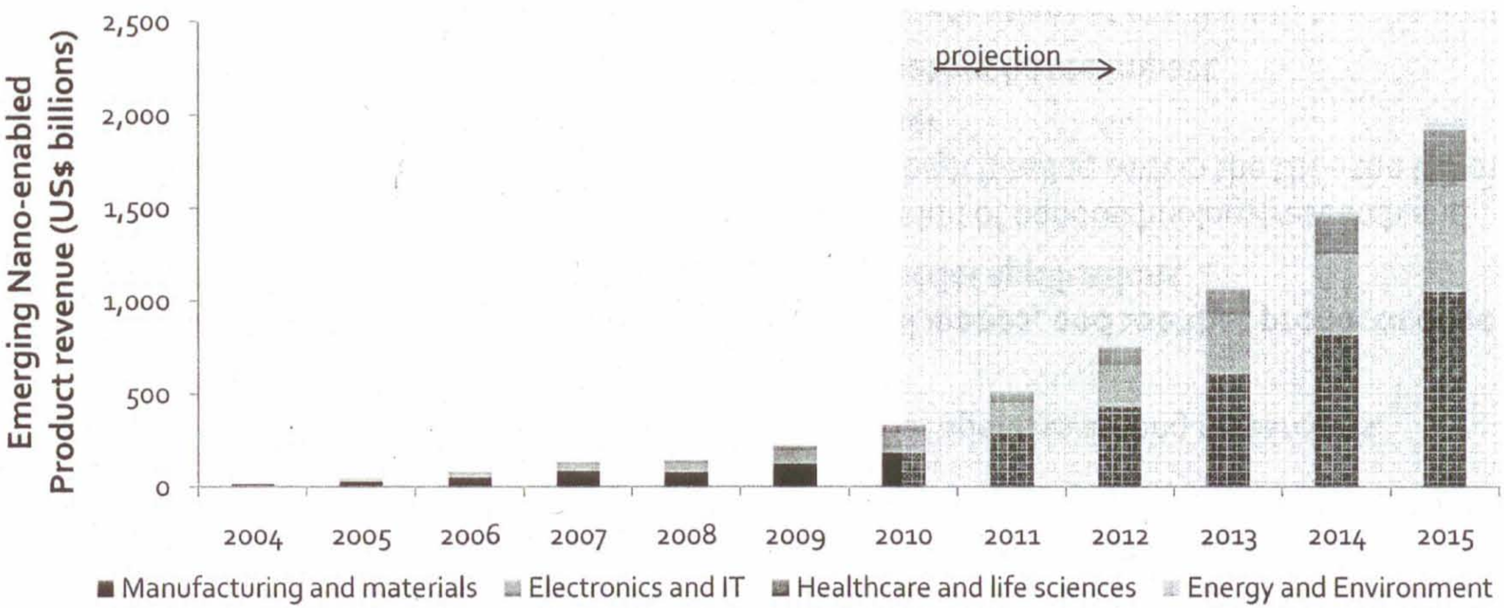


Nano2 Report, 2010, p. XXXIX. *Courtesy National Center for Manufacturing Sciences (NCMS, 2010)*

NDUSTRY STUDY (Lux Research, 2010) - THE NEXT 5 YEA

Emerging nanotechnology products will introduce modifications to today's products

- The overall growth of nano-enabled products to 2015 will consist largely of emerging applications in materials and manufacturing as well as electronics. Healthcare and life sciences will grow as these fields overcome safety, testing, and consumer acceptance barriers not faced by other applications.



Source: Lux Research

MC Roco, Jan 19 2011

2010-2020: OTHER PRIORITIES

- Advance **partnerships** between industry, academia, NGOs, multiple agencies, and international organizations
- Support precompetitive R&D and system application **platforms**
- Promote **global coordination**; Create an international co-funding mechanism for databases, nomenclature, standards, and patents
- Support horizontal, vertical, and system **integration in nanotechnology education; and personalized learning**
- Use **nanoinformatics** and computational science prediction tools
- **New strategies** for mass dissemination, public participation
- **Institutionalize**—create standing organizations and programs to fund and guide nanotechnology

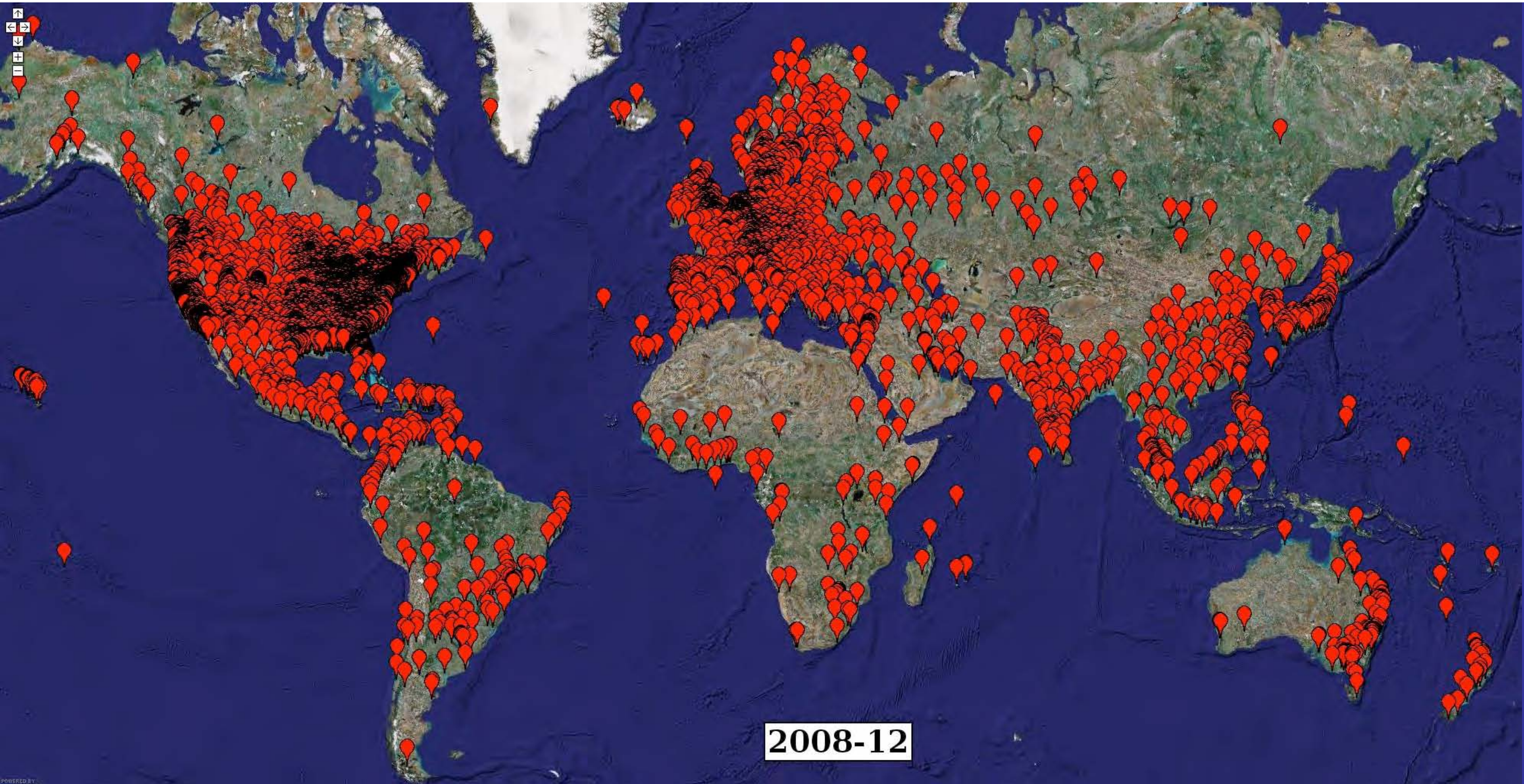
First International Dialogue on Responsible Nanotechnology R&D (2004)

Coordinated activities after the June 2004 International Dialogue

- October 2004 / October 2005 - Occupational Safety Group (UK, US,.)
- November 2004 - OECD / EHS group on nanotechnology begins
- December 2004 - Meridian study for developing countries
- December 2004 - Nomenclature and standards (ISO, ANSI)
- February 2005 - North-South Dialogue on Nanotechnology (UNIDO)
- May 2005 - International Risk Governance Council (IRGC)
- May 2005 - "Nano-world", MRS (Materials, Education)
- July 2005 - Interim International Dialogue (host: EC)
- **October 2005 - OECD Nanotechnology Party in CSTP**
- **June 2006 - 2nd International Dialogue (host: Japan)**
- **2006 Int. awareness for: EHS, public participation, education**
- **2007-2009 - new activities**

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.



2010-2020: FURTHER PRIORITIES

- Nanotechnology EHS - to be addressed as **an integral part** of the general physico-chemical-biological research

  - also for the **new generation** of active nanostructures and systems

  - include exposure and toxicity to multiple nanostructured compounds

- Besides new emerging areas, **traditional industries** may provide opportunities for application of nanotechnology mineral processing, plastics, wood and paper, textiles, agriculture, and food systems

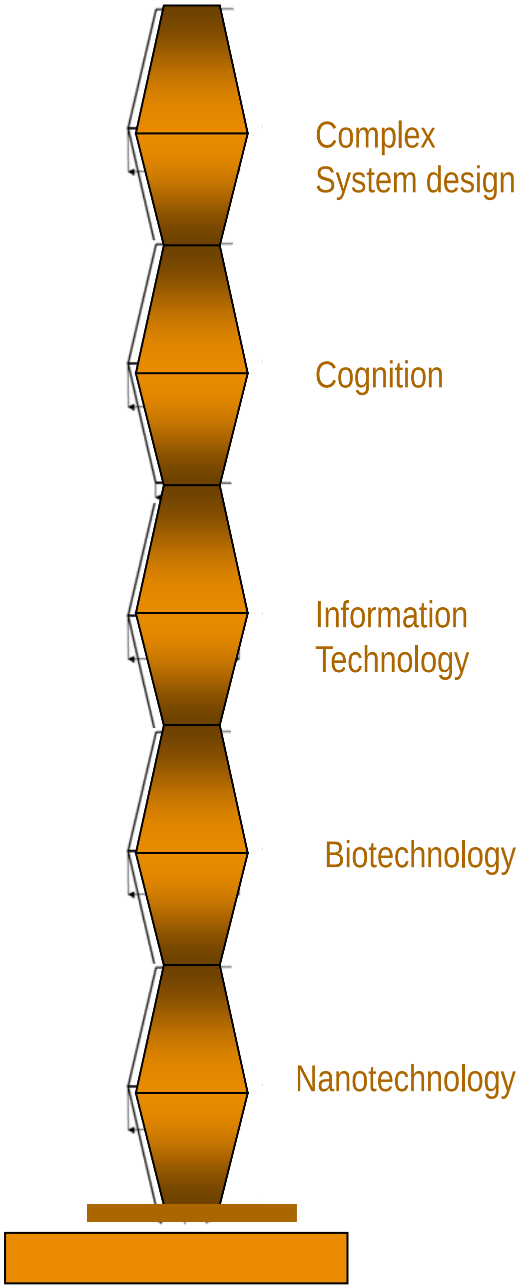
- In the next decade, nanotechnology R&D is likely to shift its focus to socio-economic needs–driven governance, with significant consequences for science, investment, and regulatory policies

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"

Emerging Technologies

M.C. Roco (2007)



"Endless Column of Human Discovery and Innovation"
(modeled after "Endless Column" of C. Brancusi, 1937)
The five blocks suggest five emerging and converging technologies,
nanotechnology, biotechnology, information technology,
cognitive sciences and complex systems design