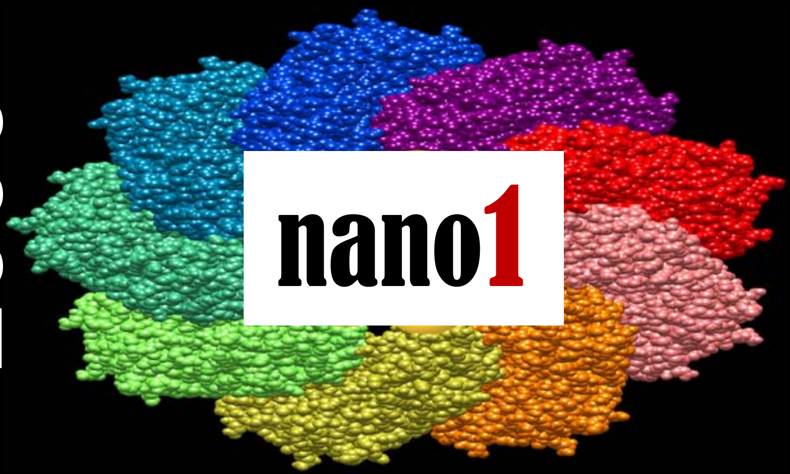
2000



2010

2020

Nanotechnology Research Directions for Societal Needs in 2020

Mike Roco
National Science Foundation and National Nanotechnology Initiative

OECD/NNI Symposium, March 28, 2012

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*					

Topics

- Nanotechnology timeline: 2000-2020
- Rapid and uneven outputs
- Main outcomes at 10 years
- Outlook for the future

Related publications

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

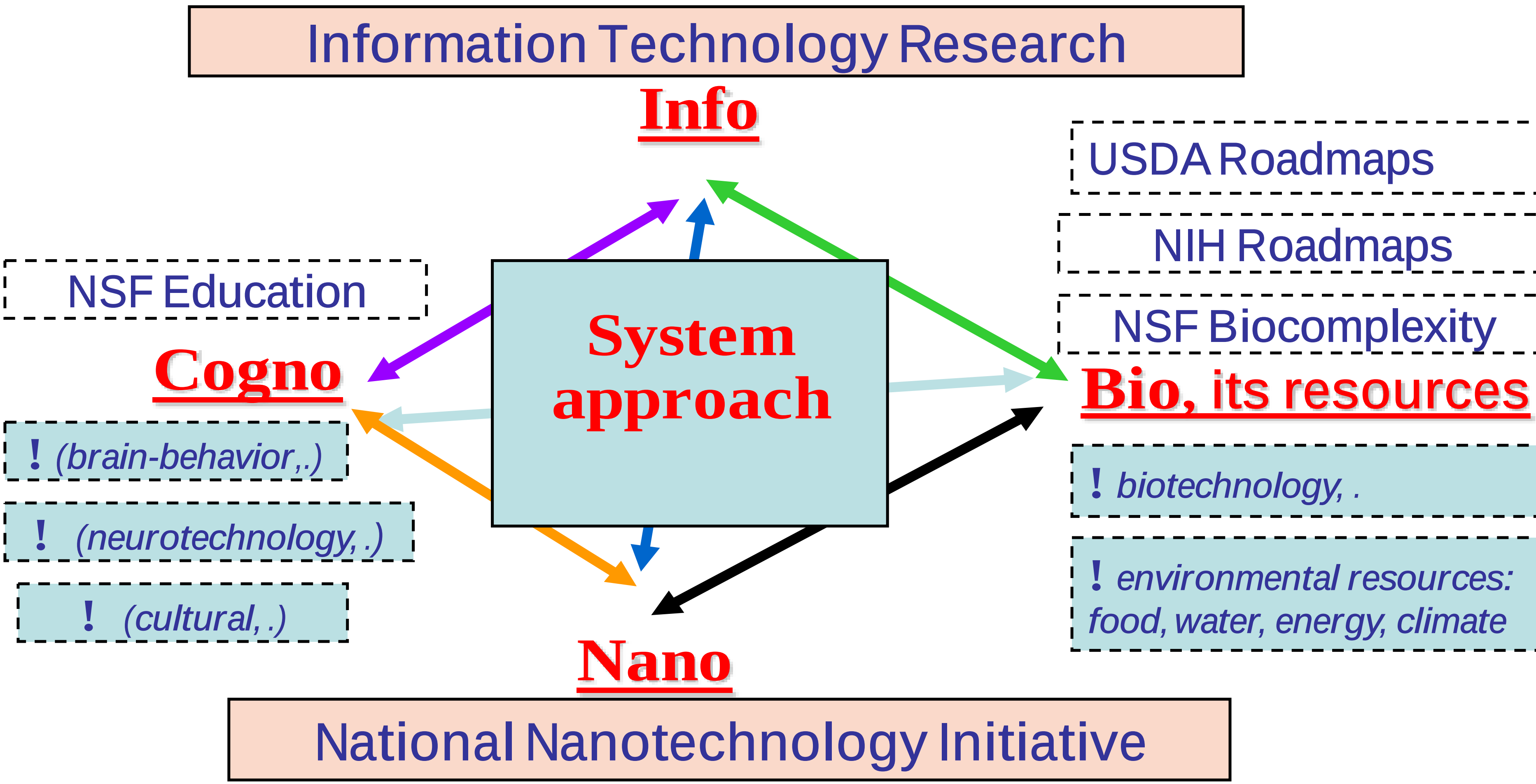
"The Long View of Nanotechnology development: the NNI at 10 Years" (2011)

"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

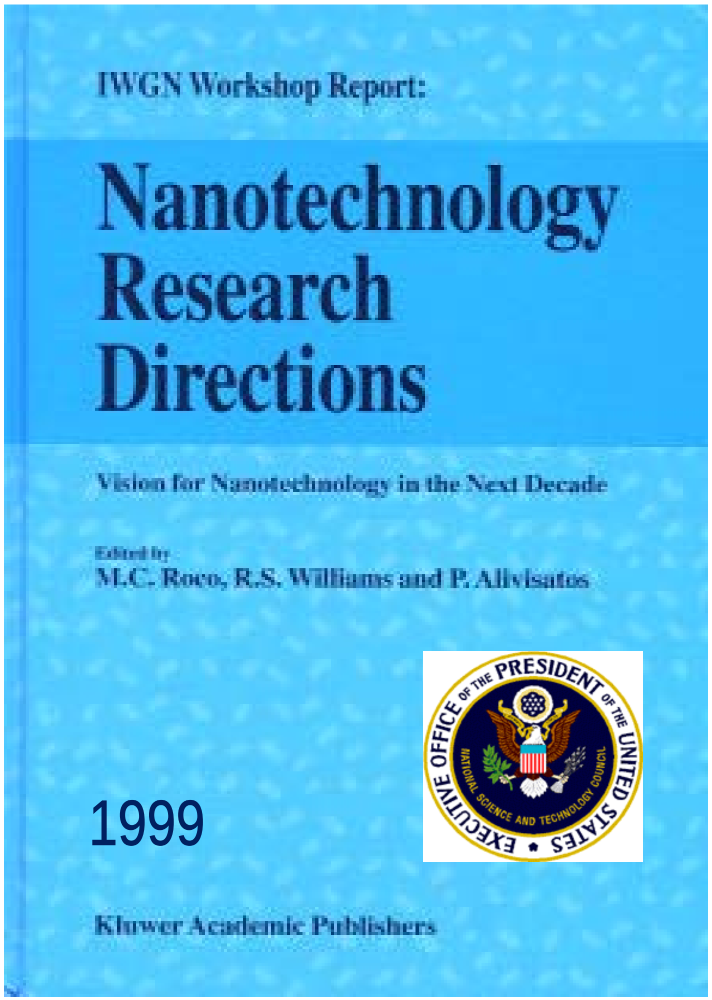
Nanotechnology at the core of convergence of new emerging technologies (foundational tools)



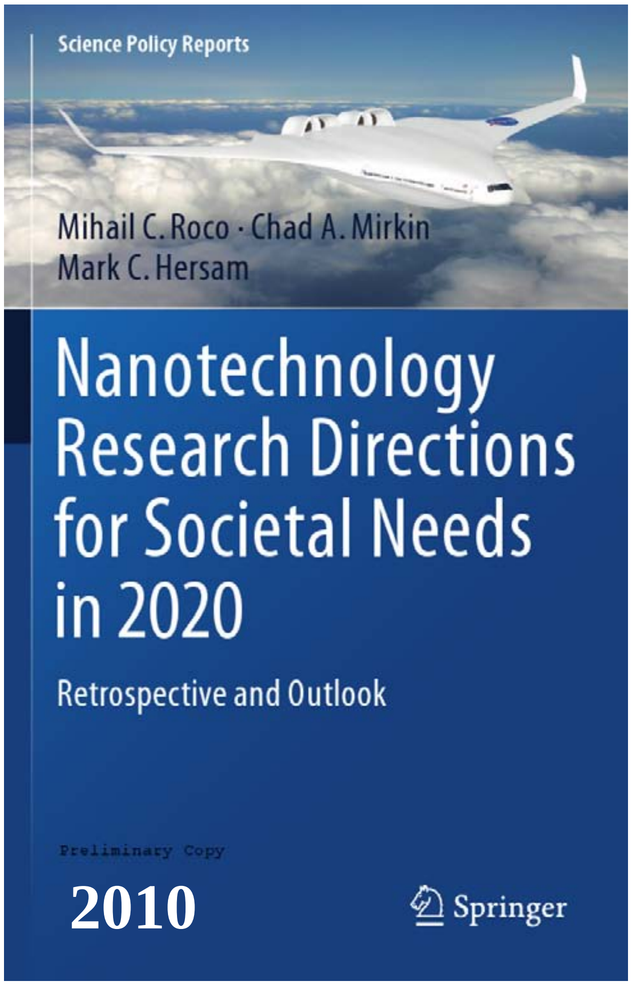
Reference: MC Roco, J Nanopart Res, 2000

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

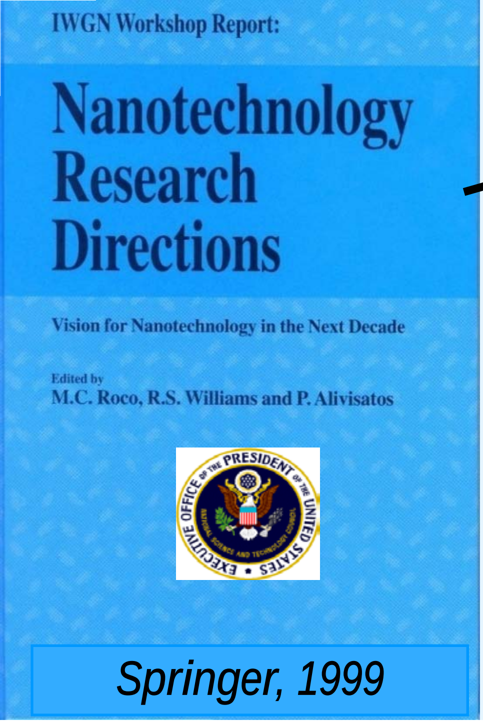
nano1 (2000-2010)



nano2 (2010-2020)



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



"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

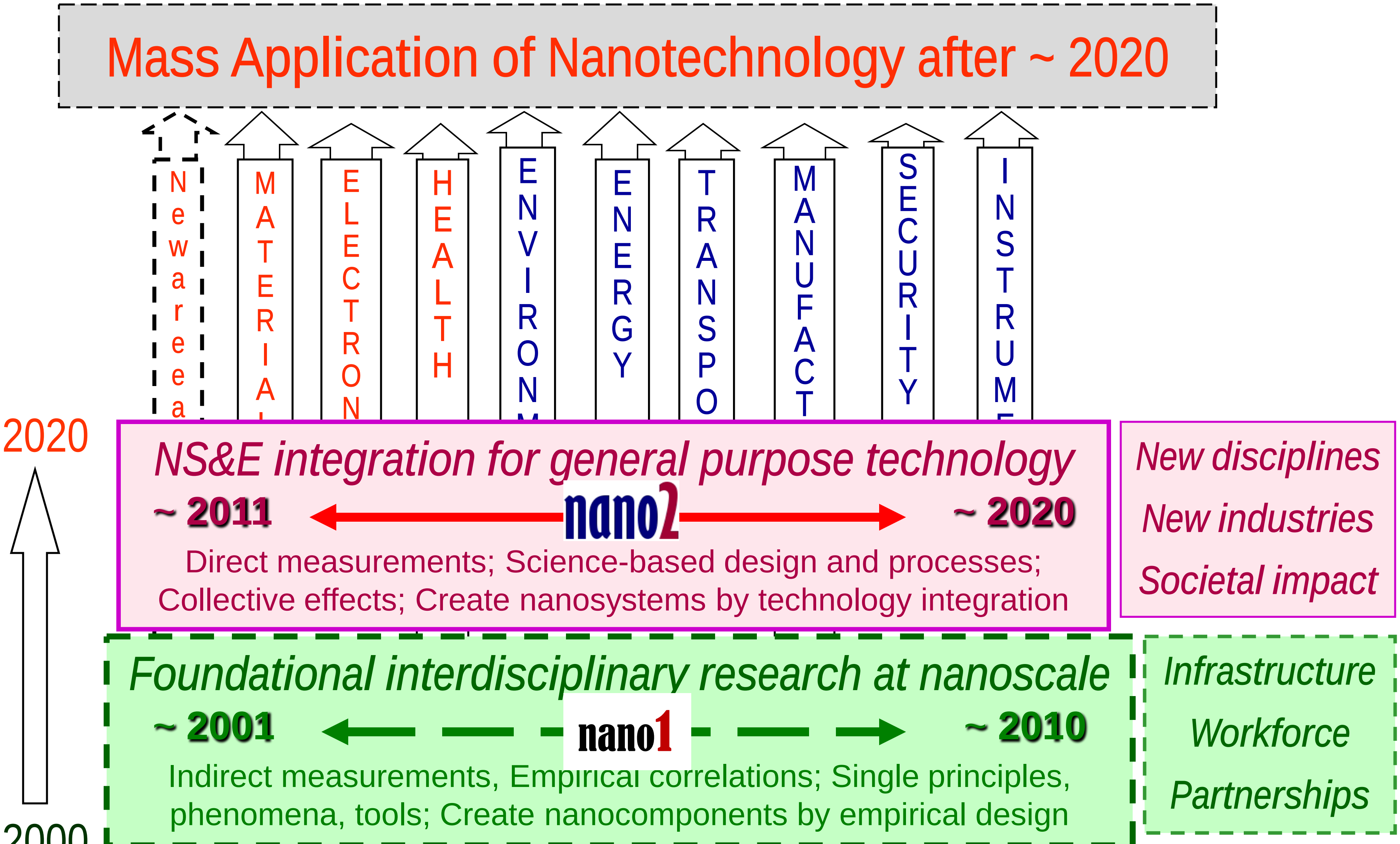
Most efficient length scale for manufacturing, biomedicine

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

MC Roco, WH, March 11 1999

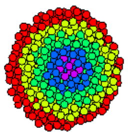
CREATING A NEW FIELD AND COMMUNITY IN TWO FOUNDATIONAL STEPS (2000~2020)



MC Roco, March 28 2012

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

Timeline for beginning of industrial prototyping and nanotechnology commercialization

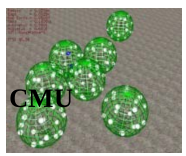


2000

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

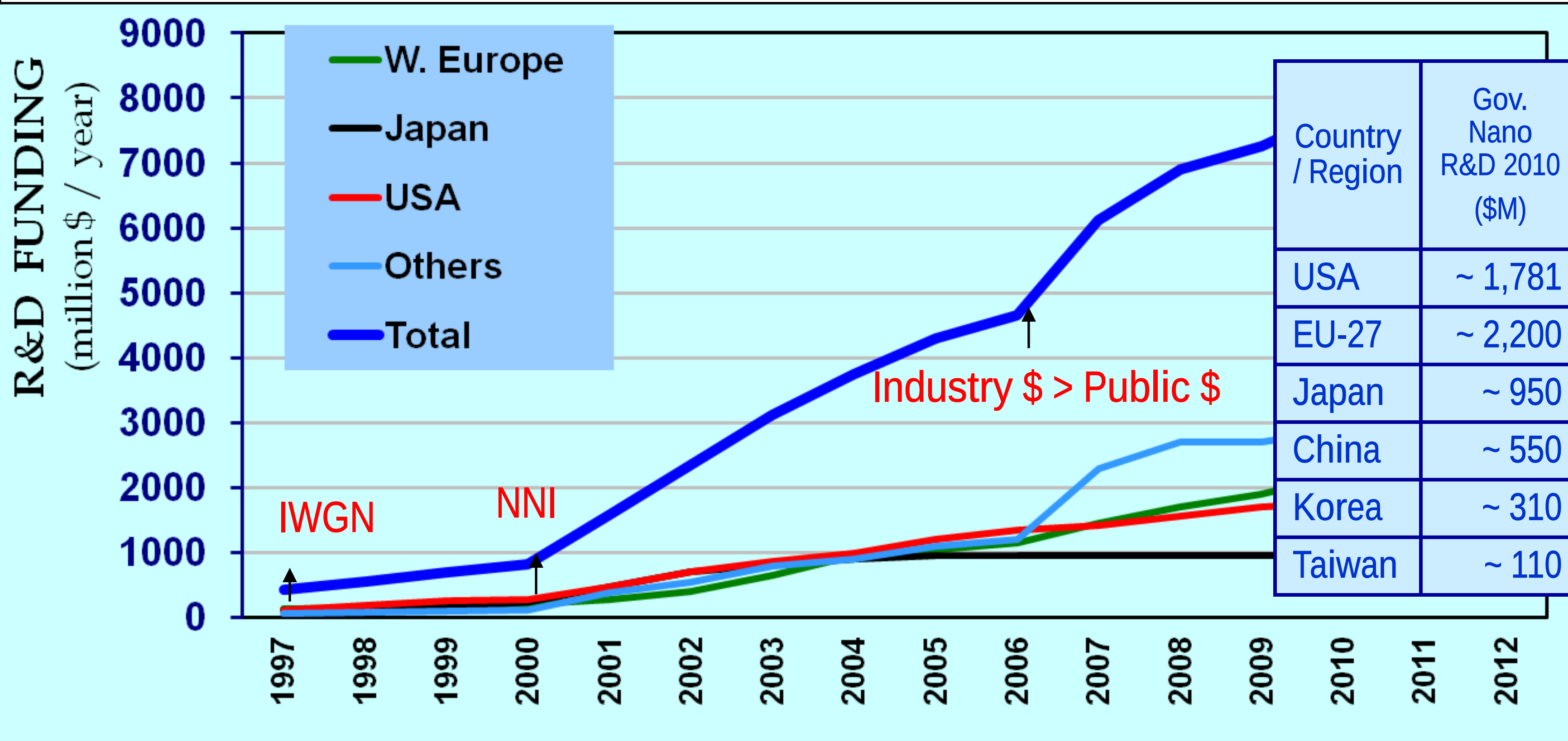
Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

Higher uncertainty & risk

Increased Complexity, Dynamics, Transdisciplinarity

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

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

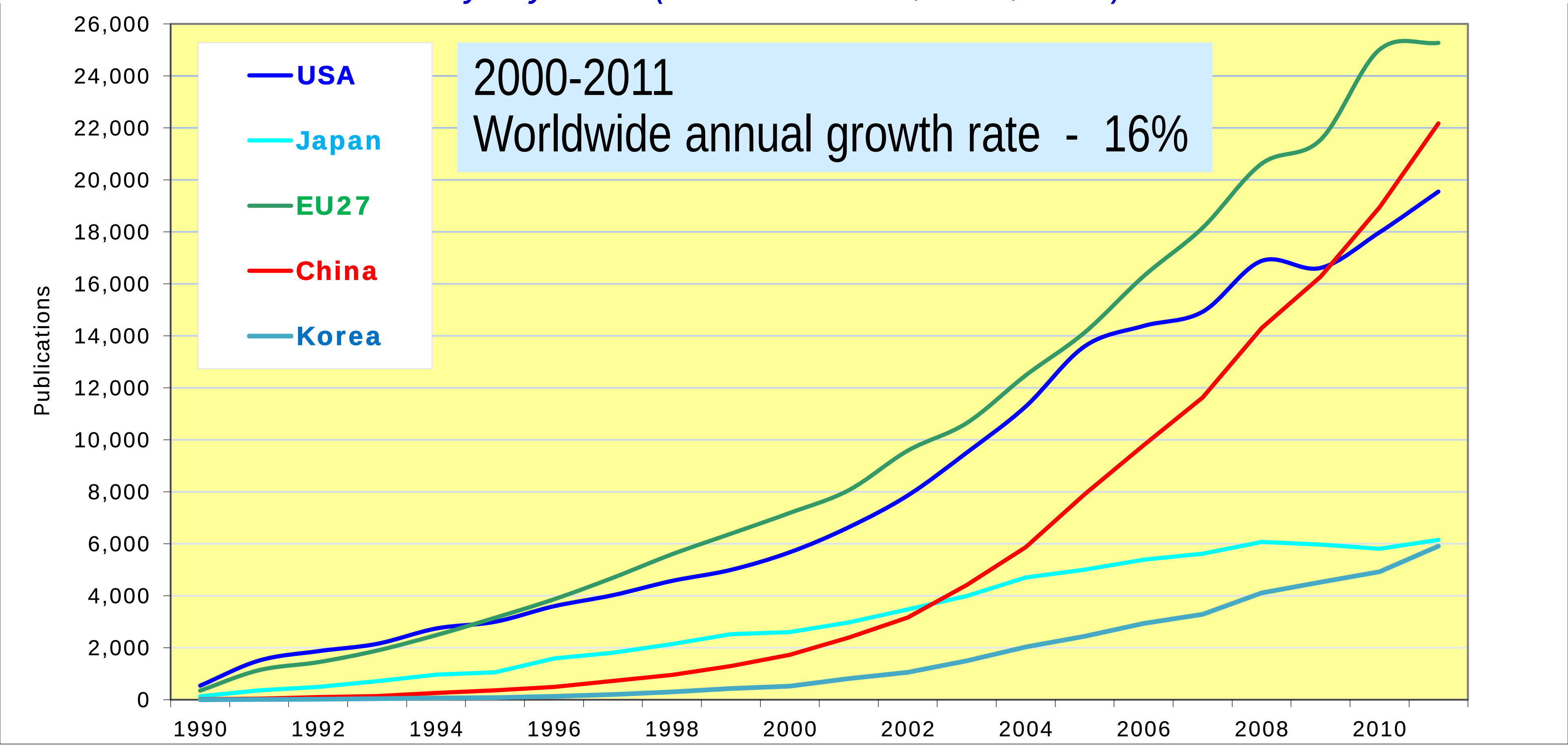
Rapid, uneven growth per countries

MC Roco, March 28 2012

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)

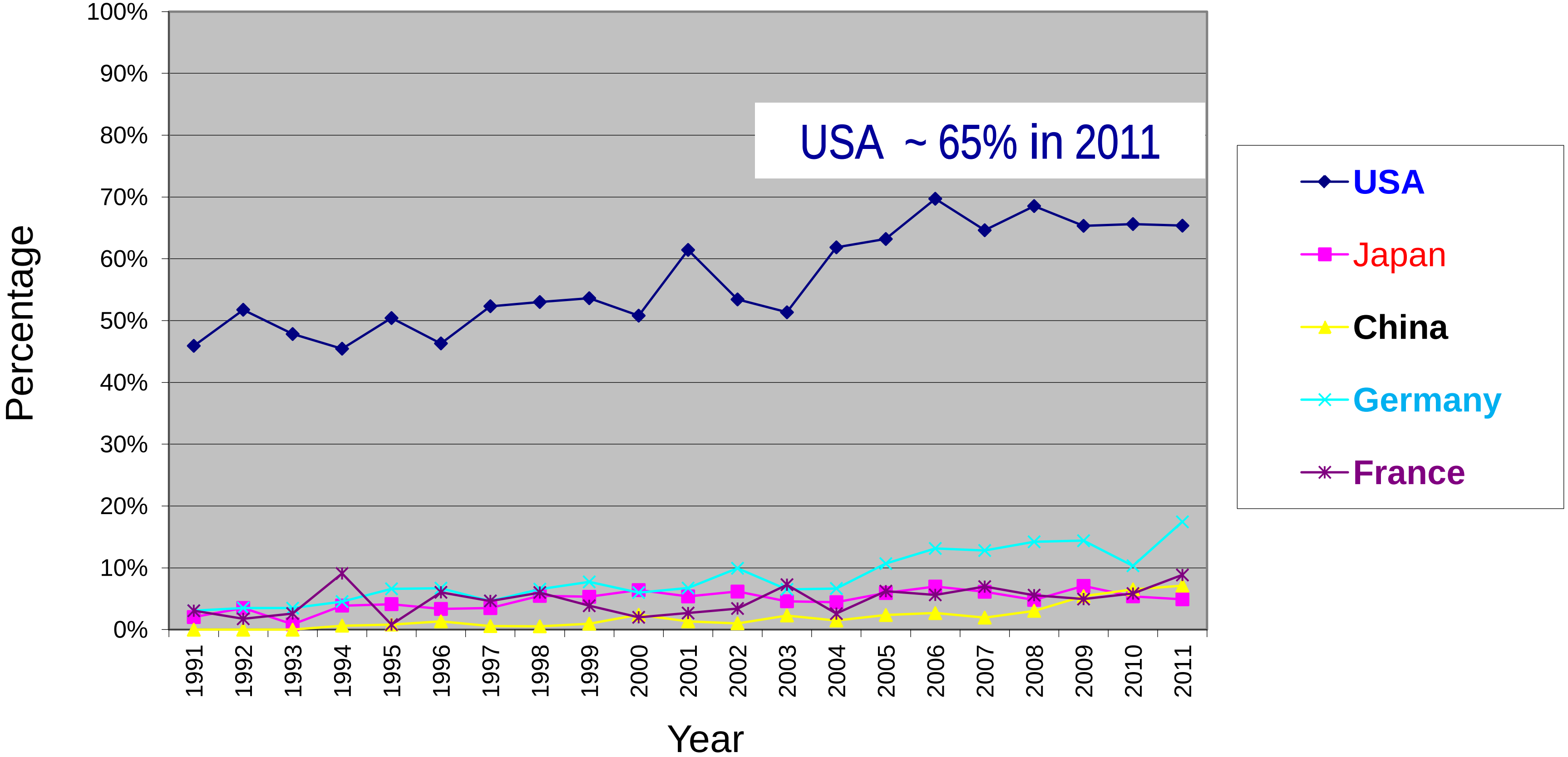


Rapid, uneven growth per countries

MC Roco, March 28 2012

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

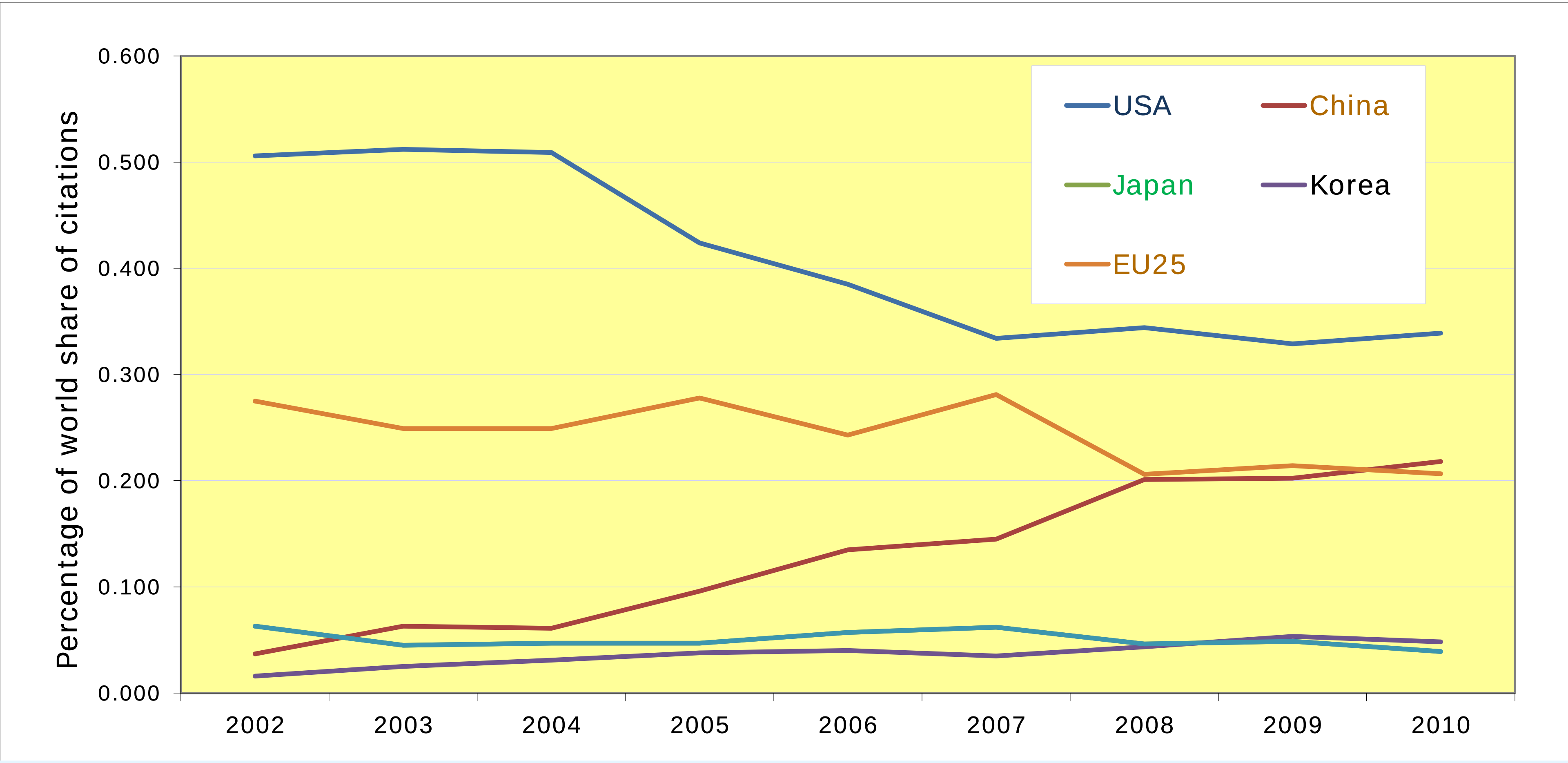
Data was generated using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen and Roco, NRC, 2012)



U.S. maintain the lead in highly cited publications

Nanotechnology citations in 10 specialized journals using the Science Citation Index (SCI) for 1990 - 2011

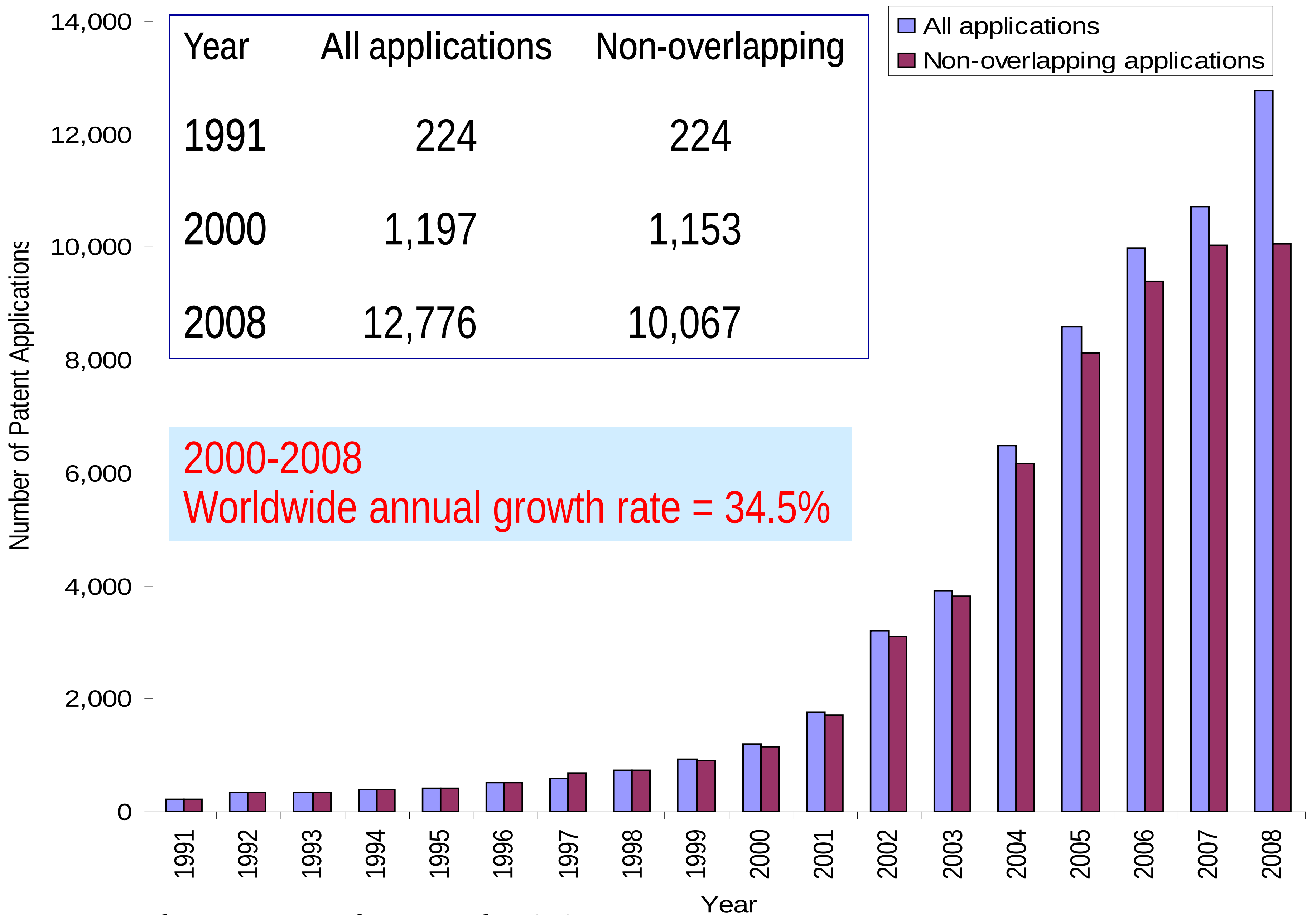
Data was generated using "Title-abstract" search in SCI database by keywords (Chen and Roco, NRC, 2012)



Rapid, uneven changes in the last ten years

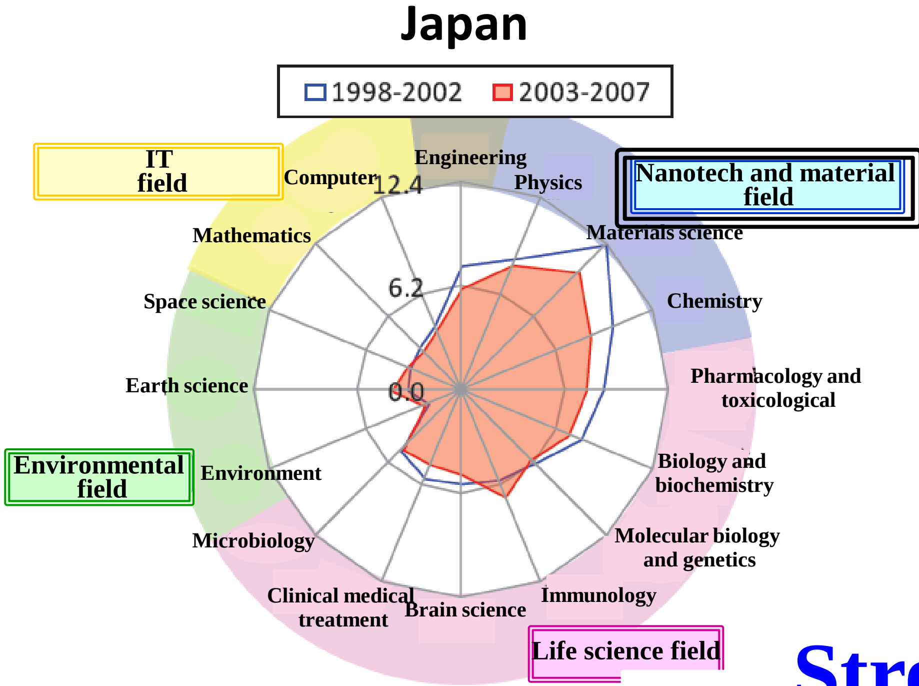
MC Roco, March 28 2012

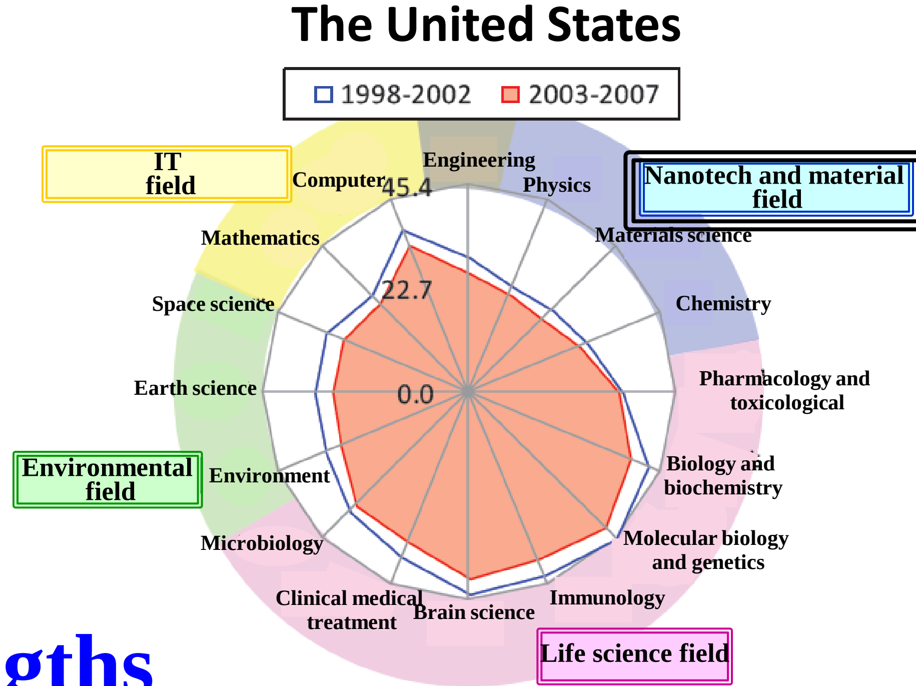
WORDWIDE NUMBER OF NANOTECHNOLOGY PATENT APPLICATIONS

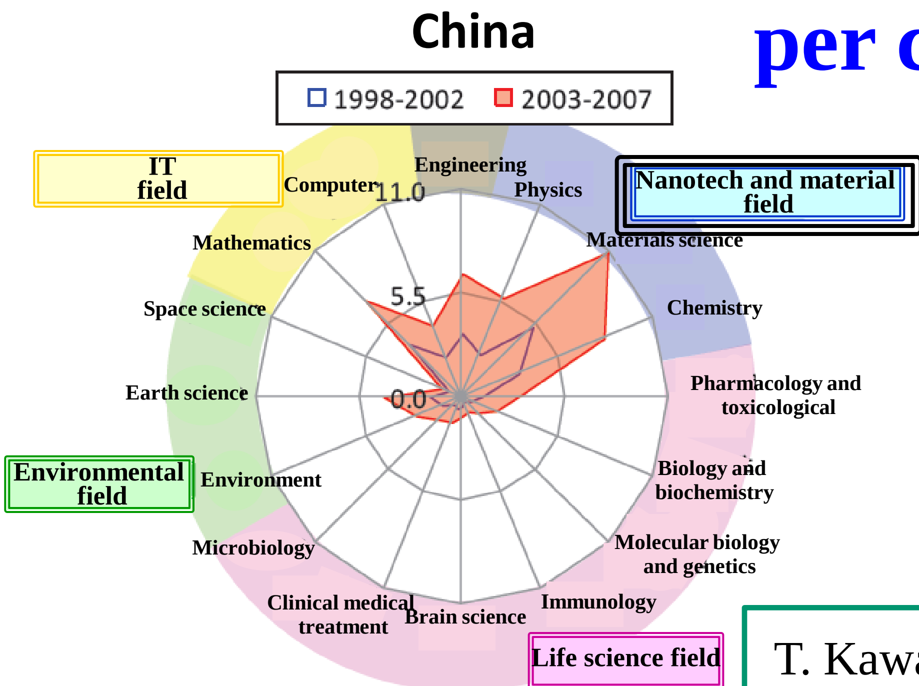


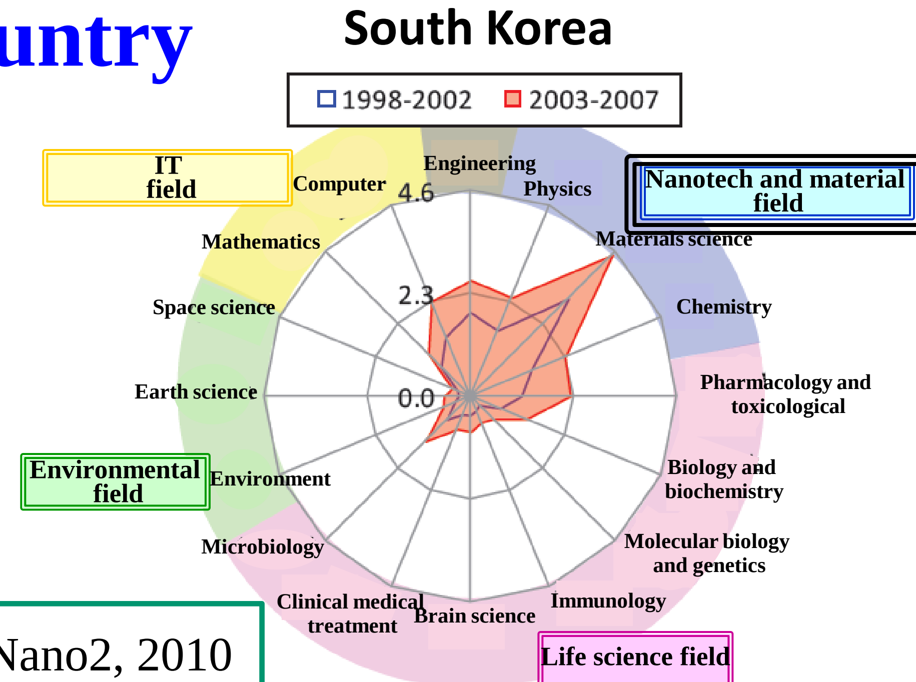
Y. Dang, et al., J. Nanoparticle Research, 2010

Strengths per country





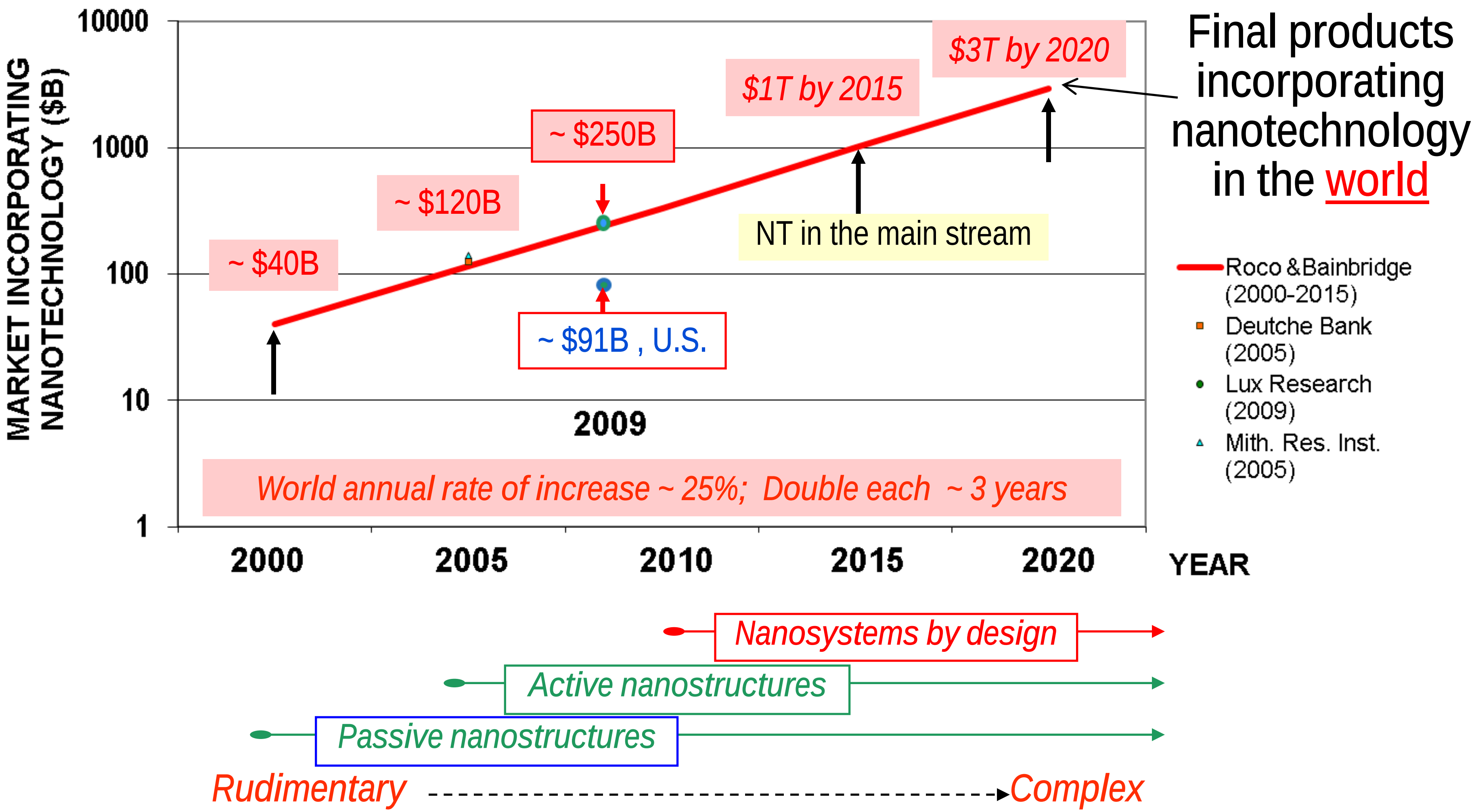




T. Kawai, Nano2, 2010

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

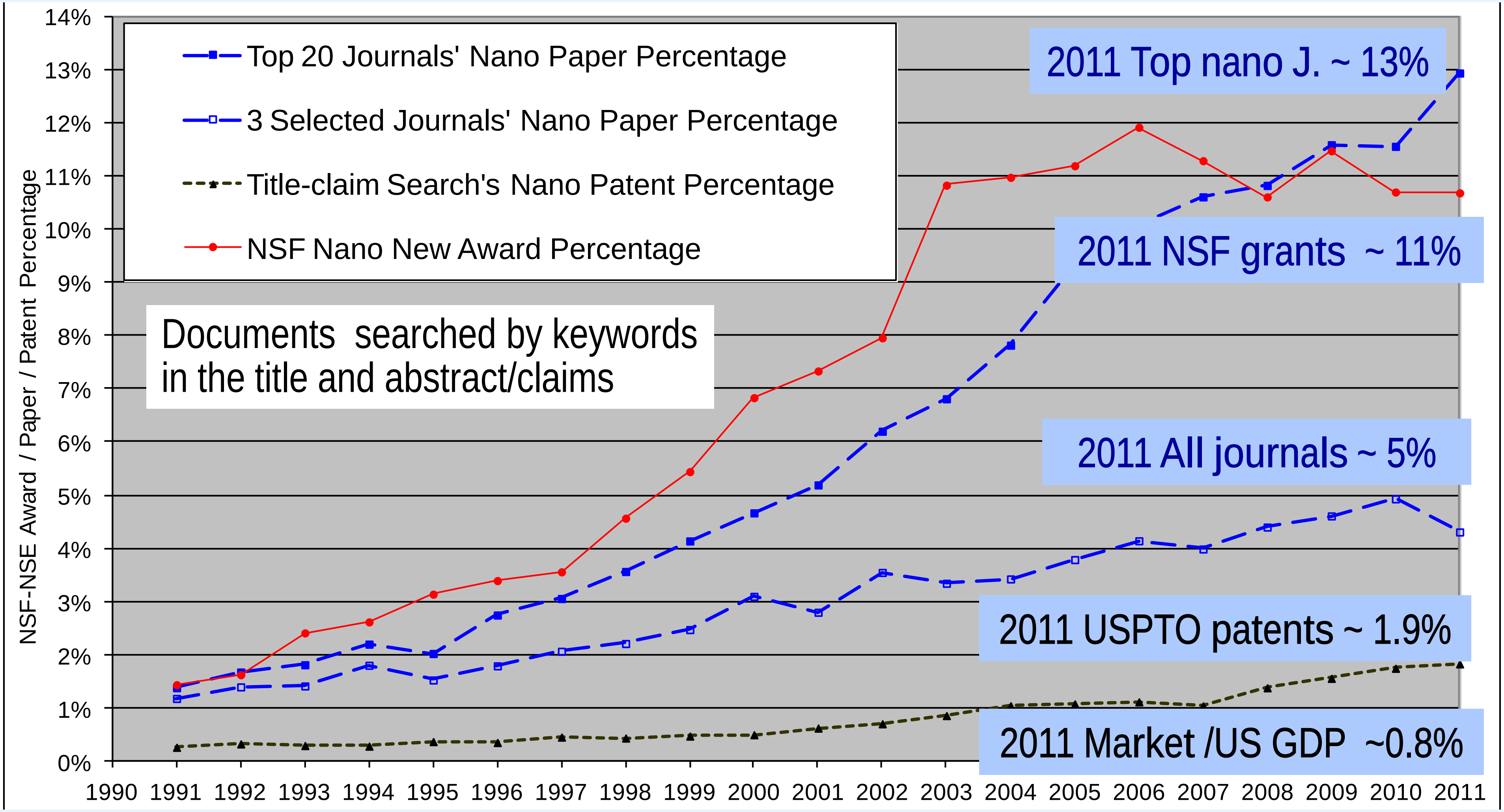
(Estimation made in 2000 after international study in > 20 countries)



Reference: Roco and Bainbridge, Springer, 2001

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, March 28 2012

Main nanotechnology outcome at 10 years

- ***Foundational knowledge of nature*** by control of matter at the nanoscale
- ***Global interdisciplinary community*** (~ 600,000) 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***

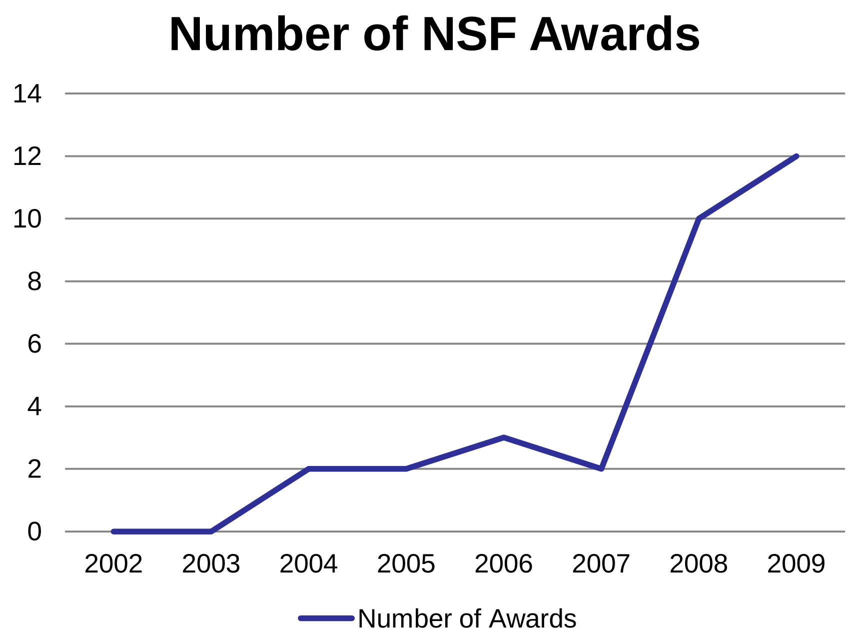
(A) 2000-2010 S&T Outcomes

- *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.**

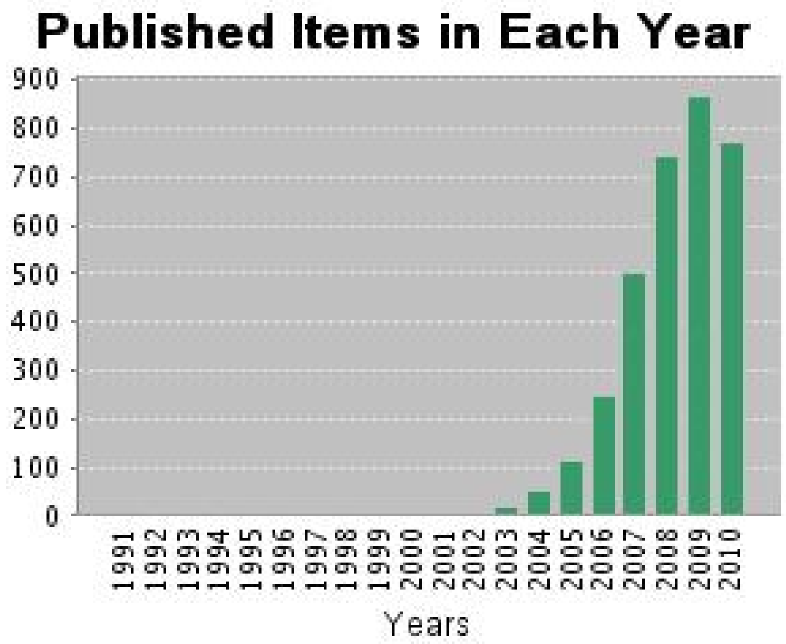
- *New S&E fields have emerged* such as: *spintronics (2001), plasmonics (2004), metamaterials, carbon nanoelectronics, molecules by design, nanofluidics, nanobiomedicine, nanoimaging, nanophotonics, opto-genetics, synthetic biology, branches of nanomanufacturing, and nanosystems*

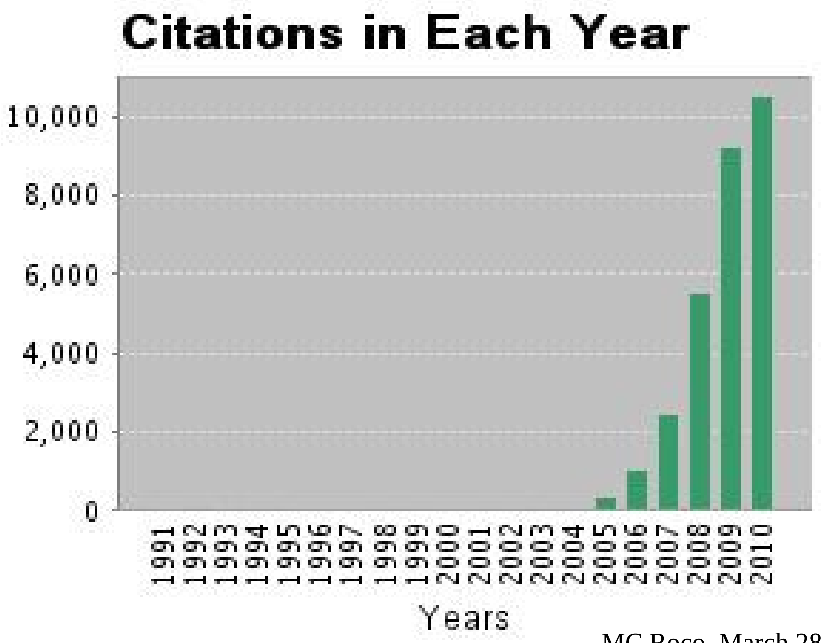
- *Technological breakthroughs* in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; **expansion into** energy resources and water filtration, agriculture and forestry; and **integration of nanotechnology with other emerging areas** such as quantum information systems, neuromorphic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

Example: Emergence of Plasmonics after 2004



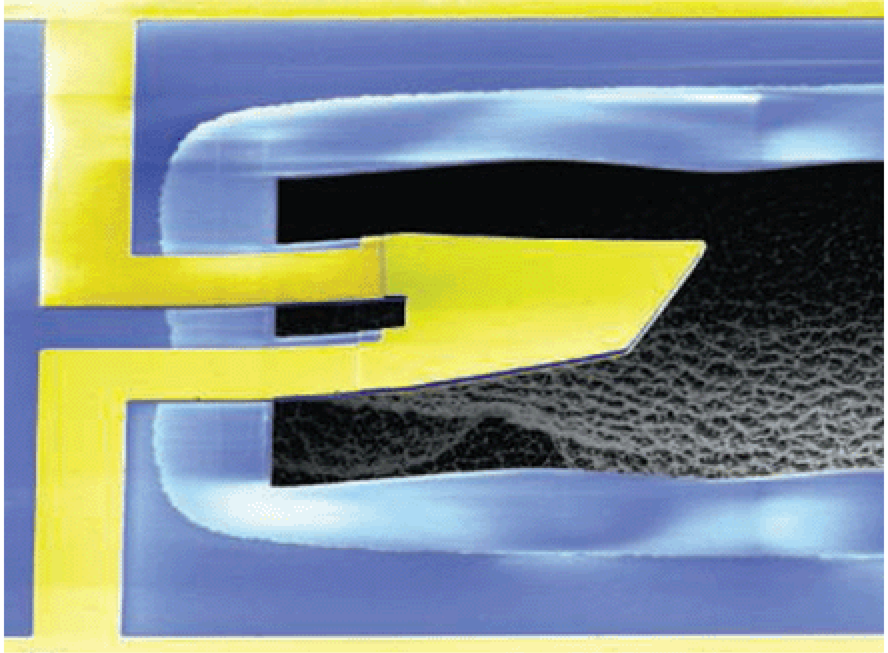
Plasmonics: Merging photonics, electronics and materials at nanoscale dimensions





The First Quantum Machine

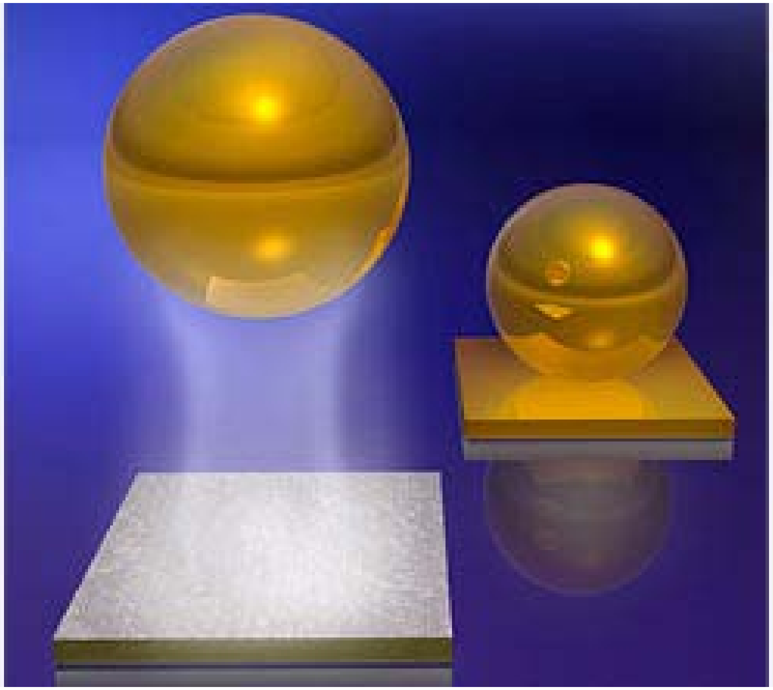
Science 17 December 2010: vol. 330 no. 6011 1604



The simplest quantum states of motion with a vibrating device was measured (the board of aluminum is as long as a hair is wide). It can absorb and emit energy only in quanta proportional to the beam's frequency; continuously in motion about a zero-point motion; two states (Aaron O'Connell and Andrew Cleland, UCSB, 2010)

Discovery of Nanoscale Repulsion

Federico Capasso, Harvard University



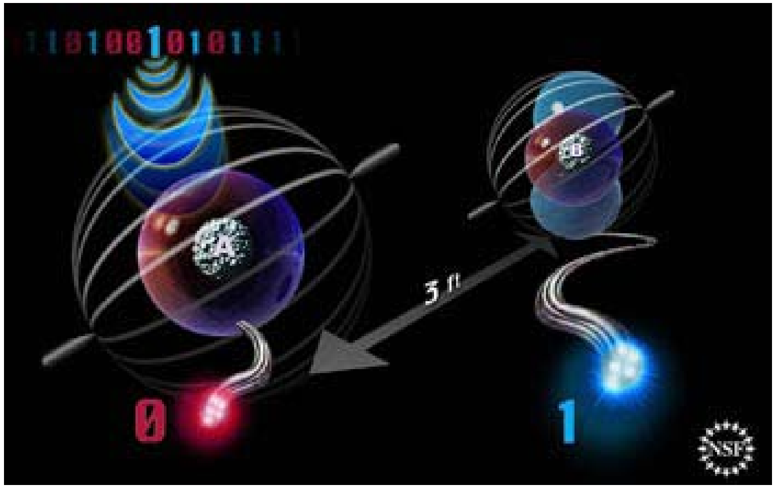
A repulsive force arising at nanoscale was identified similar to attractive repulsive Casimir-Lifshitz forces.

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

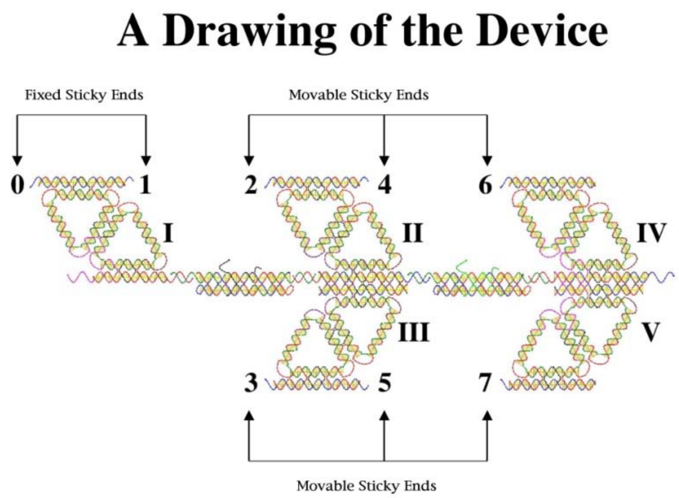
Experiments have attempted to teleport states tens of thousands of times per second. But only about 5 times in every billion attempts do they get the simultaneous signal at the beam splitter telling them they can proceed to the final step.

Self-Assembling DNA Makes 3-D Nano Machines

Ned Seeman, NY University

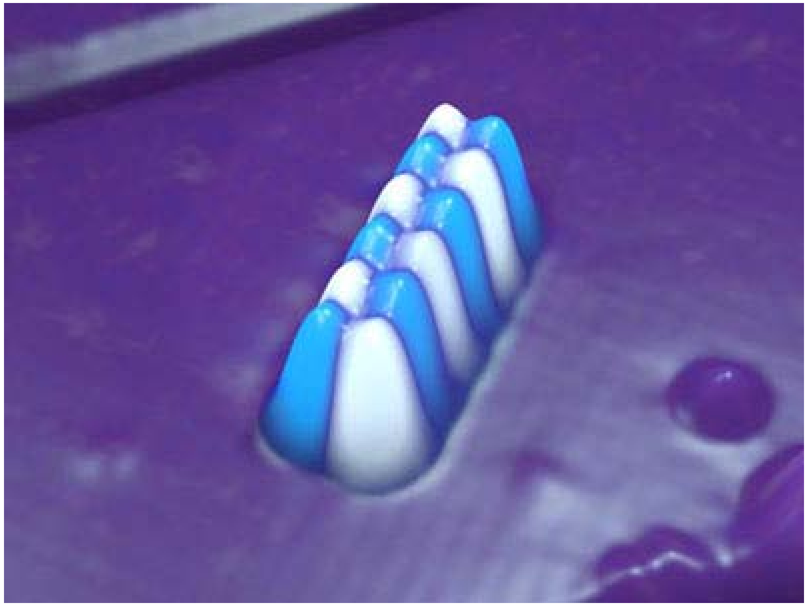
Examples:

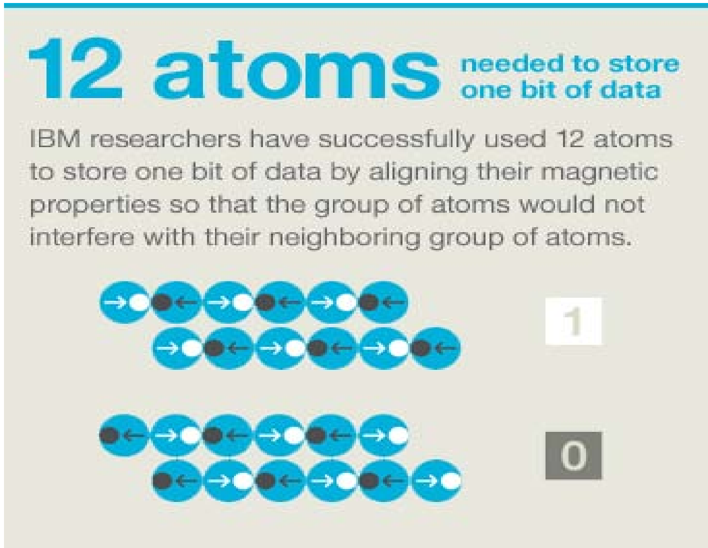
- *Programmable nanoscale machines* achieved by DNA Self-assembly



- *A two-armed nanorobotic device* that can manipulate molecules within a device made of DNA

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





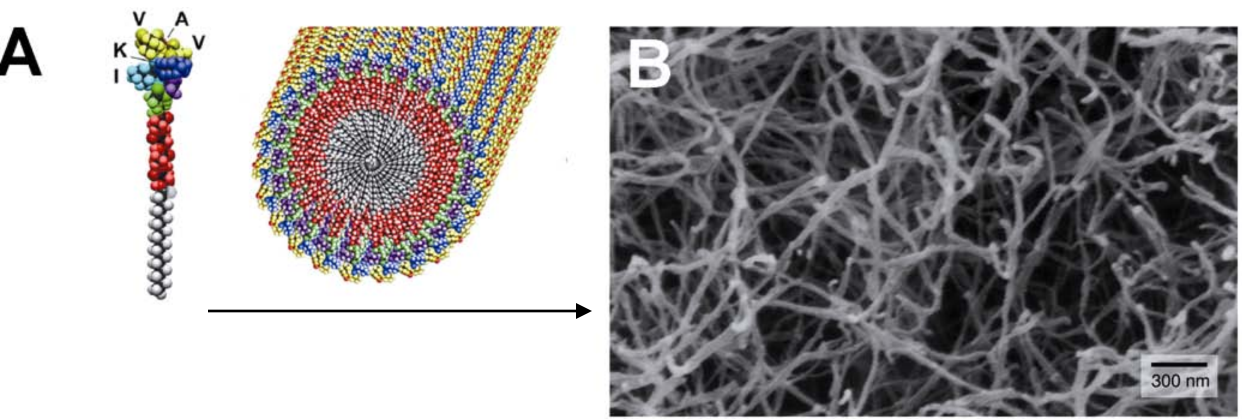
Antiferromagnetic order in an iron atom array on copper nitrate revealed by spin-polarized imaging with a scanning tunneling microscope - area 4 x 16 nm (Bistability in Atomic-Scale Antiferromagnets, Loth, Baumann, C Lutz, Eigler and Heinrich, Science Jan 2012)

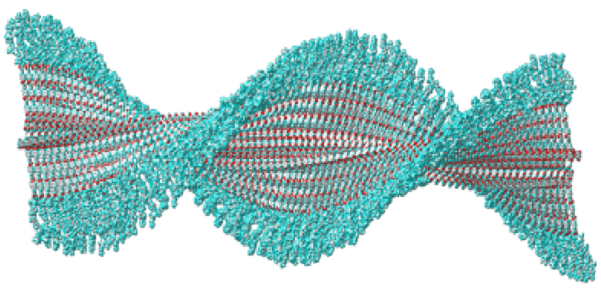
Example for hierarchical selfassembling - 4th NT generation (in research)

Example: Designing new molecules

with engineered structures and functionalities

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





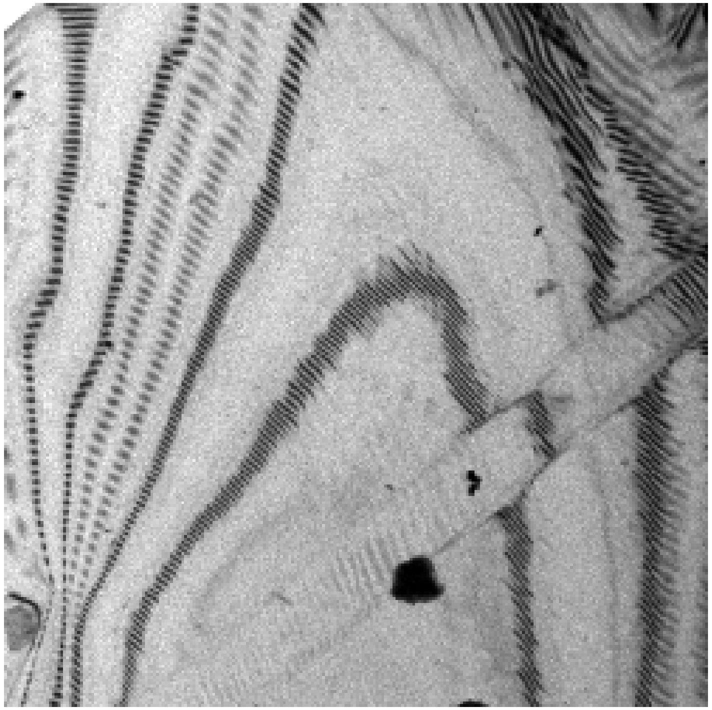
- *New nanomachines, robotics -* DNA architectures (Ned Seeman, Poly. Inst.)
- Designed molecules for *self-assembled porous walls* (Virgil Percec, U. PA)
- Self-assembly processing for *artificial cells* (Matt Tirrell, UCSB)
- Block co-polymers for *3-D structures on surfaces* (U. Mass, U. Wisconsin)

(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



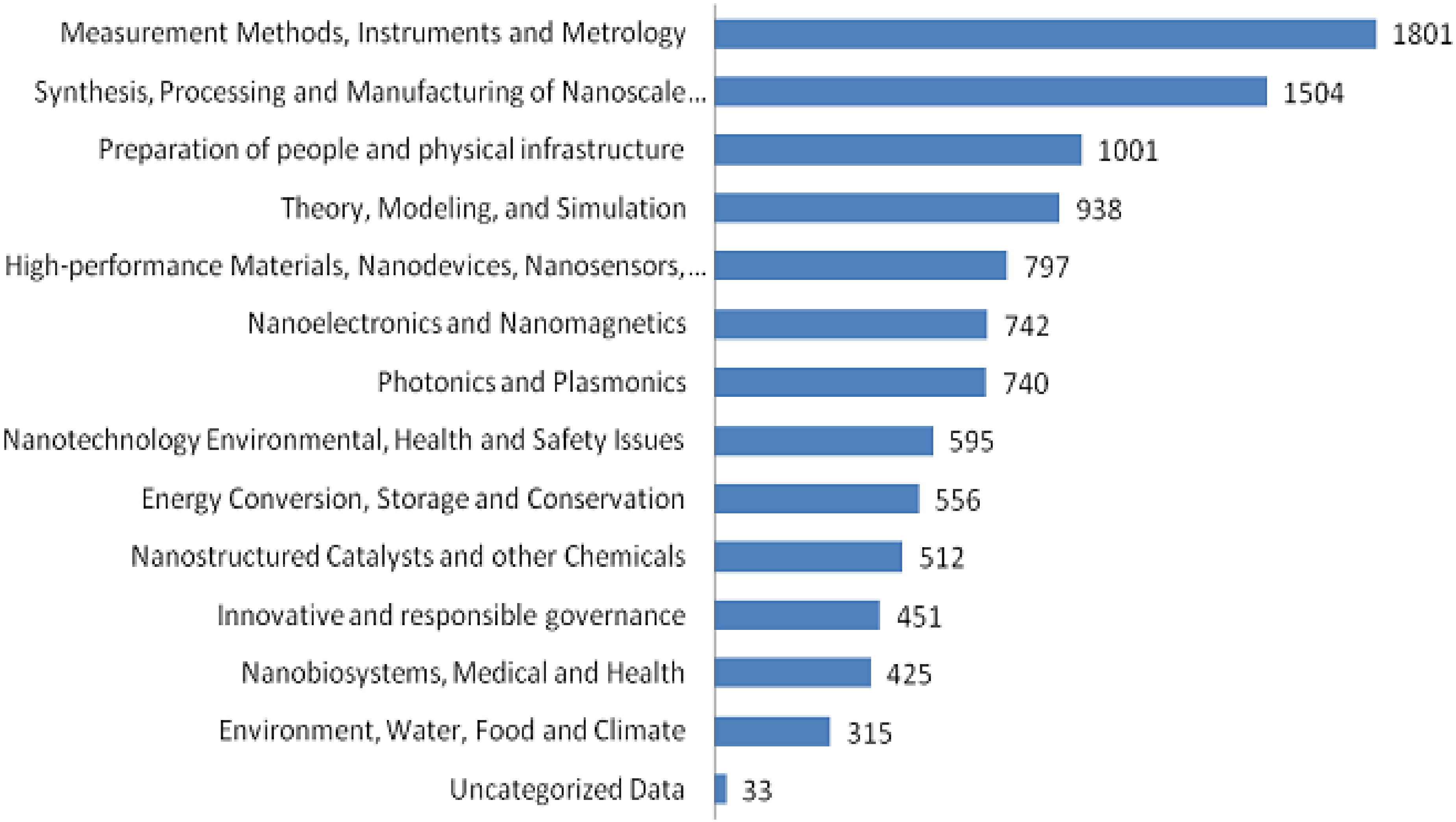
Nanodrumming of graphite, visualized with 4D microscopy.

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

Number of NSF Awards between 2001 and 2009 by "Nano 2020" themes (topical search of full proposals)



Courtesy William Neufeld

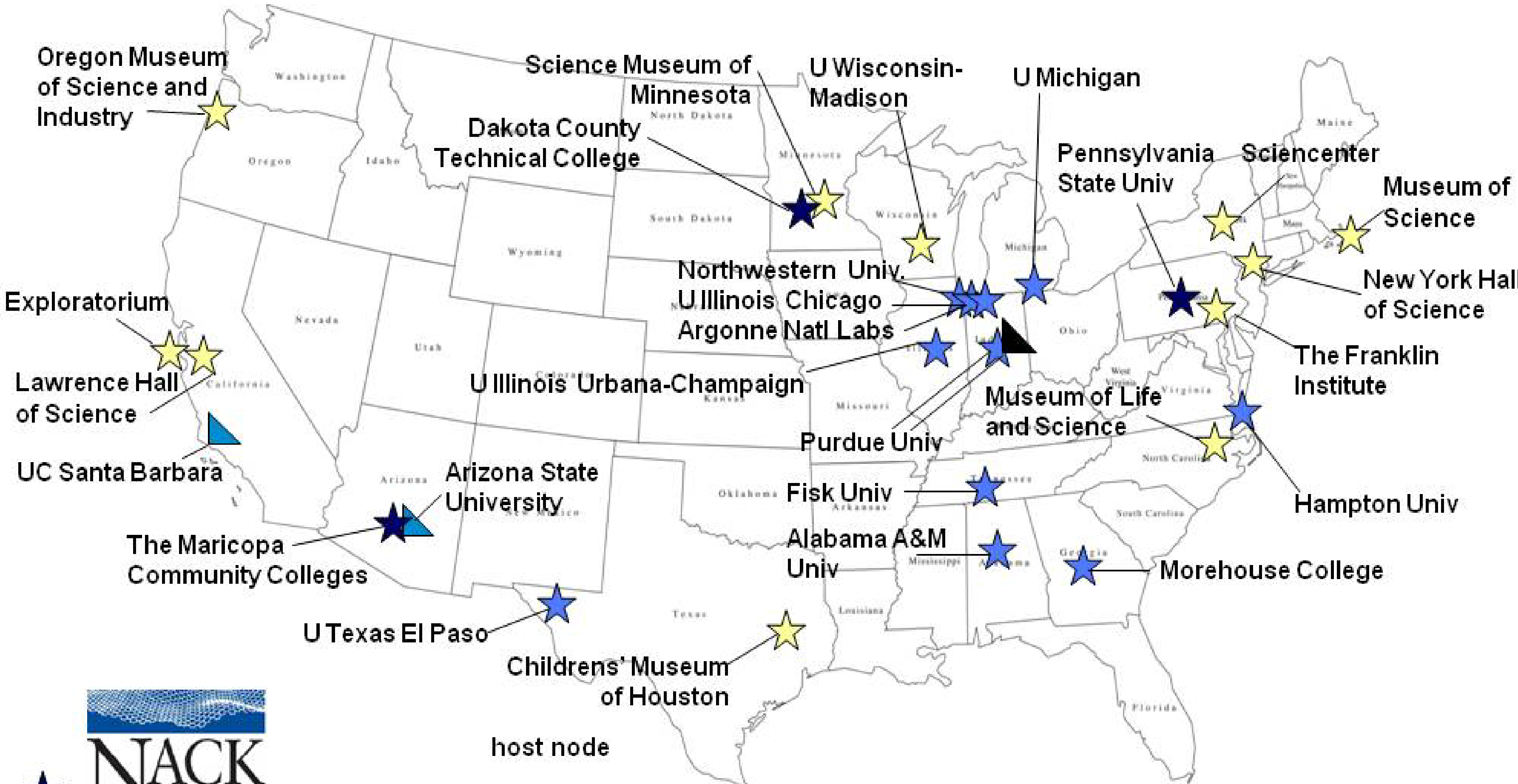
(C) 2000-2010 Infrastructure and R&D
- NNI illustrations -

- 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

Key NSF/NNI education networks in 2010



host node

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, March 28 2012

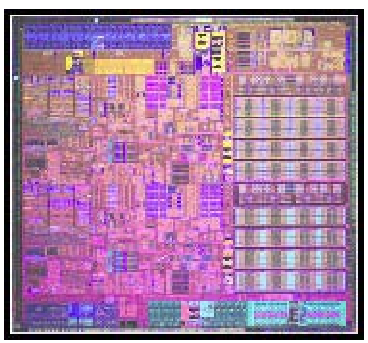
(D) 2000-2010: Ten highly promising products incorporating nanotechnology

- *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*

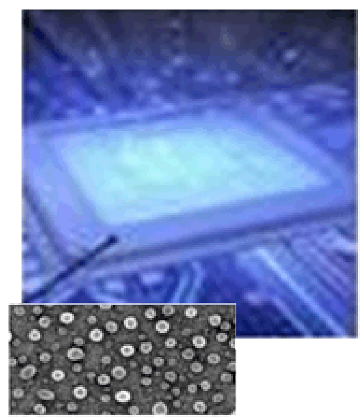
Leading to new industries, some with safety concerns: cosmetics, food, disinfectants,..

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

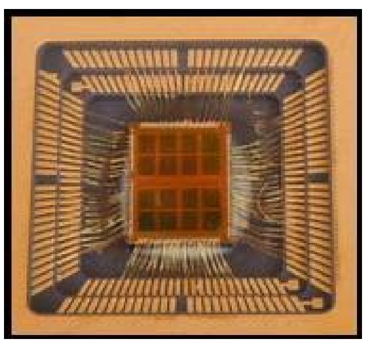
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



32 nm CMOS processor technology by Intel (2009)

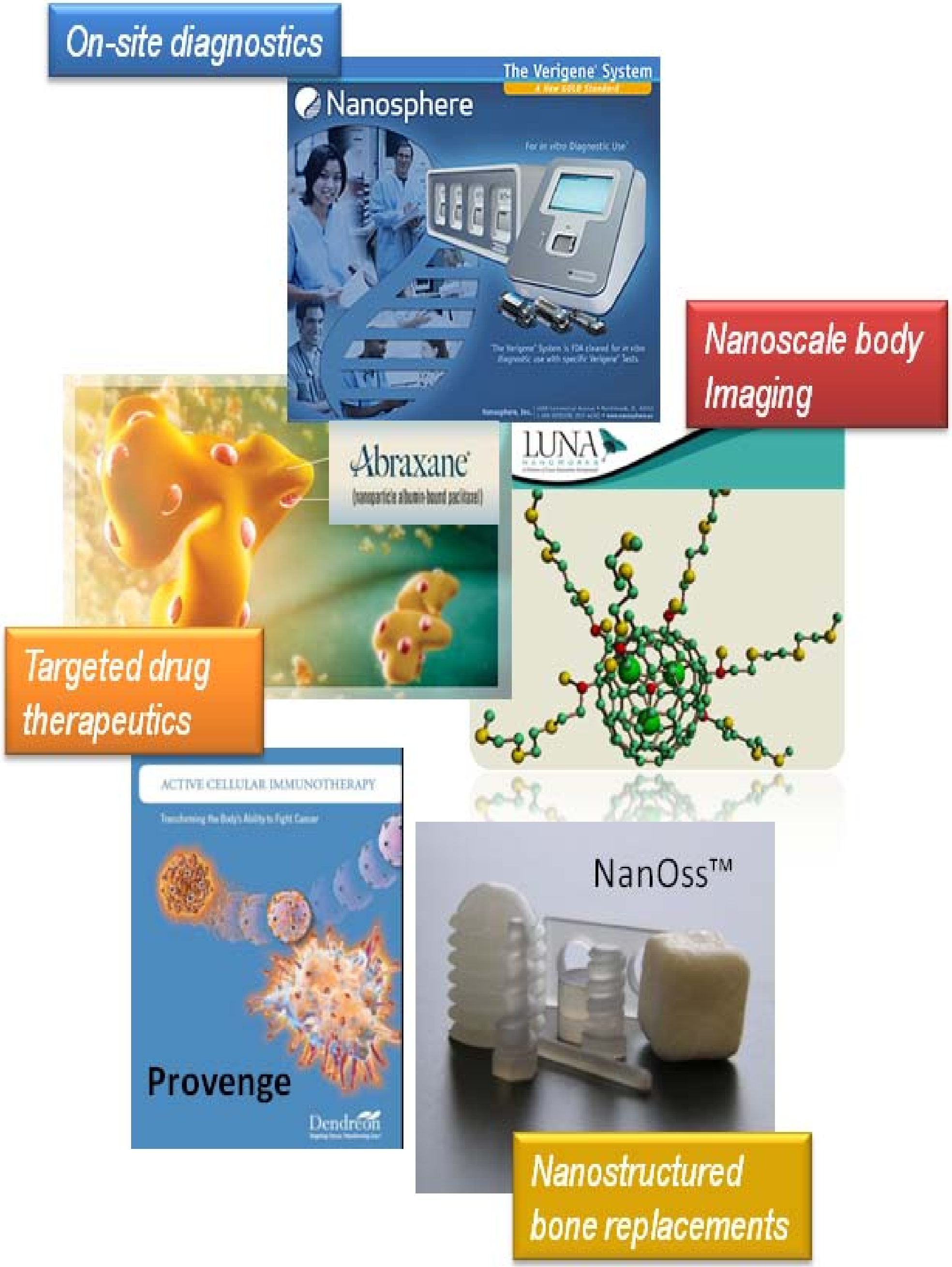


90 nm thin-film storage (TFS) flash flexmemory by Freescale (2010)



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

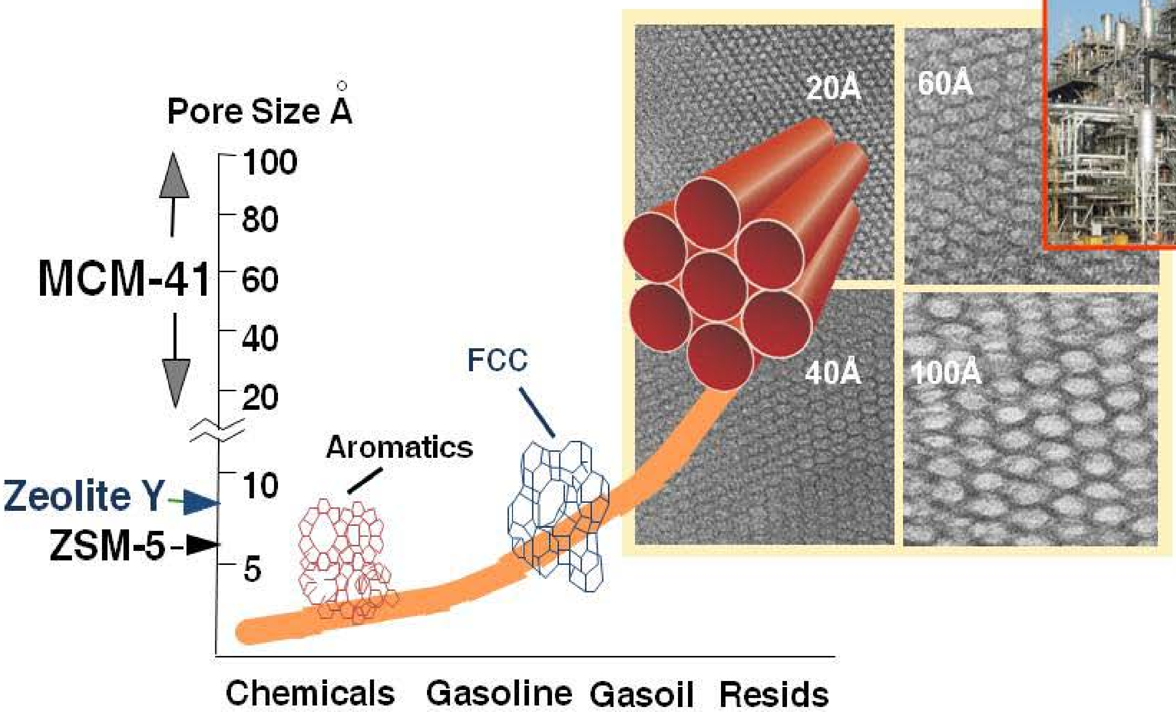
Nano2 Report, 2010, p. XII



Nano2 Report, 2010, p. XIV

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

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

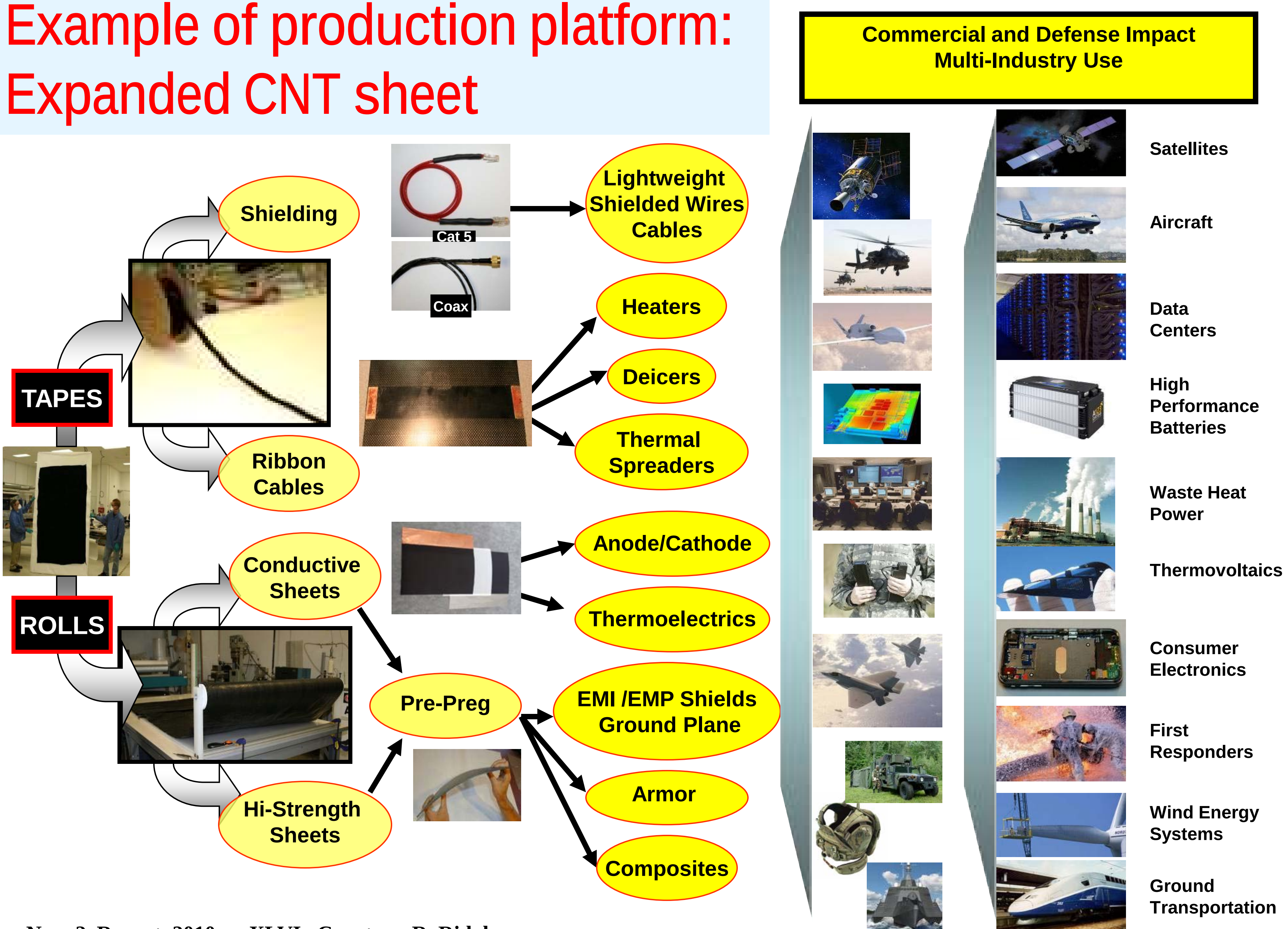


Redesigned since 2000 mesoporous silica materials, like MCM-41, along with improved zeolites, are used in a variety of processes such as fluid catalytic cracking (FCC) for producing gasoline from heavy gas oils, and for producing polyesters. Nano-engineered materials now constitute 30–40% of the global

catalyst market

Nano2 Report, 2010, p. XVII

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

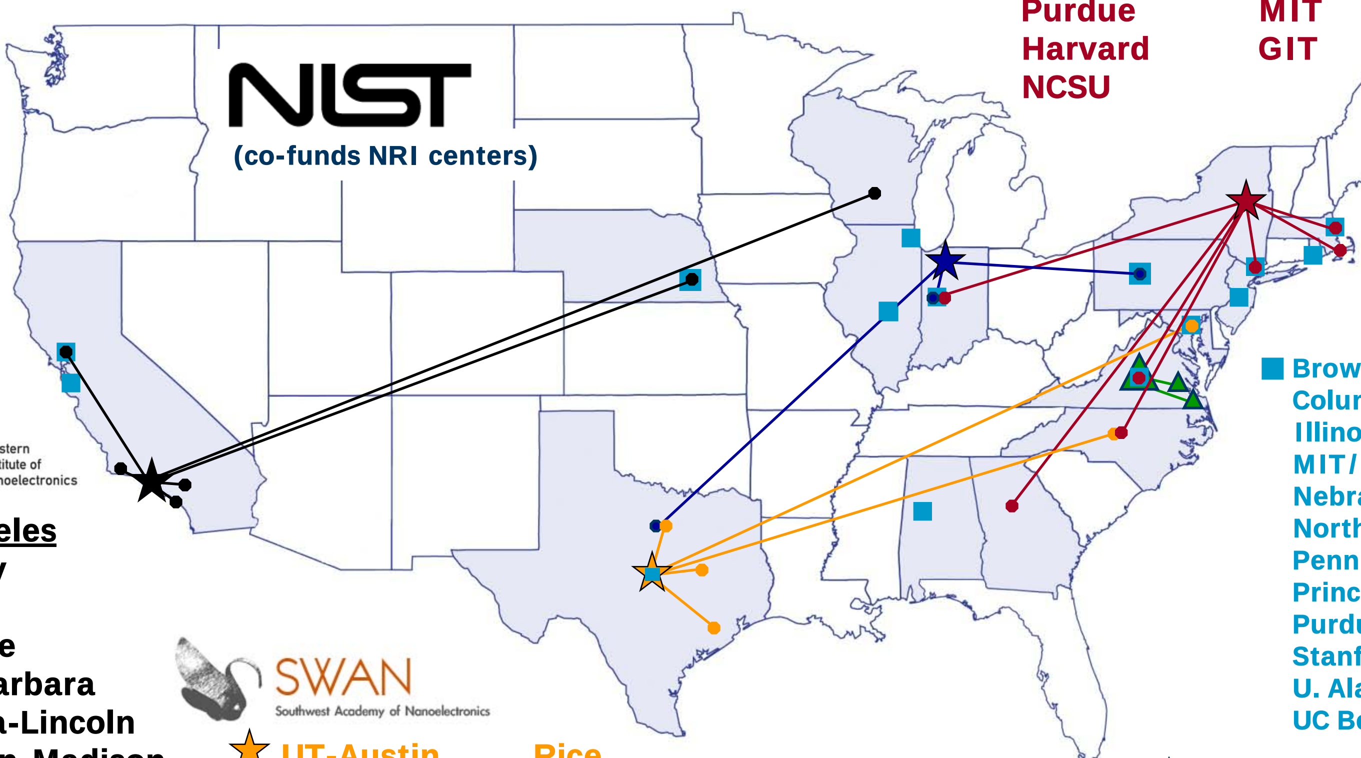
★ **Notre Dame** | **Purdue**
Penn State | **UT-Dallas**

INDEX
INSTITUTE FOR NANOELECTRONICS DISCOVERY AND EXPLORATION

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

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** | **Rice**
UT-Dallas | **Texas A&M**
U. Maryland | **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: Solutions for 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*

Distributed evaluation

example NNI, NSF

NSF (statistics of inputs, outputs and expert opinions)

- Annually: overall government (GPRA, PART); reviews of each center (NSEC, NSEE..); annual grantees conferences
- NSF Committees of Visitors (expert review)
- Output collection: SRI (2005-2006), NSECs (2010), NSEE (2011-2012)
- International evaluation and long-term vision, WTEC (2000, 2010)
- Topical NSE workshops sponsored NSF/NNI (> 15 meetings / year)
- Longitudinal evaluation (see next slide)

National review of NNI (expert opinions)

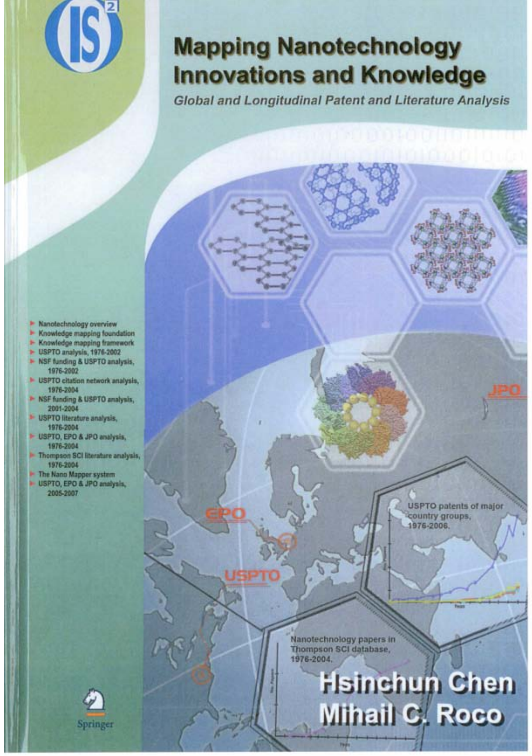
- OMB, OSTP, group of agencies, and Congress - annually
- PCAST - 1999, 2005, 2008, 2010, 2011-2012
- Academies, NRC - 2002, 2005, 2008, 2011-2012
- GAO - 2007, 2009, 2010, 2011-2012
- by industry, NGOs, and other private sector organizations

Examples evaluations

A. Longitudinal evaluation
   for NNI at NSF 1991-2012:

- NSF with University of Arizona

  Knowledge mapping analysis (1976-2011);
  Patent mapping; NSF awards, papers and patent contents analysis maps; Publication citation network; Patent publication network; Geographical distribution



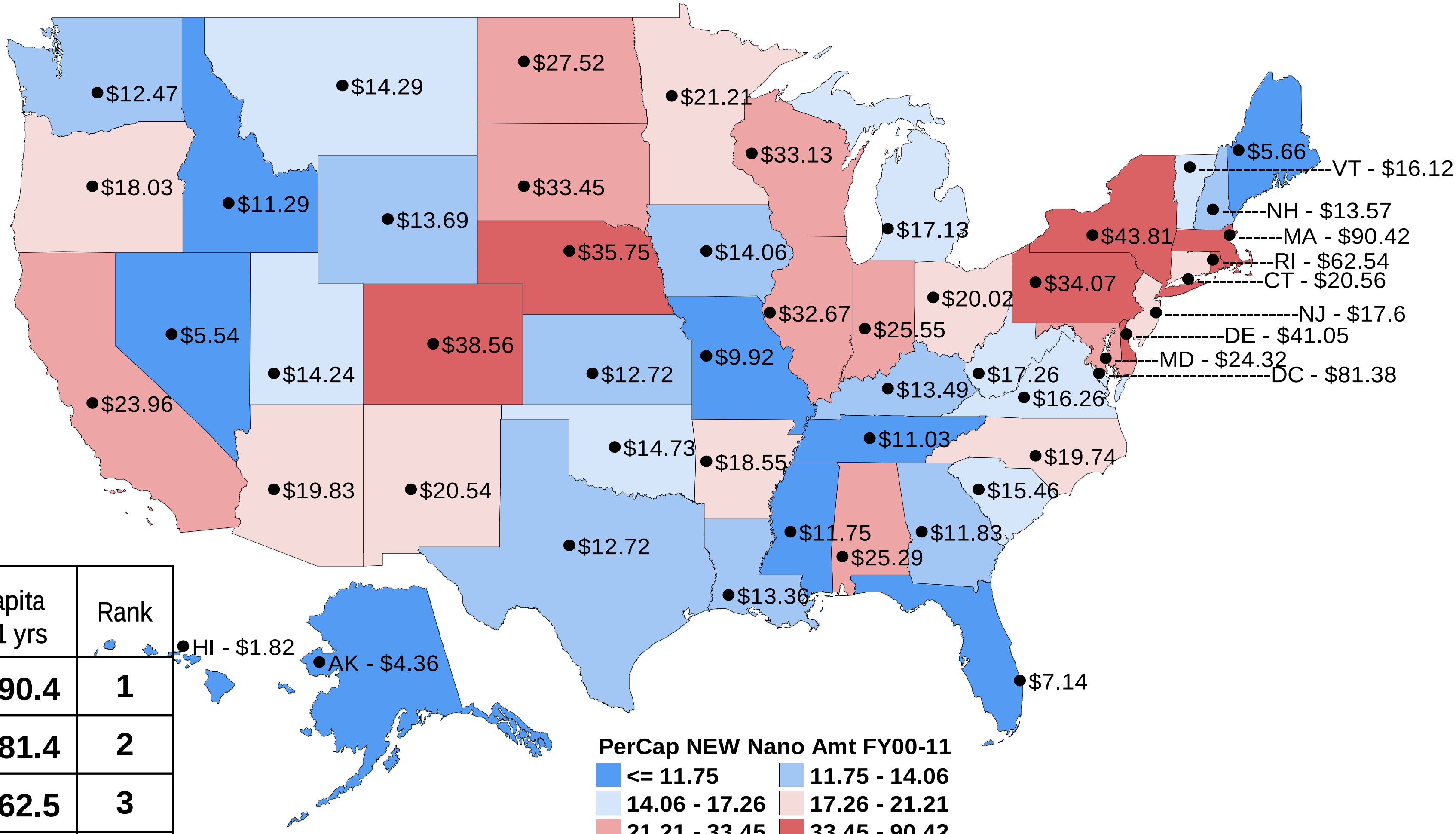
- Nanotechnology in Society centers (ASU Gatech, UCSB)

B. U.S. Government wide: R&D I/O data bases

- RADIUS (Rand Corporation., until 2008)
- Research.gov (Federal Government, established in 2008)

C. U.S. Government wide: Content analysis of data bases
   STAR Metrics (May 2010 -)

Per capita NNI investment for new NSF Awards by State FY 2000 – 2011 (national average ~ $22 per capita)

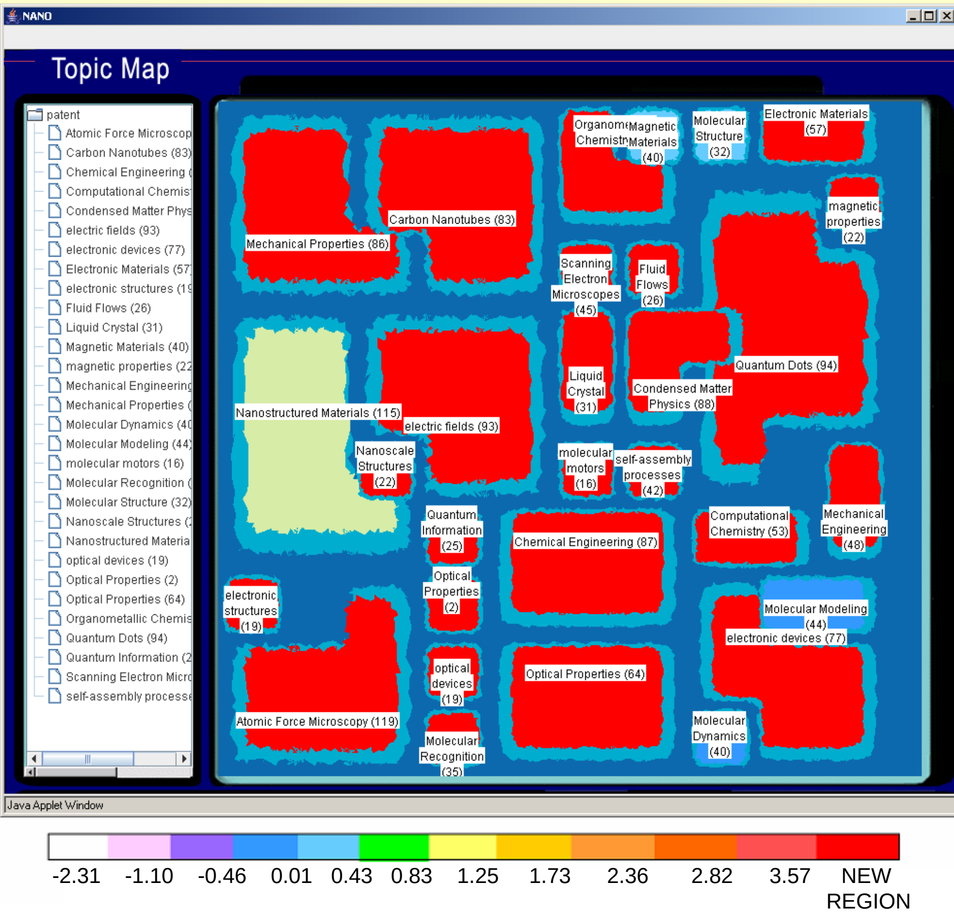


State	$ / capita per 11 yrs	Rank
MA	90.4	1
DC	81.4	2
RI	62.5	3
NY	43.8	4
DE	41.1	5
CO	38.6	6

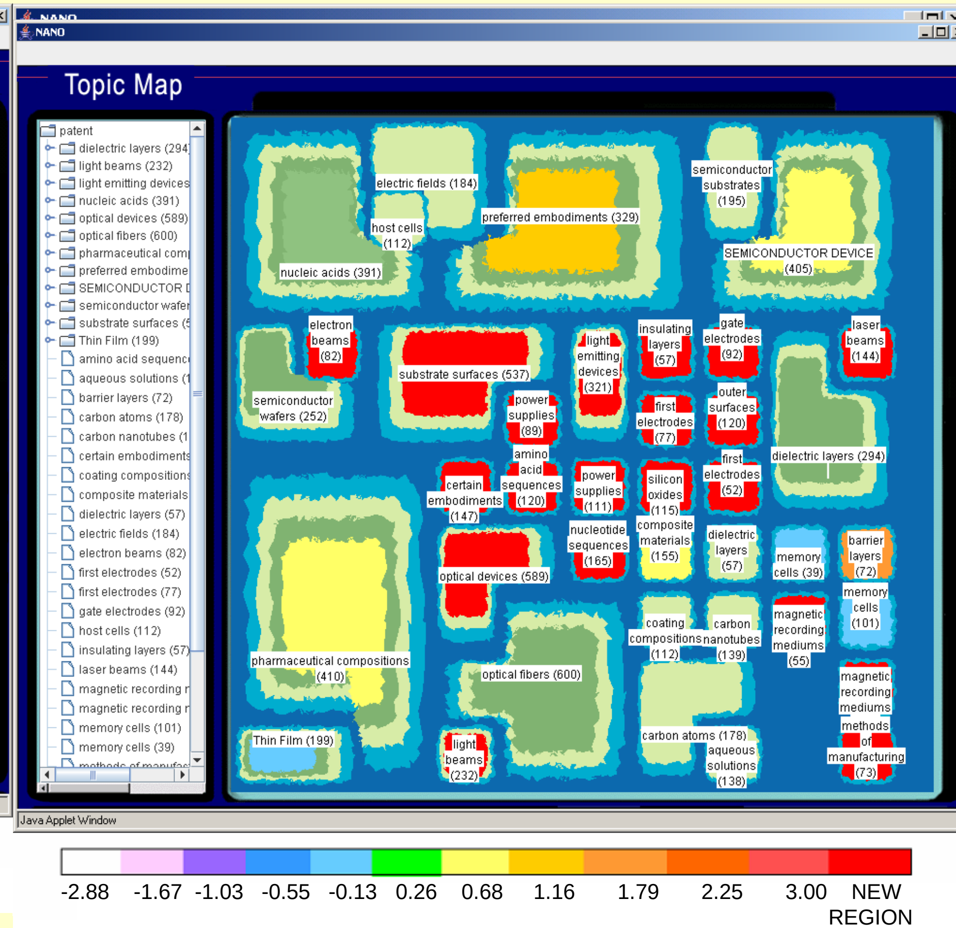
MC Roco, Feb 7 2012

The rate of change in topics was highest in 2003-2004
NSE content map analysis grant – patent topic association

NSE Grant Content Map (2003-2004)



NSE Patent Content Map (2003-2004)



Region color indicates the relative growth rate (red – highest rate)

(source: NSF sponsored research)

MC Roco, 11/08/05

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

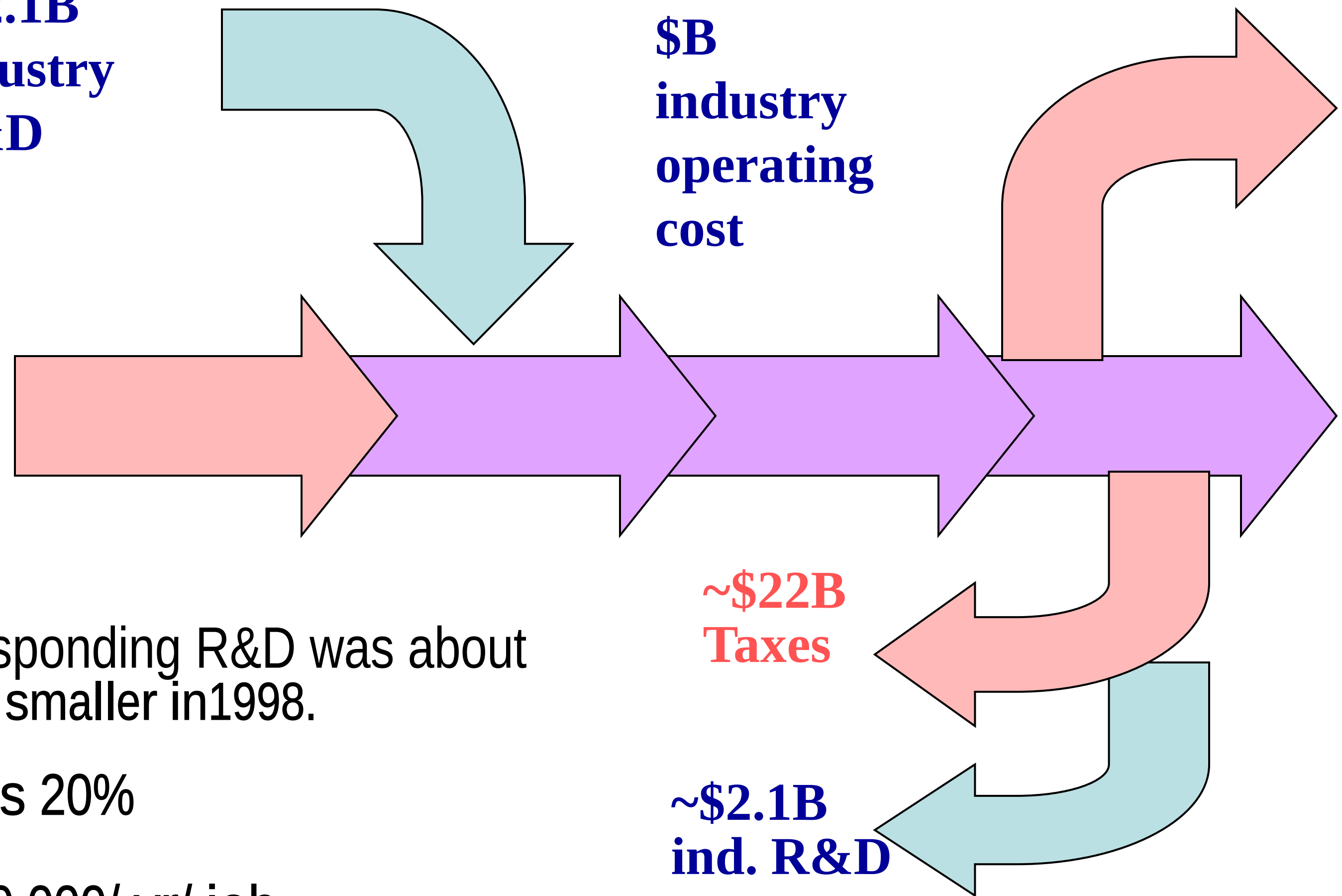
Number of patent citations by NSF P.I.-Inventors

```
                                  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

Estimation of Annual Implications of U.S. Federal Investment in Nanotechnology R&D (2010)



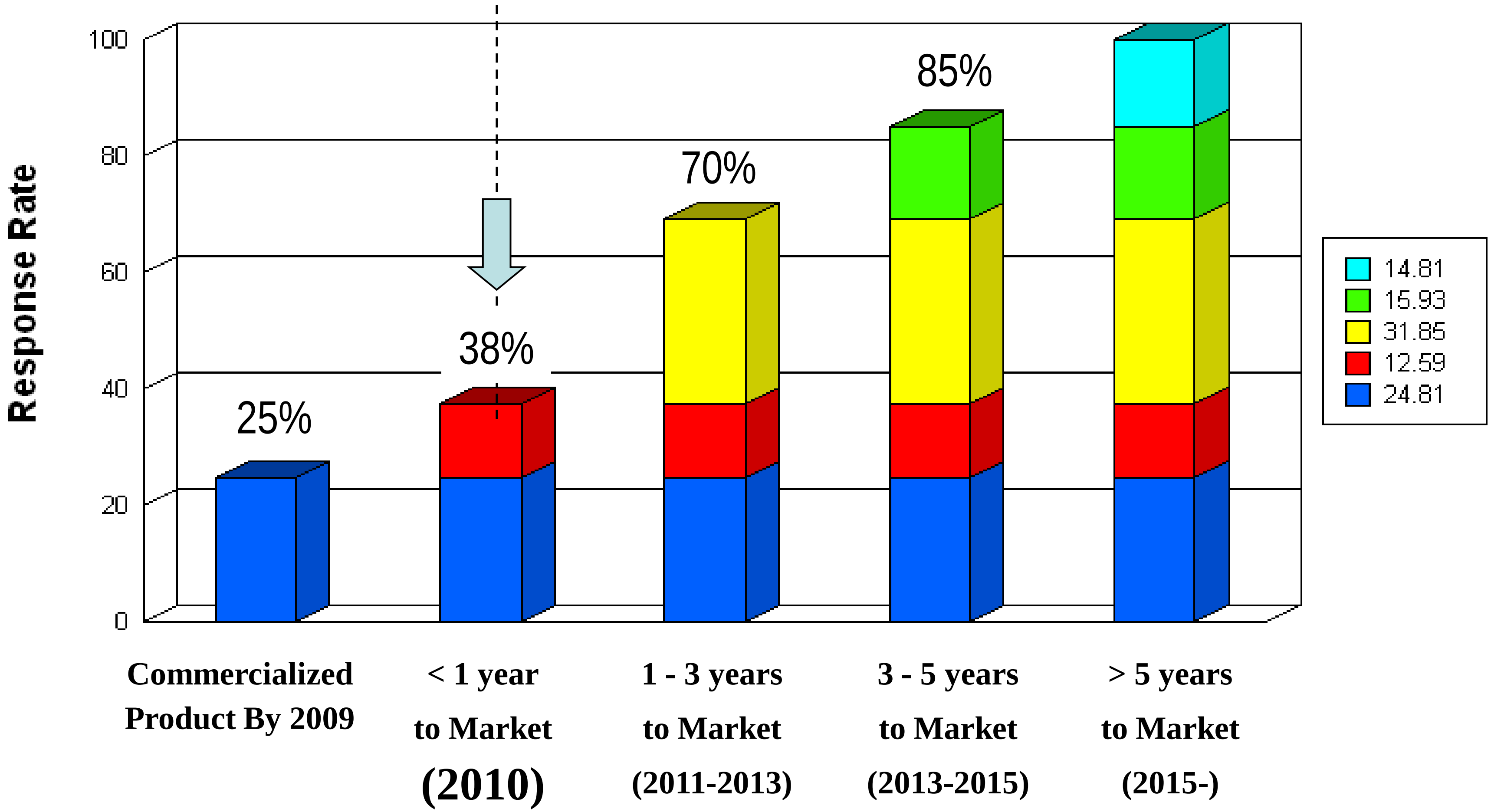
* The corresponding R&D was about 10 times smaller in1998.

** Est. taxes 20%

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

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)*

Advances in EHS and ELSI in 2000-2010

Regulation - two approaches are developing in parallel

- Probing extendability of regulatory schemes ("developing the science" approach)
- Exploratory (soft) regulatory and governance models that work with insufficient knowledge for risk-assessment

International collaboration

- several different formats for international dialogue have emerged, each with strengths and limitations, such as International Dialogue on Responsible Development , OECD Working Groups, ISO Working Groups and IRGC

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

- ✓ Major industry involvement after 2002-2003
  Ex: >5,400 companies with papers/patents or products (US, 2008); NBA in 2002; Keeping the Moore law continue 10 years after serious doubt raised din 2000
- ✓ Unanticipated discoveries and advances in several S&E fields: plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, quantum information ..
- ✓ The formation / strength of the international community, including in nanotechnology EHS and ELSI that continue to grow

nano2

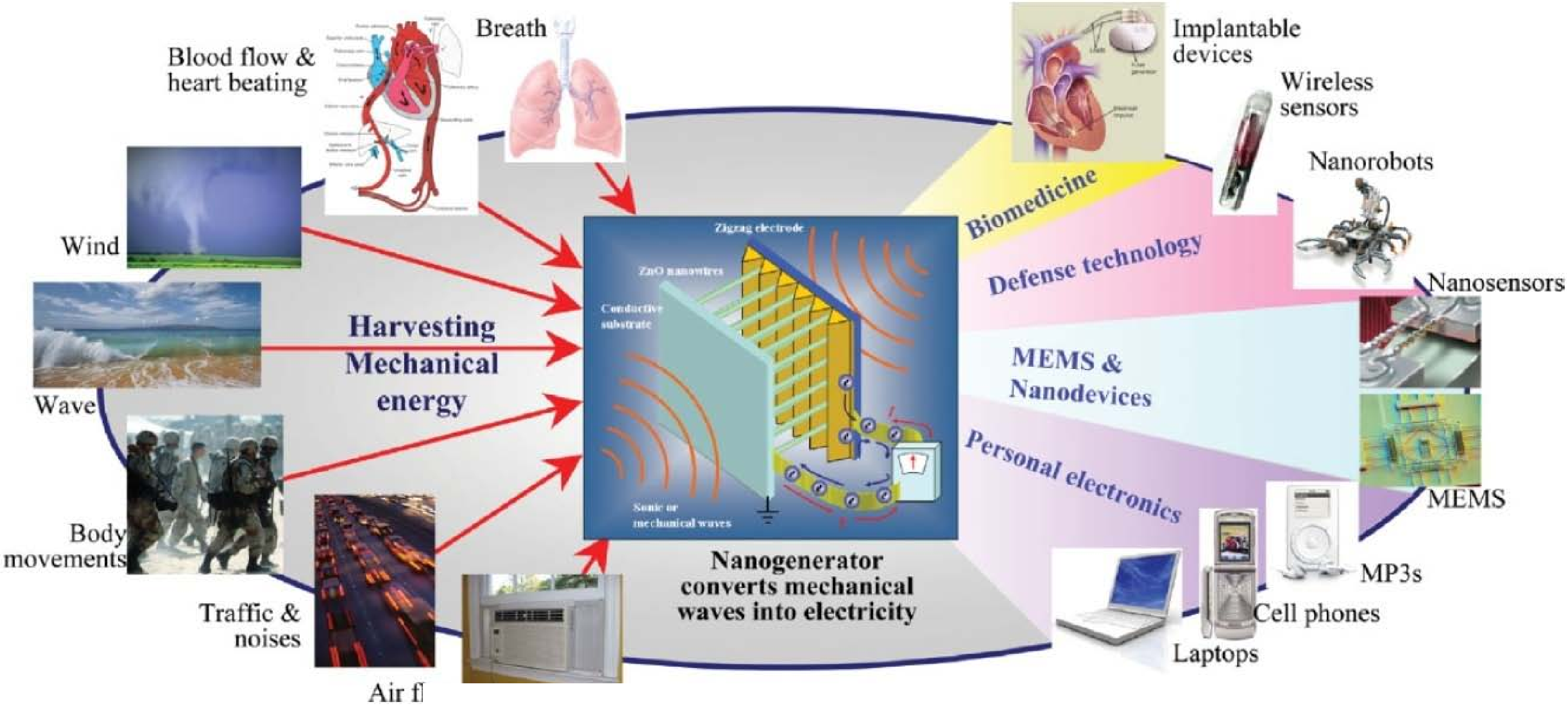
Twelve trends to 2020

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

Exemple: Self-powered nanosystems

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



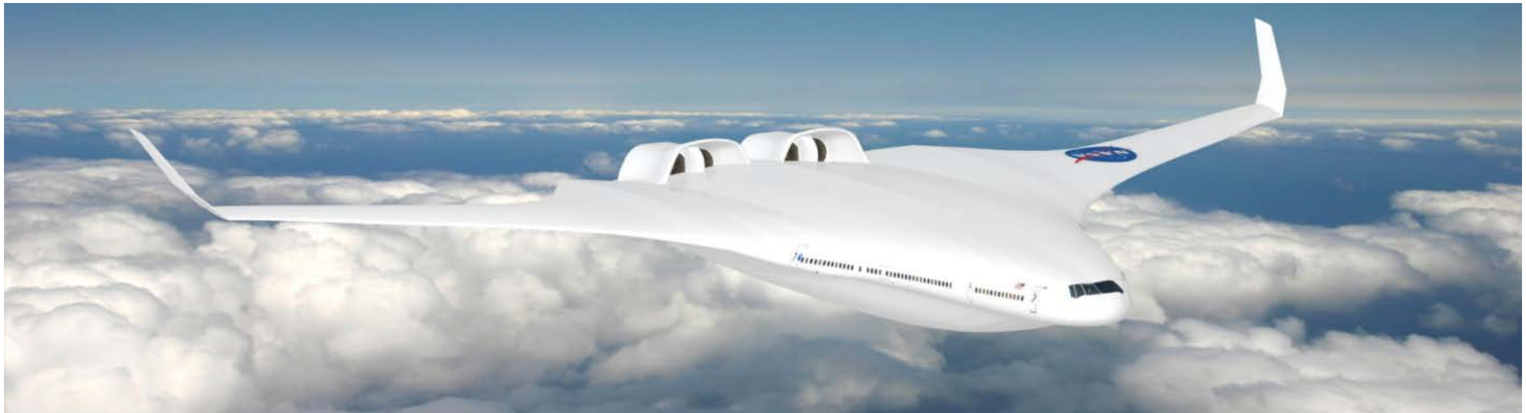
(Z. L. Wang, Adv. Funct. Mater., 2008)

Example: Nanosystems 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



2010-2020: Key areas of S&T emphasis

- Integration of knowledge at the nanoscale and of nanocomponents in nanosystems and 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 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

Vision for 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. Risk governance deficits in knowledge, uncertainty, institutional

- **Greater emphasis on innovation and commercialization:** incentives for greater use of public/private partnerships to foster innovation. Create new models for innovation

- **Focus on return to society** - high-added value nanomanufacturing

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

Several Goals for 2010-2020

- Nanotechnology is emerging as a *general purpose technology*
- *The shift to new generations of nanotechnology products*,
  - uncertainty in risk management
  - taking decision with incomplete information
- Several possibilities for improving the governance of nanotechnoogy in the global self-regulating ecosystem:
  - using open-source and incentive-based models,
  - implementing long-term planning with international perspective
  - institute voluntary measures for risk management
  - adopt an anticipatory, participatory, real-time technology assessment and adaptive governance of nanotechnology

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”**

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