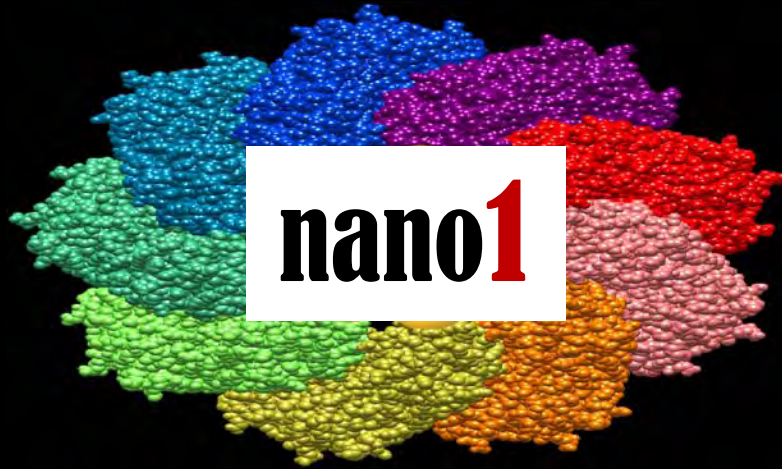
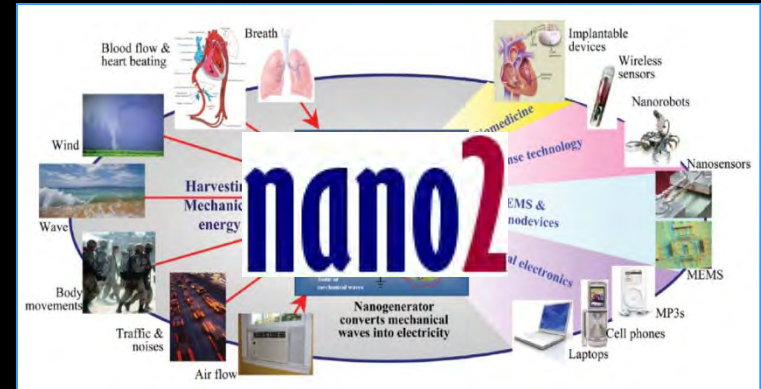


2000



2010



2020

Nanotechnology Research Directions for Societal Needs in 2020

Mike Roco
NSF and NNI

WWCS
December 1, 2010

Context: Emergence of new technologies Nanotechnology is a prime example

■ Knowledge generation has 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) & development with limited natural resources (sustainability constrain)

■ Emerging technologies governance

- *Integration of new tools and separated disciplines,*
- *General purpose integrators:
nanotechnology, IT, and complex systems*

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

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 $\rightarrow$ new phenomena $\rightarrow$ novel applications***
- ***integration along length scales, systems and applications***

Nanotechnology Research Directions

Vision for Nanotechnology in the Next Decade

Edited by
M.C. Roco, R.S. Williams and P. Alivisatos

nano1

Springer, 1999

“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

Nanotechnology Research Directions for Societal Needs in 2020



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

Nanotechnology Research Directions for Societal Needs in 2020

Approach



- Leading expert panel (US); questionnaires; five brainstorming workshops in Chicago (US), Hamburg (EU and US), Tokyo (Japan, Korea, Taiwan and US), Singapore (Singapore, Australia, China, India, Saudi Arabia) and Arlington (all); input from over 35 countries; peer / industry / public review
- Inclusive study with input from and evaluations for industry, academe, government and public
- Open source approach: on <http://www.wtec.org/nano2> and Springer book publication (2010)

Moderators and Contributors



Mike Roco
(NSF Coordinator)



Chad Mirkin, Co-Chair
(Northwestern)



Mark Hersam, Co-Chair
(Northwestern)



Dawn
Bonnell
(Penn)



C. Jeffrey
Brinker
(Sandia)



Evelyn
Hu
(Harvard)



Mark
Lundstrom
(Purdue)



André
Nel
(UCLA)



Jeffrey
Welser
(IBM)



Mark
Tuominen
(U Mass)



Mamadou
Diallo
(Caltech)



Jim
Murday
(USC)



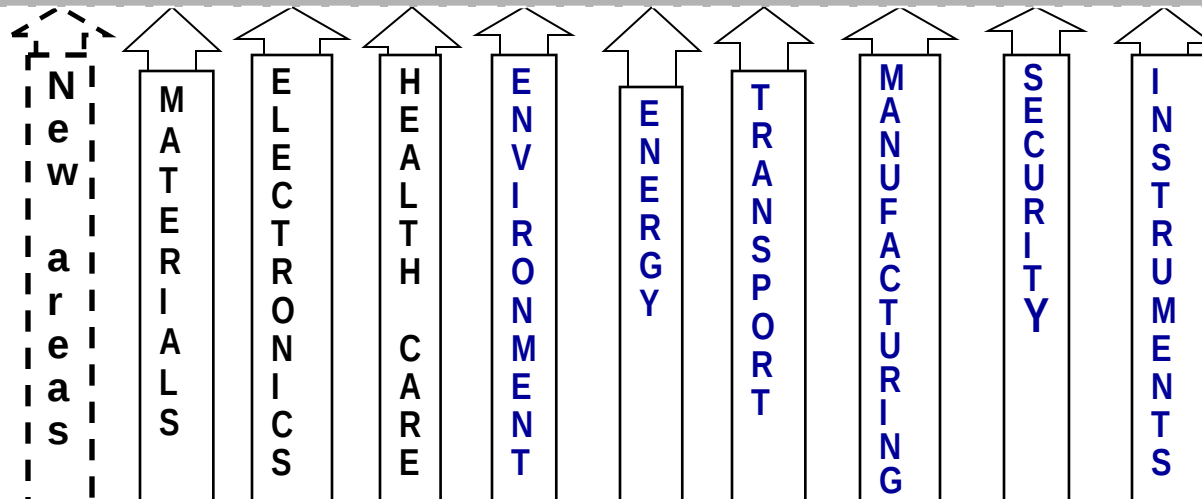
Stuart
Wolf
(U Va)

Topical

Main topics of the study

- ❑ Fundamental scientific and engineering Issues for nanotechnology
- ❑ Investigative tools: Theory, modeling, and simulation
Measure, instrumentation and metrology
- ❑ Synthesis, processing and manufacturing
- ❑ Nanotechnology environmental, health and safety (EHS) issues
- ❑ Sustainability: Environment, Water, Food and Climate
Energy conversion, storage and conservation
- ❑ Applications: Nanobiosystems, medical and health
Nanoelectronics and nanomagnetism
Photonics and plasmonics
Nanostructured catalysts and other chemicals
High performance materials, systems, emerging areas
- ❑ Governance: Preparation of people and physical infrastructure
Innovative and responsible governance

Mass Application of Nanotechnology after ~ 2020



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

NS&E integration for general purpose technology

~ 2011

nano2

~ 2020

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

New disciplines

New industries

Societal impact

Foundational interdisciplinary research at nanoscale

~ 2001

nano1

~ 2010

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

Infrastructure

Workforce

Partnerships

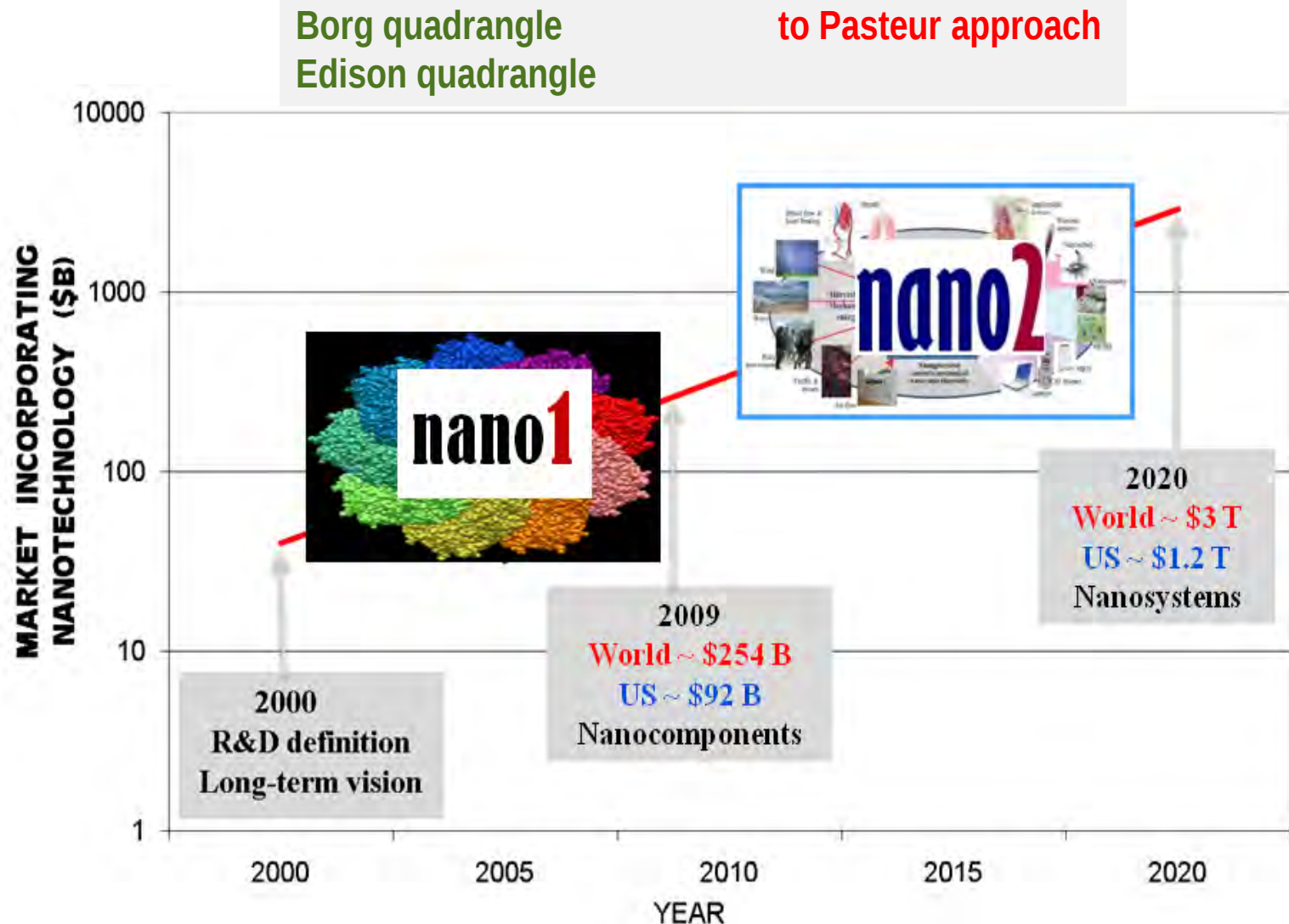
2020

2000

Market of final products incorporating nanotechnology

Nano1: R&D focus on fundamental discoveries and empirical processing (2000-2010)

Nano2: focus on applications-driven fundamental and system research (2010-2020)



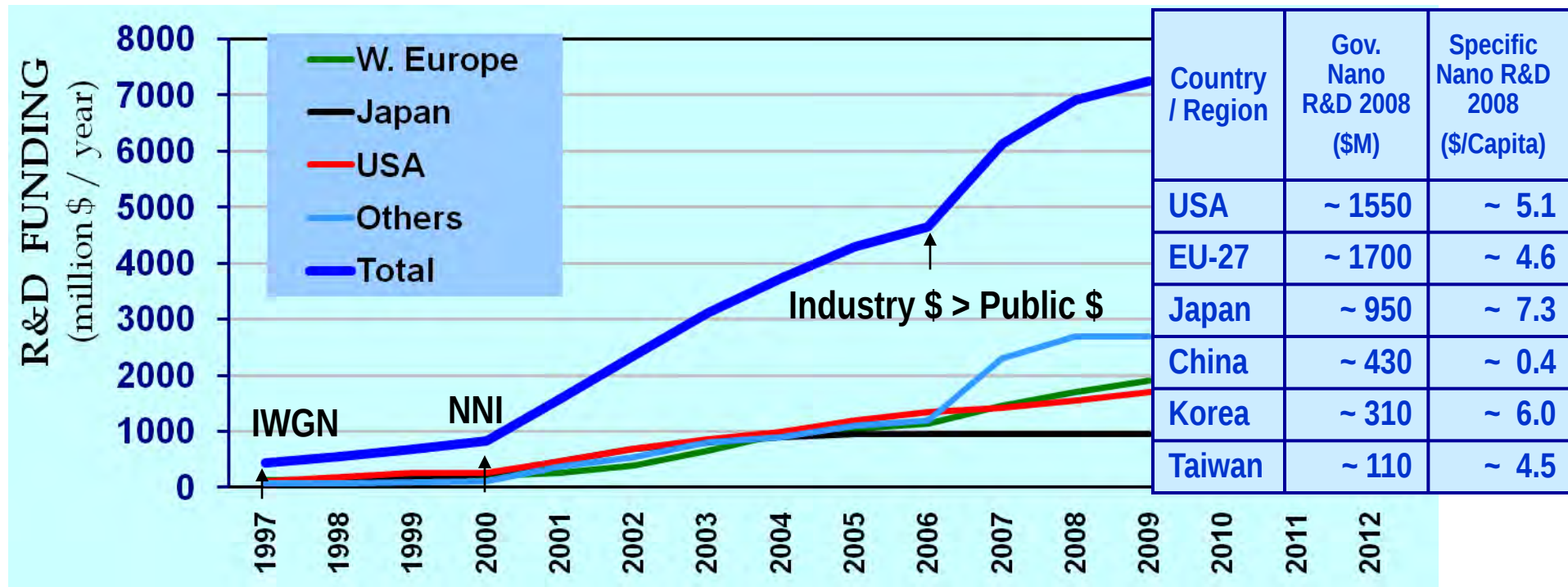
2000-2008

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	<i>Research frontiers change from <u>passive nanostructures</u> in 2000-2005, to <u>active nanostructures</u> after 2006, and to <u>nanosystems</u> after 2010</i>					

2000-2009

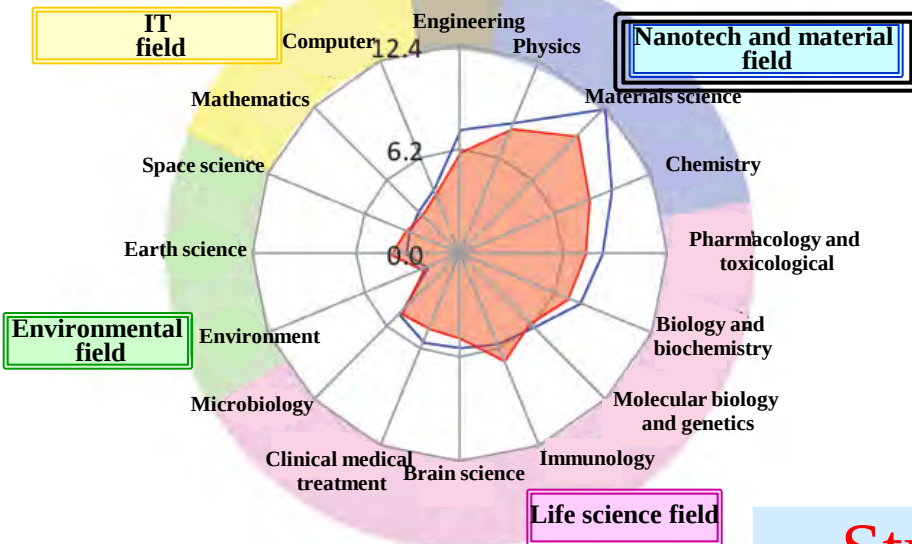
Changing international context: federal/national government R&D funding (NNI definition)



Rapid, uneven growth per countries

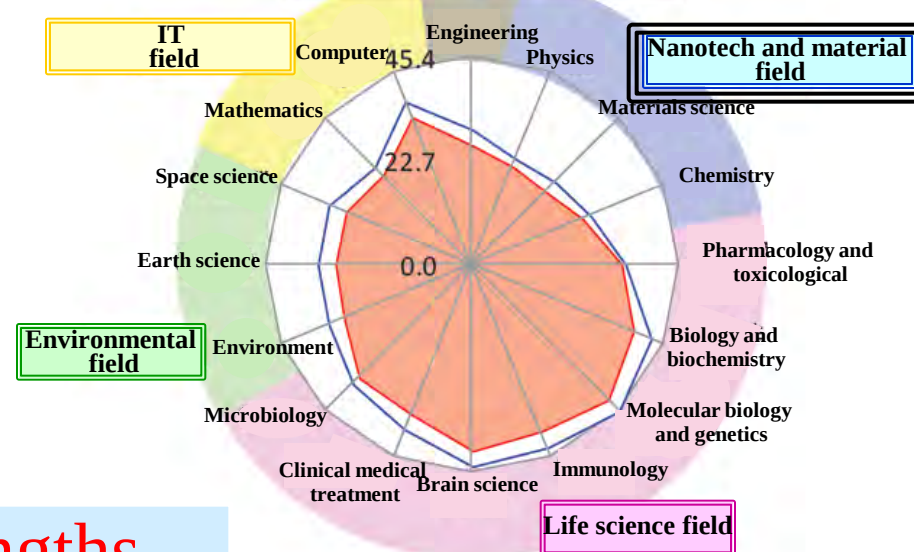
Japan

1998-2002 2003-2007



The United States

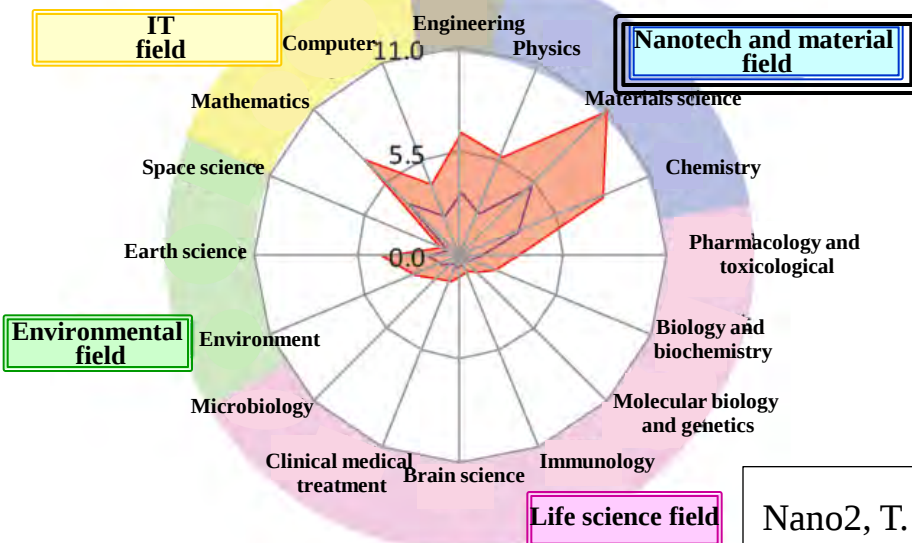
1998-2002 2003-2007



Strengths
per country

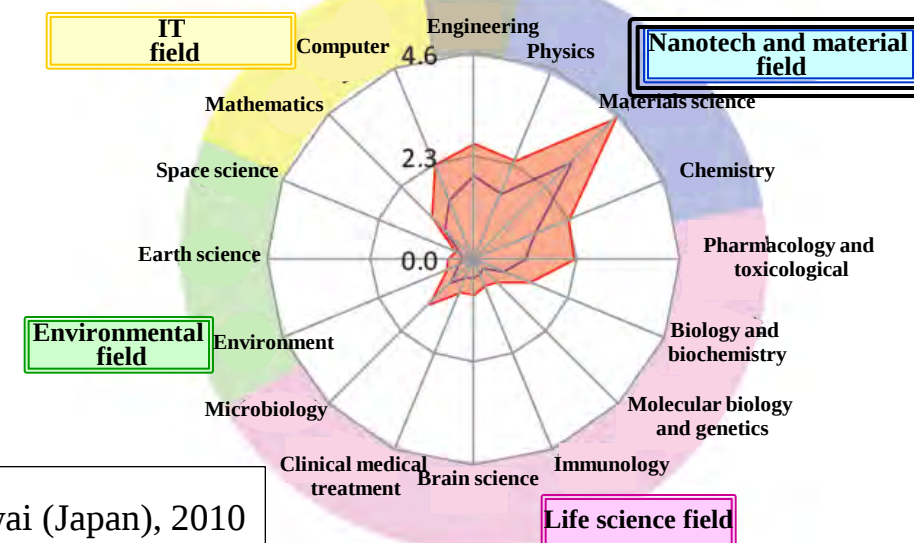
China

1998-2002 2003-2007



South Korea

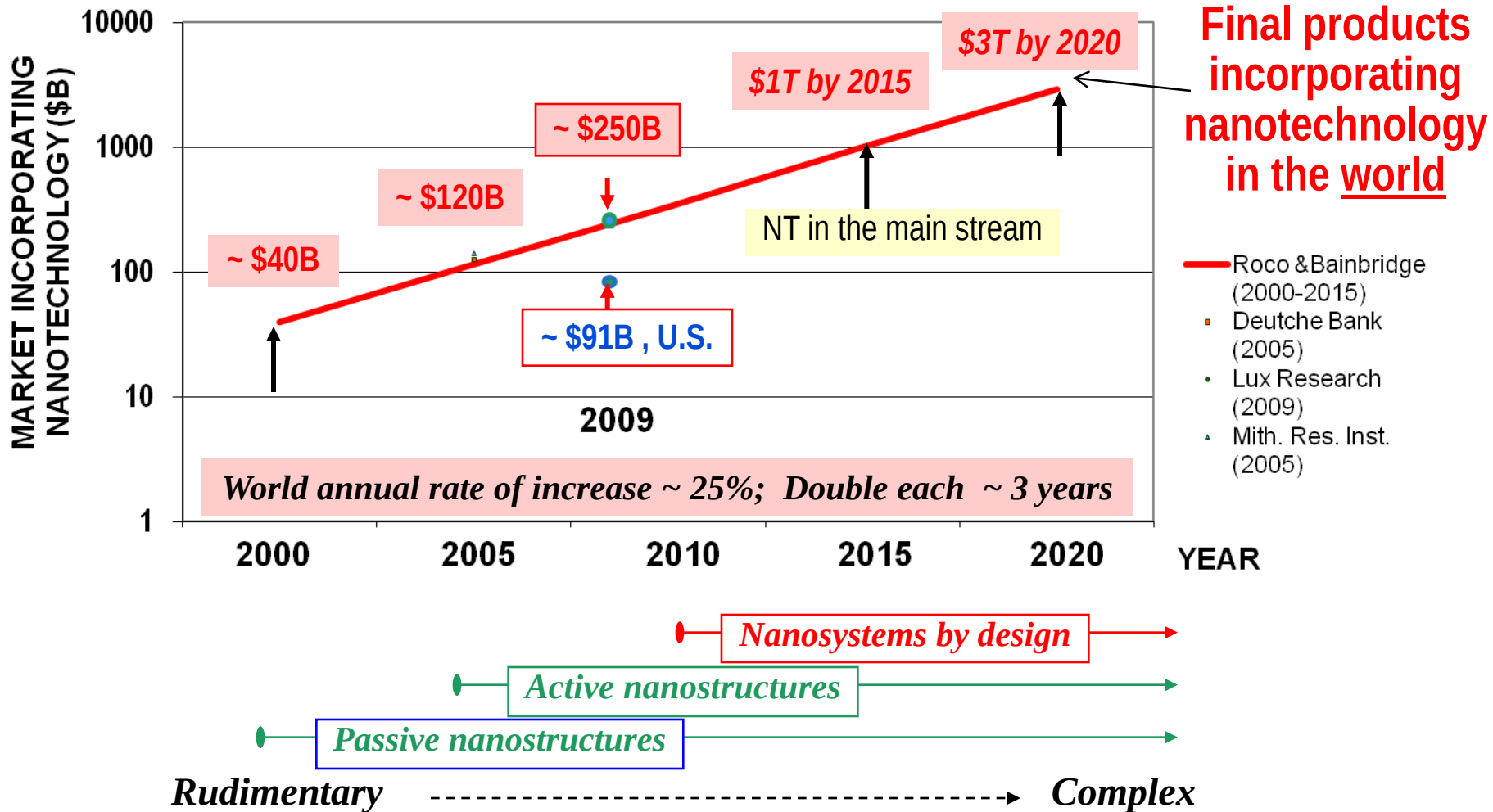
1998-2002 2003-2007



Nano2, T. Kawai (Japan), 2010

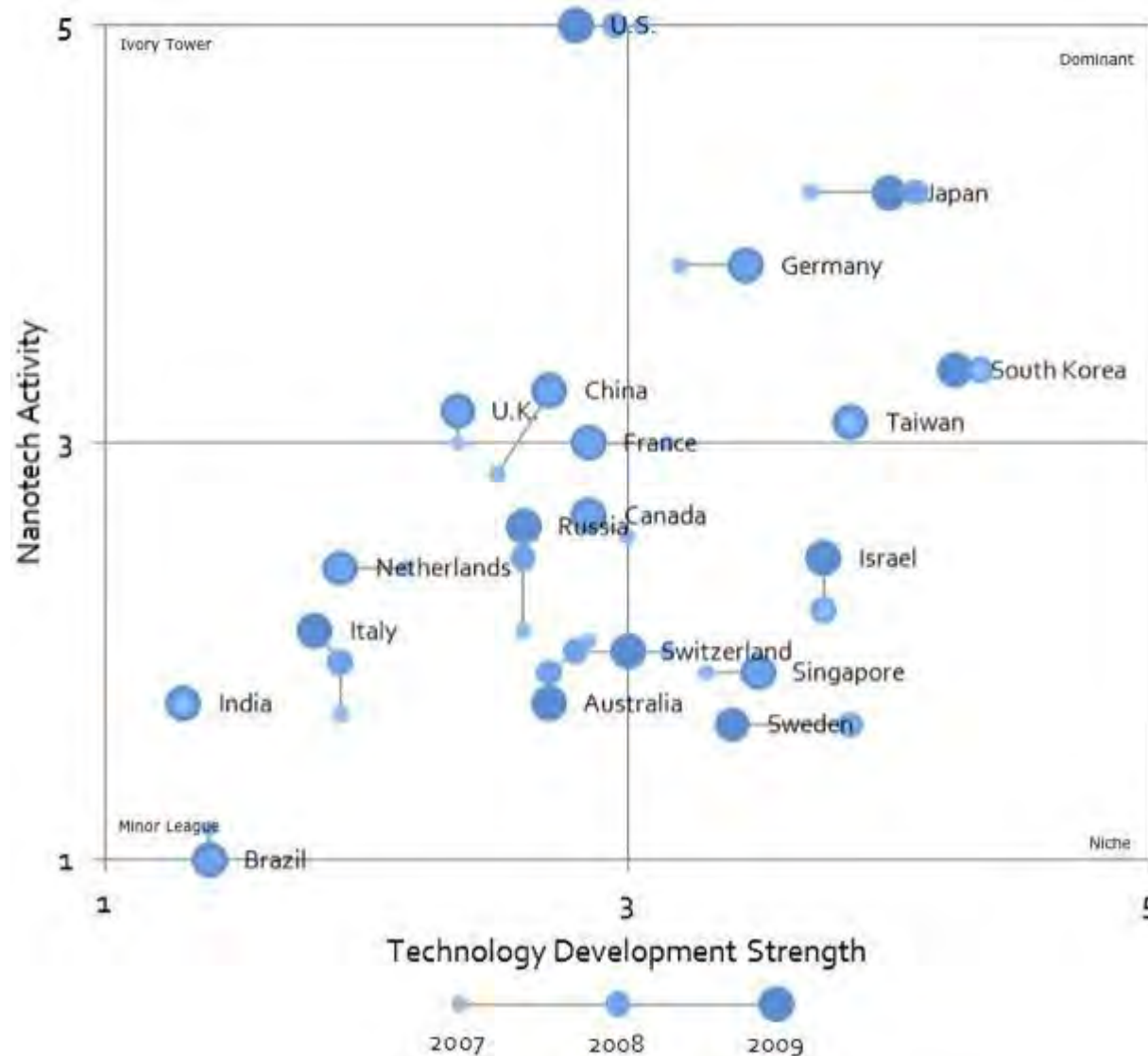
WORLDWIDE MARKET INCORPORATING NANOTECHNOLOGY

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



Ranking the nations on nanotechnology

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

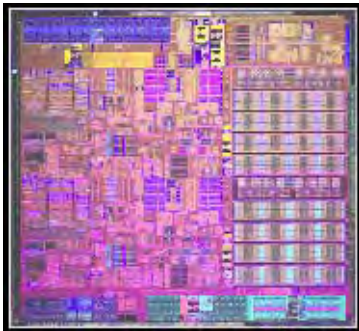
2000-2010: Methods and Tools

- **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

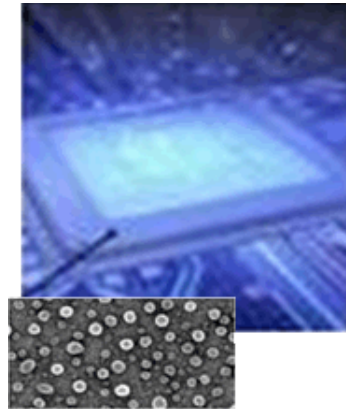
2000-2010: Examples of innovations

- **An illustration is the 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

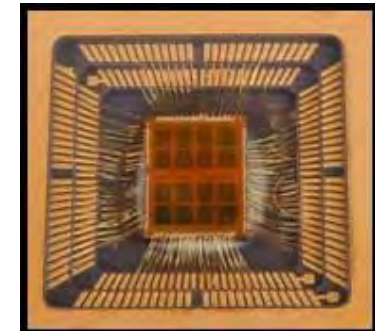
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



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)

2000-2010: Safe Development

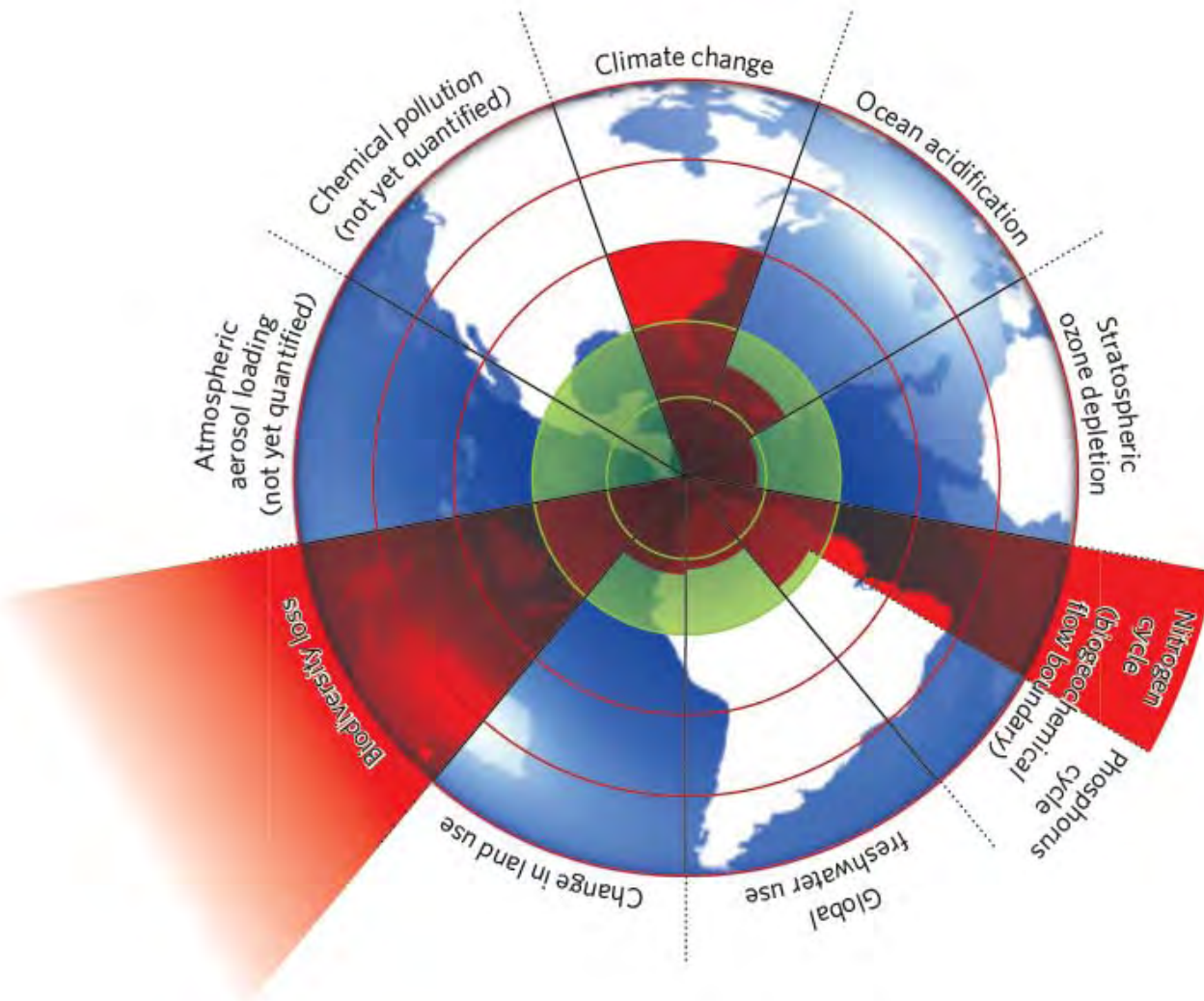
There is greater recognition of the **essential areas** of nanotechnology-related EHS and ELSI issues

- 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 CO₂ 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)

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** is 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**

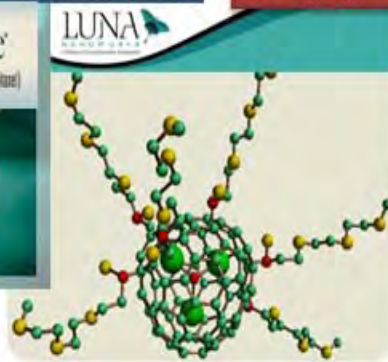
On-site diagnostics



*Nanoscale body
Imaging*



*Targeted drug
therapeutics*



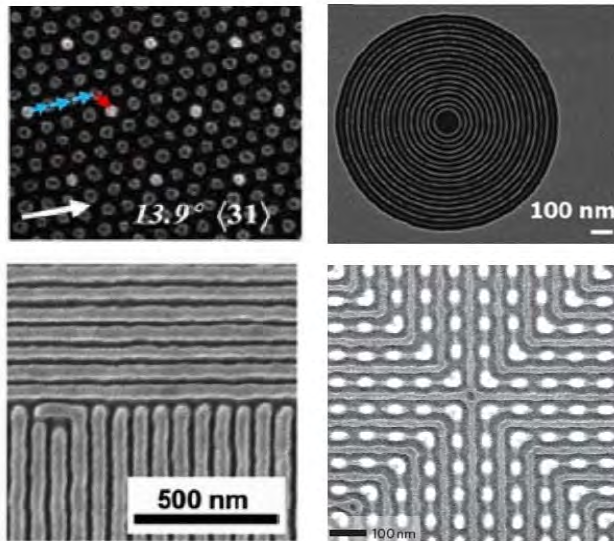
*Nanostructured
bone replacements*

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

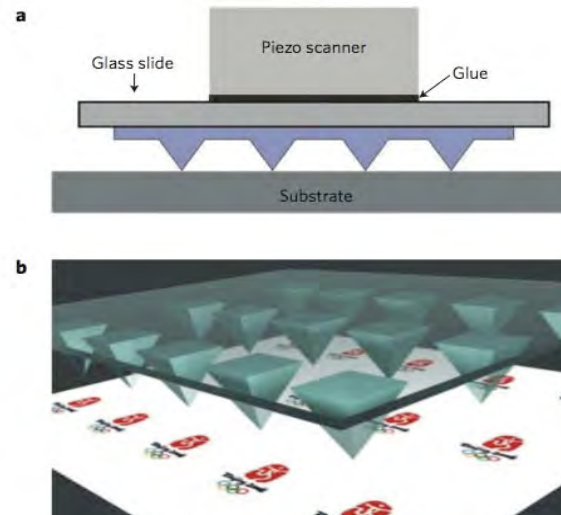
2000-2010: Towards nanotechnology applications

- 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

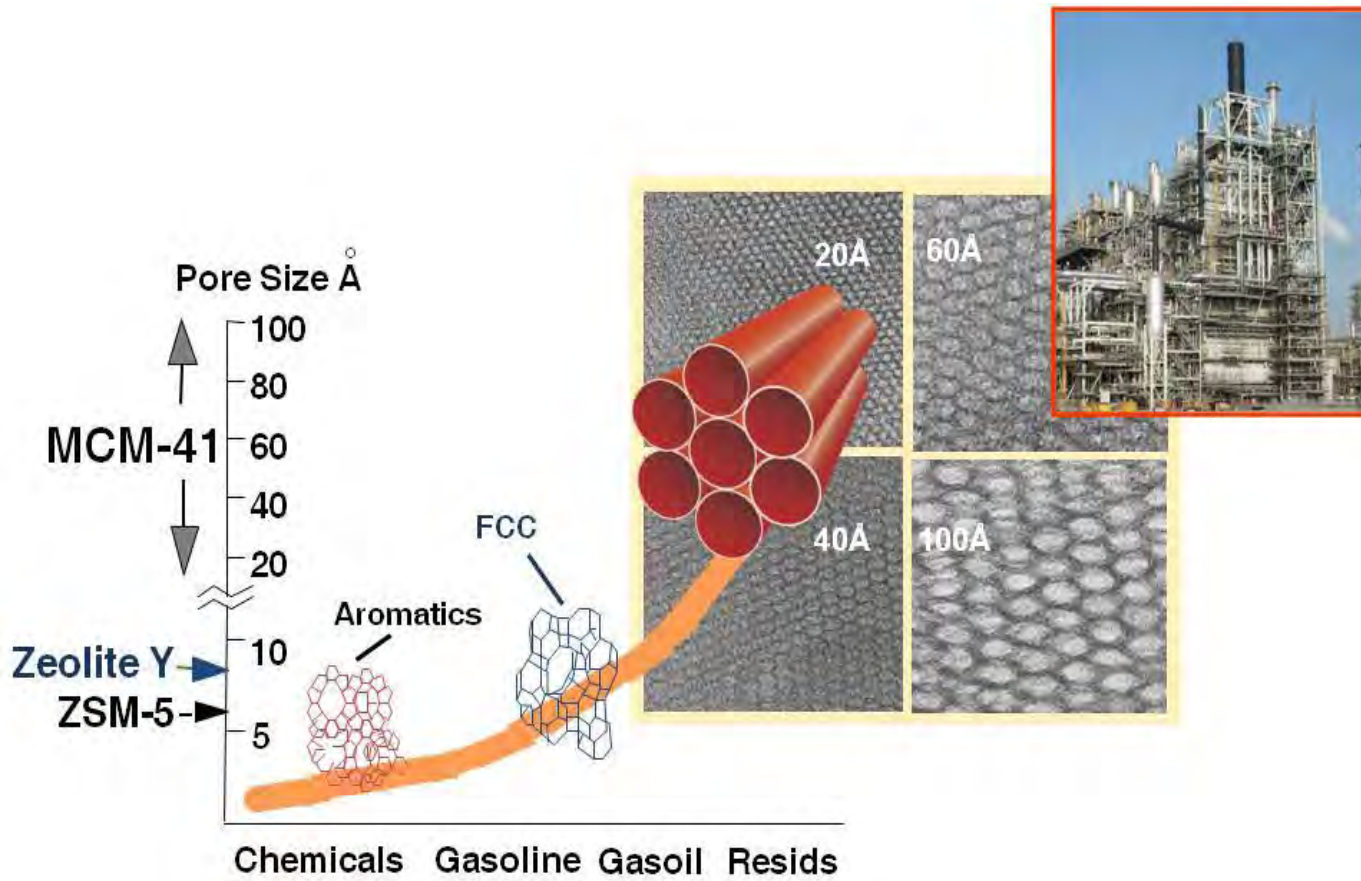


**Diblock copolymer
directed selfassembling**



**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

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%
Pharmaceuticals (therapeutics and diagnostics)	0	~ 15% (~\$70B)	~ 50%
Wood	0	0	~ 20%

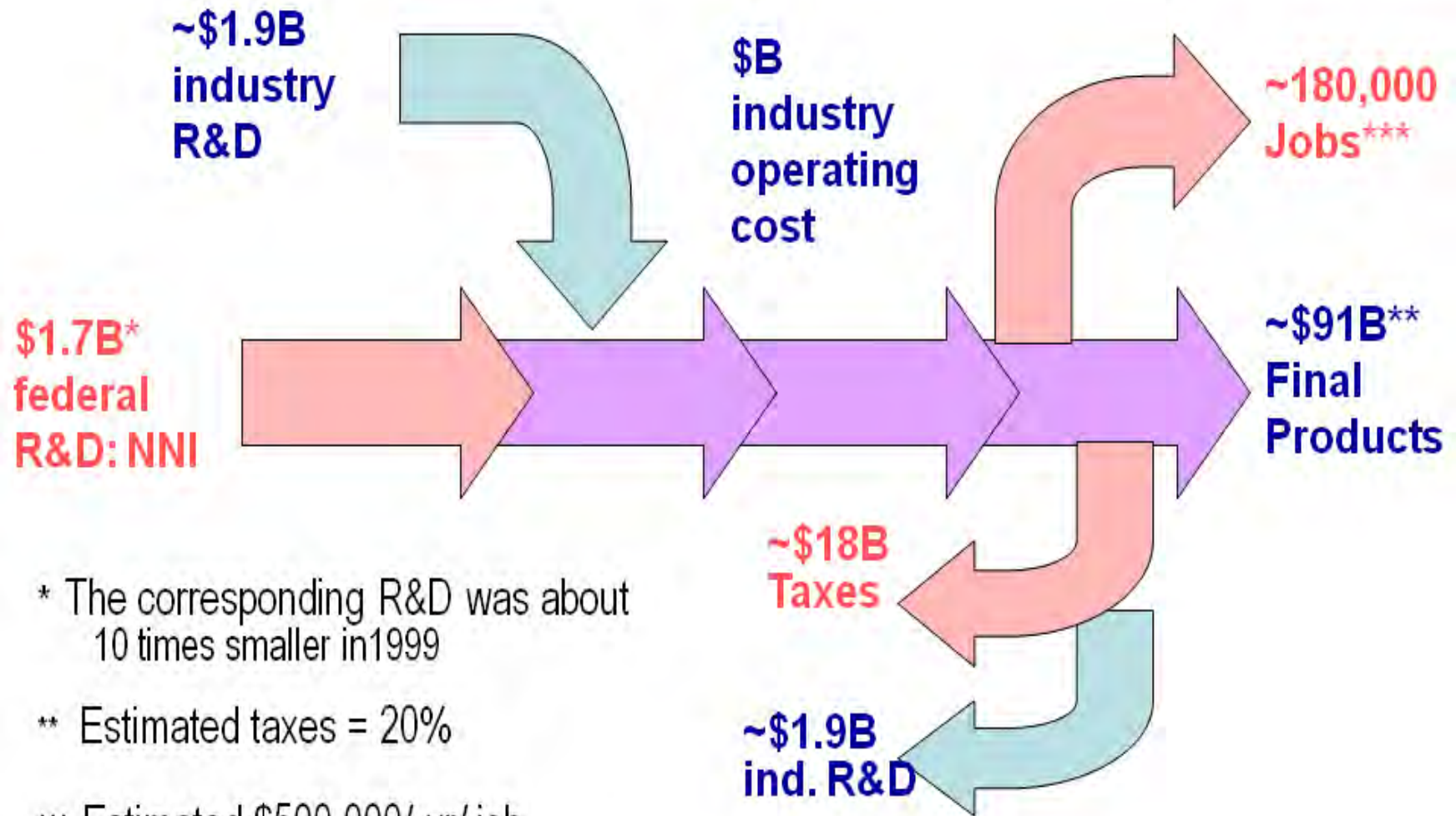
Ten highly promising products incorporating nanotechnology in 2010

- 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

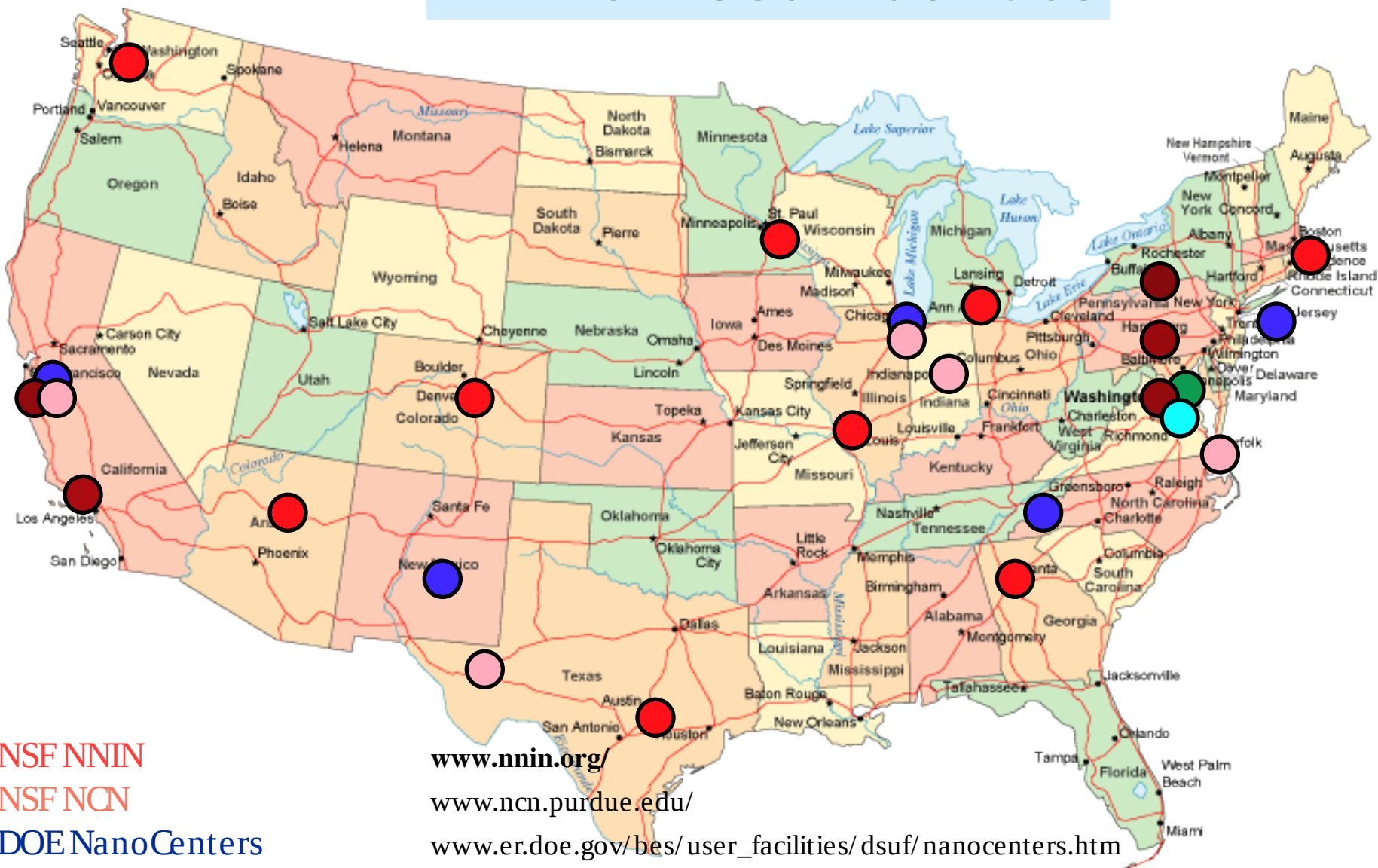
With safety concerns: cosmetics, food, disinfectants,..

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

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



NNI R&D User Facilities



NSF NNIN

NSF NCN

DOE NanoCenters

NIST CNST NanoFab

NIH NCI NCL

www.nnin.org/

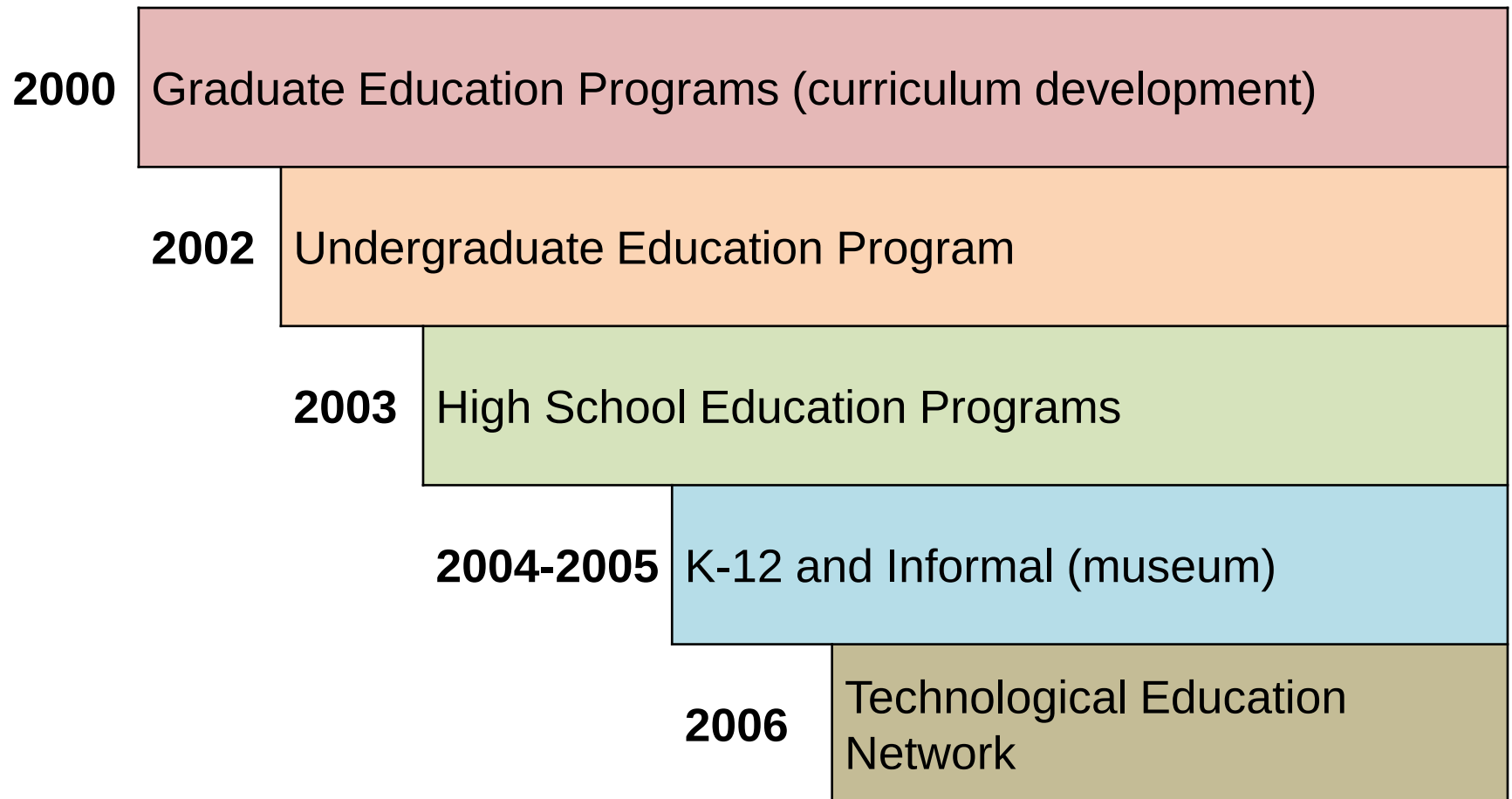
www.ncn.purdue.edu/

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

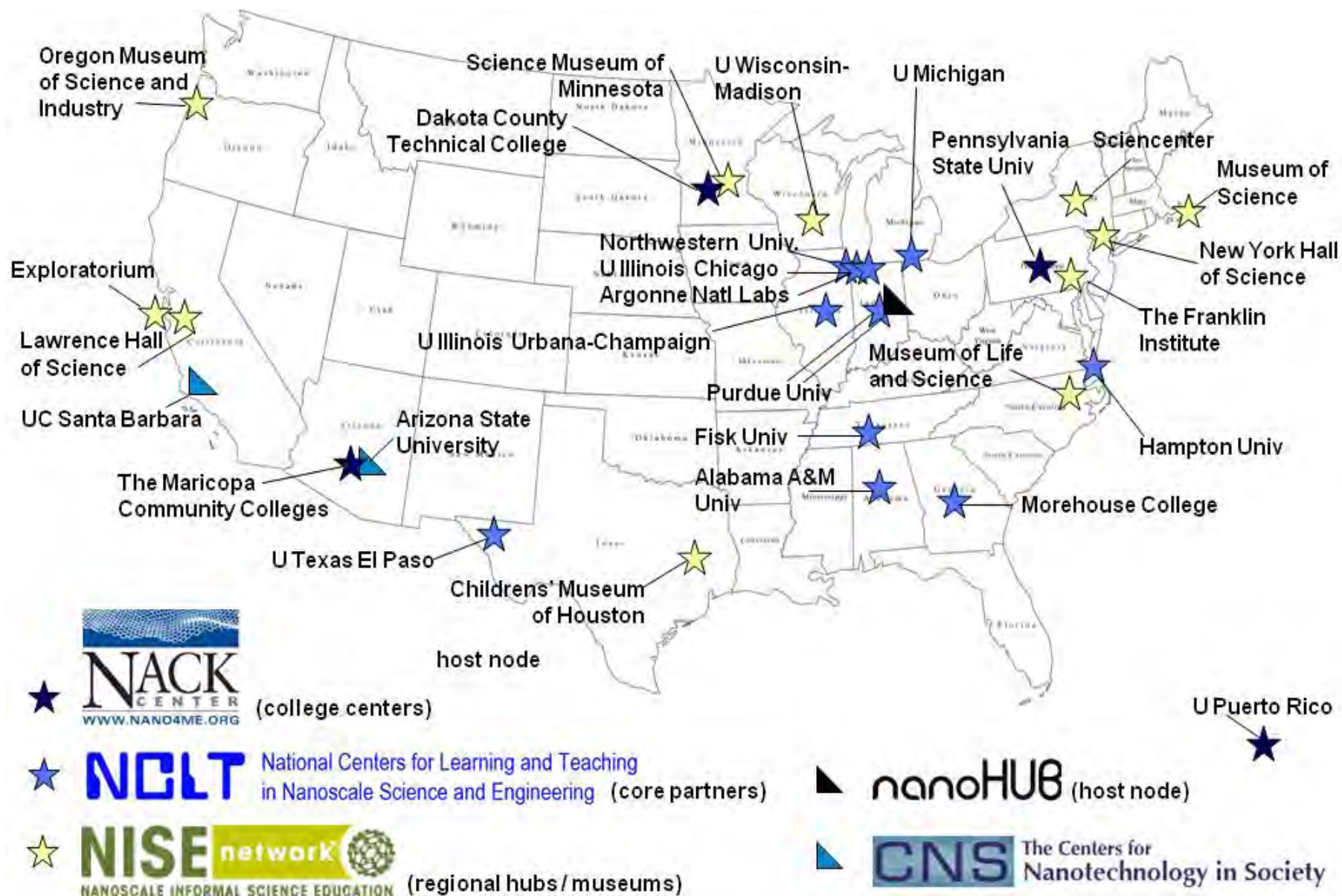
www.cnst.nist.gov/nanofab/nanofab.html

ncl.cancer.gov/

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



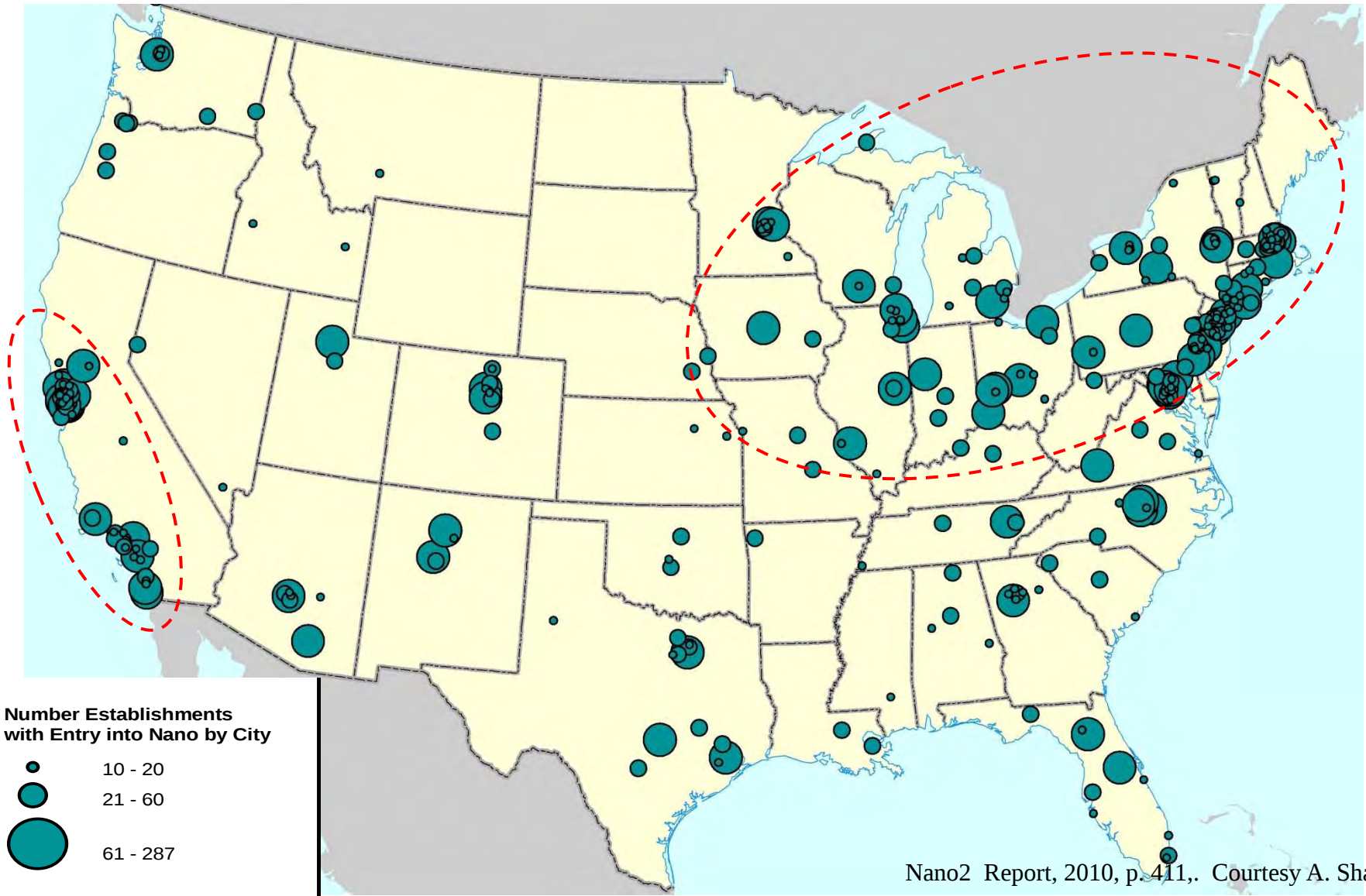
Key NNI education networks in 2010



Corporate entry into nanotechnology by city in 2008

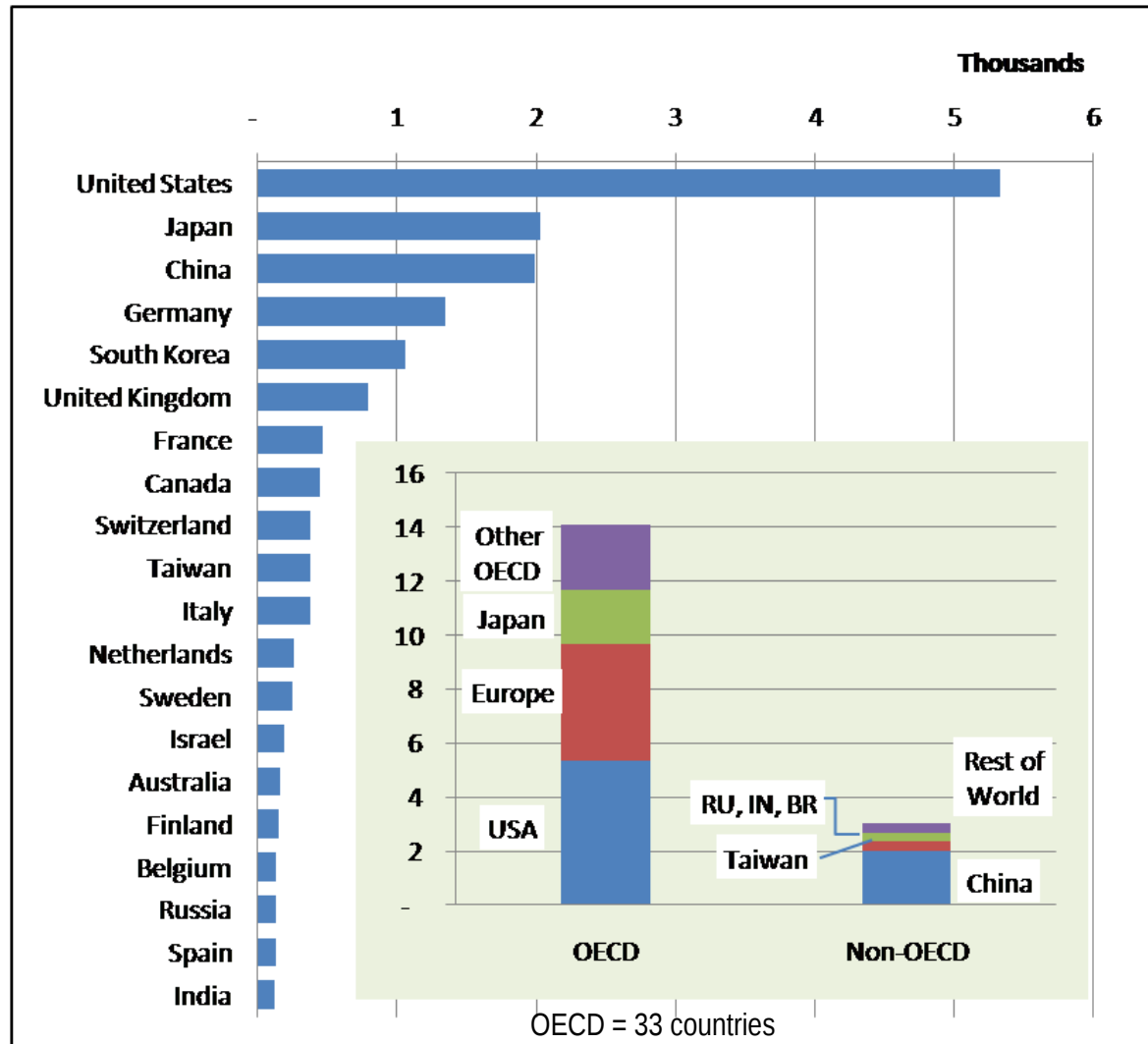
(establishments with nano publications or patents for cities with 10 or more establishments)

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



Transformative governance

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



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 in 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

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

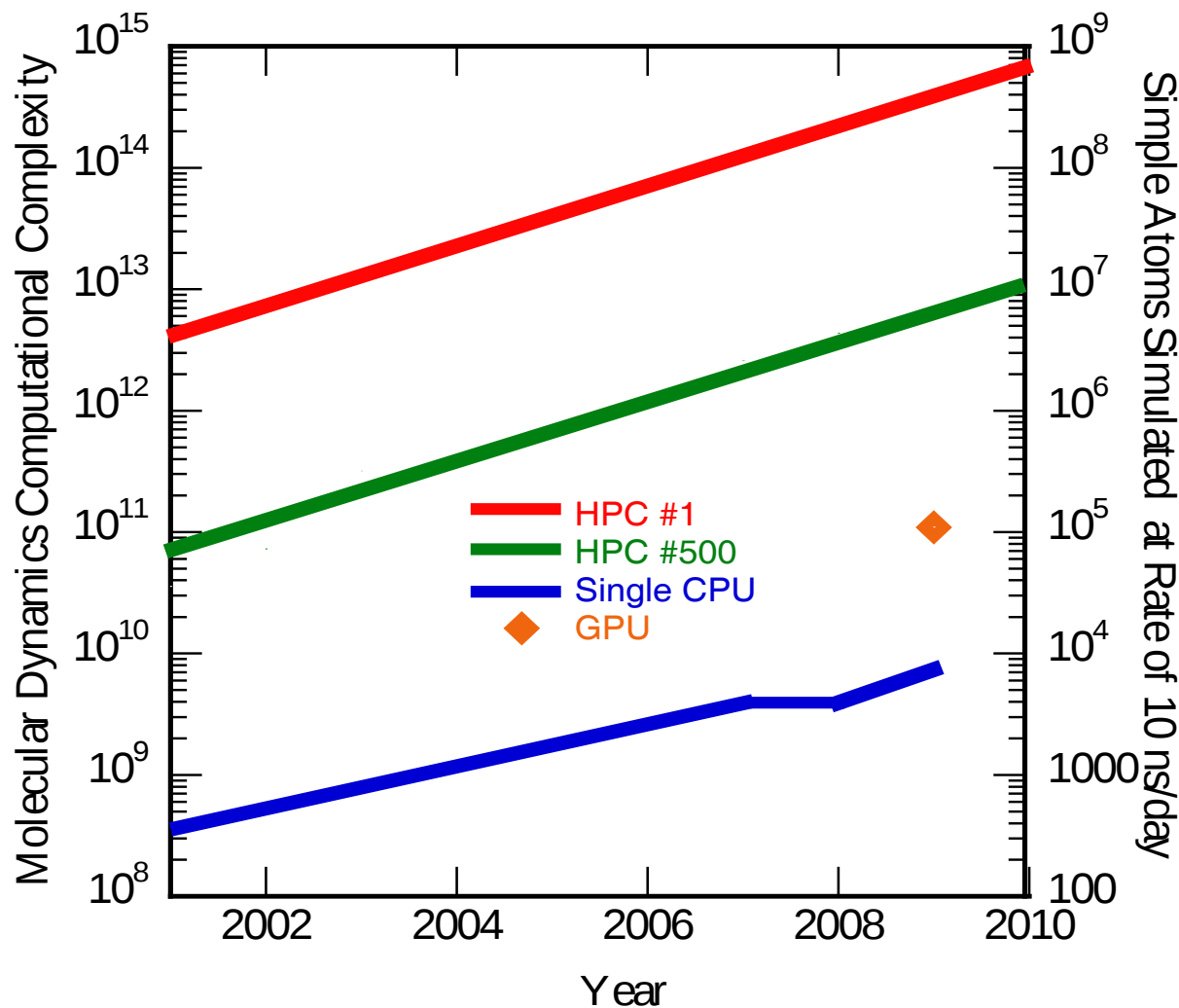
Twelve trends to 2020

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



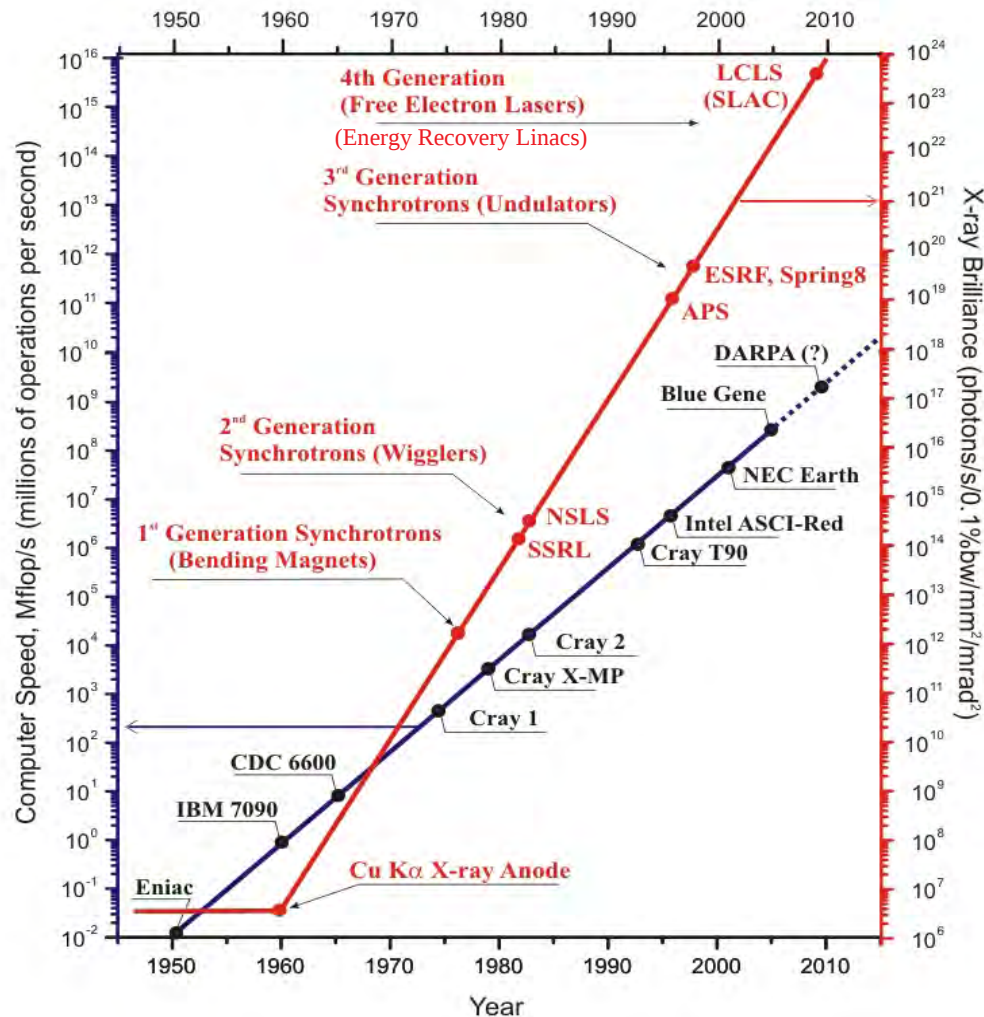
Left axis:
CMD computational complexity

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
~ 1000 times
in next decade

2. "Direct" measurements and metrology

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



Semiconductor
Moore's law
(black):

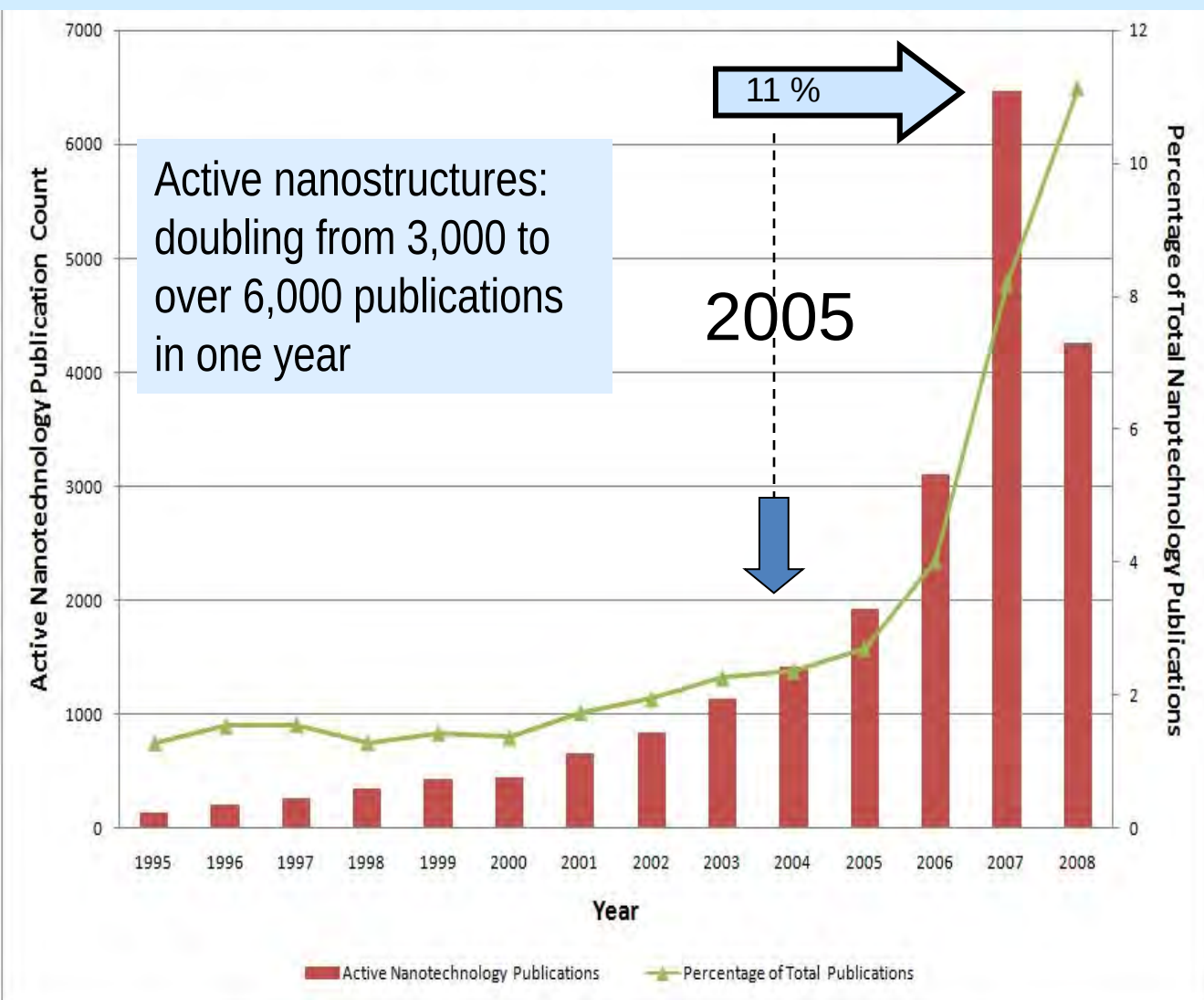
2 orders
of magnitude
in last
decade

X-ray source
brilliance (red):

estimated
3.6 orders
of magnitude

To increase
~ 5,000 times
in next decade

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)

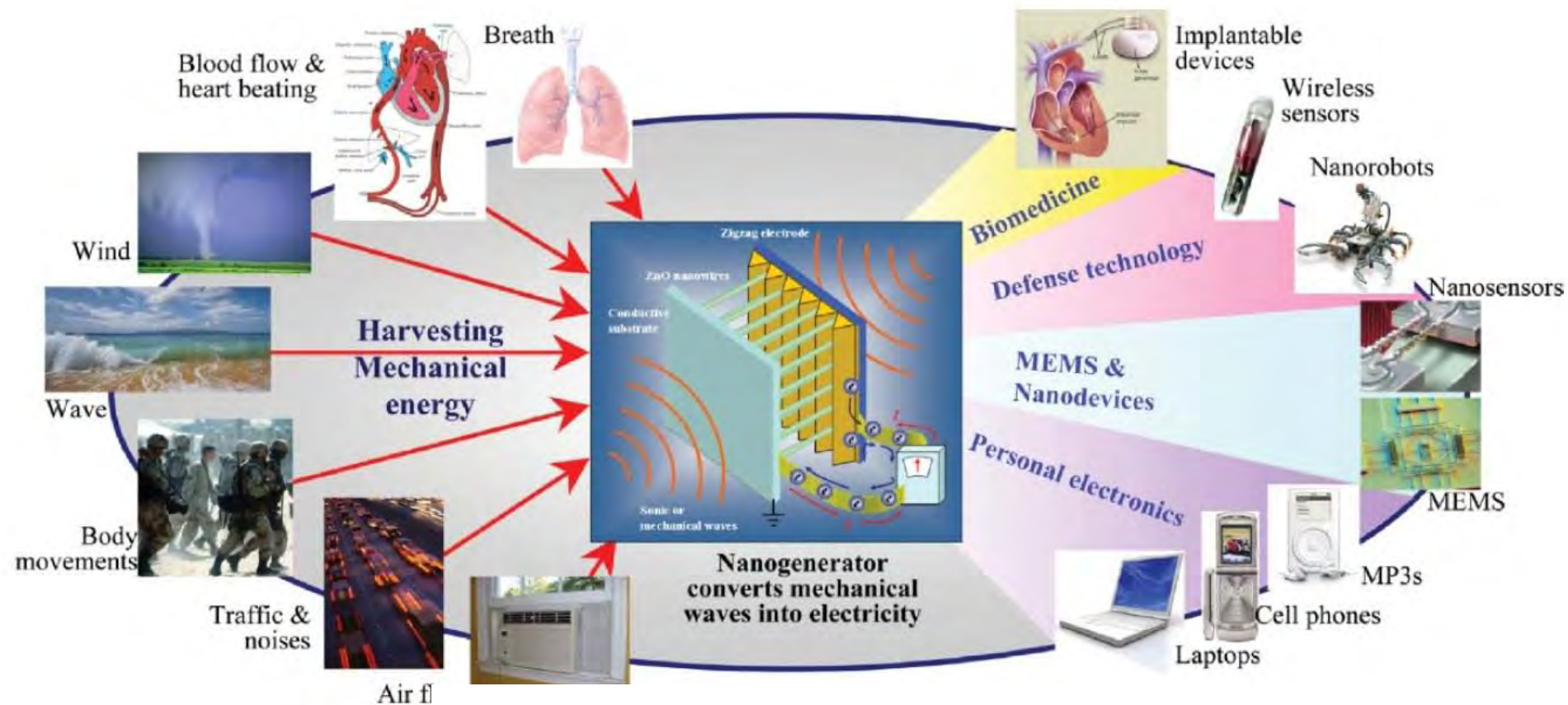
Environmentally responsive

Energy storage devices

Semiconductors, molecular electronics

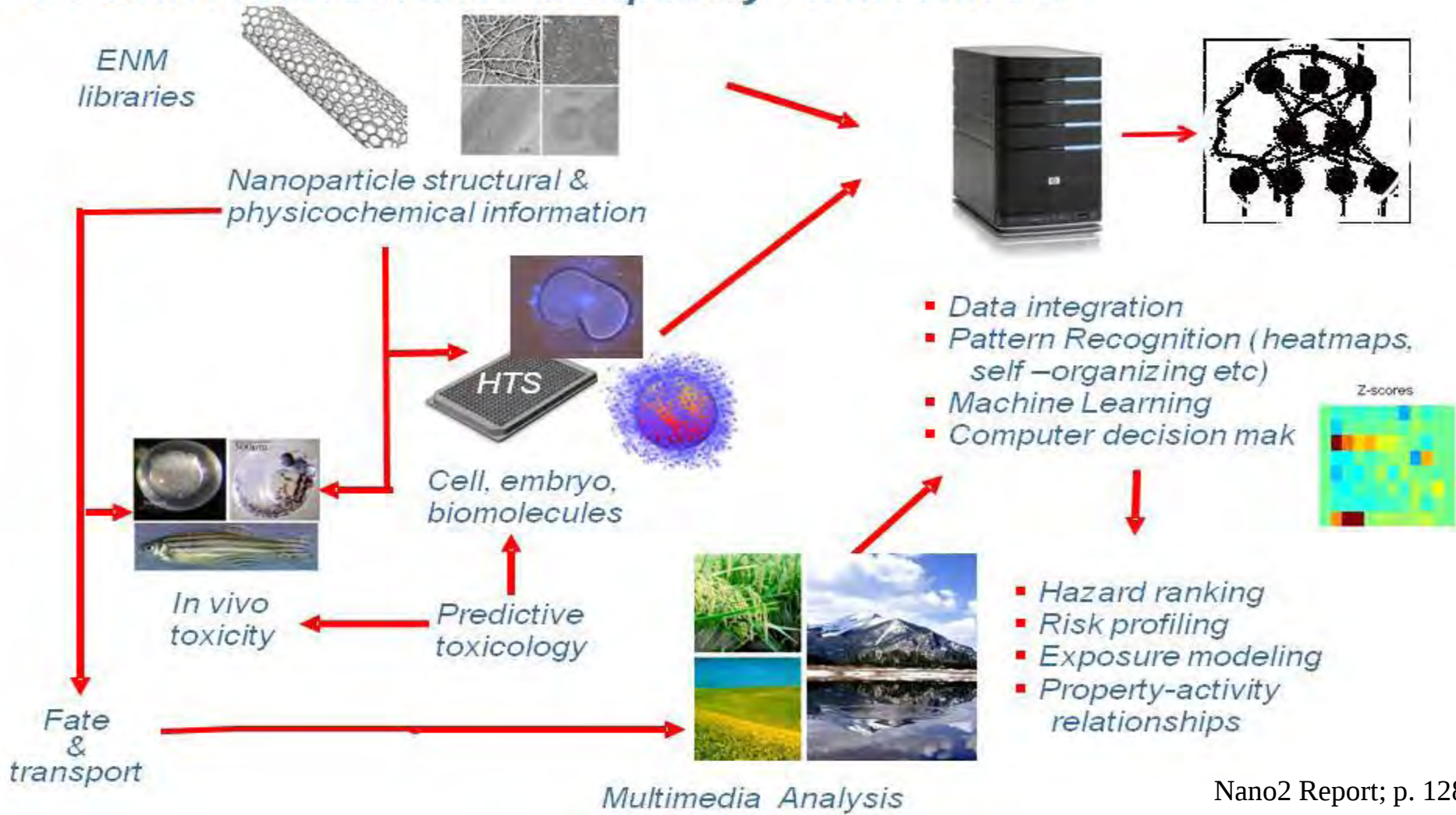
4. Ex: Self-powered nanosystems

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

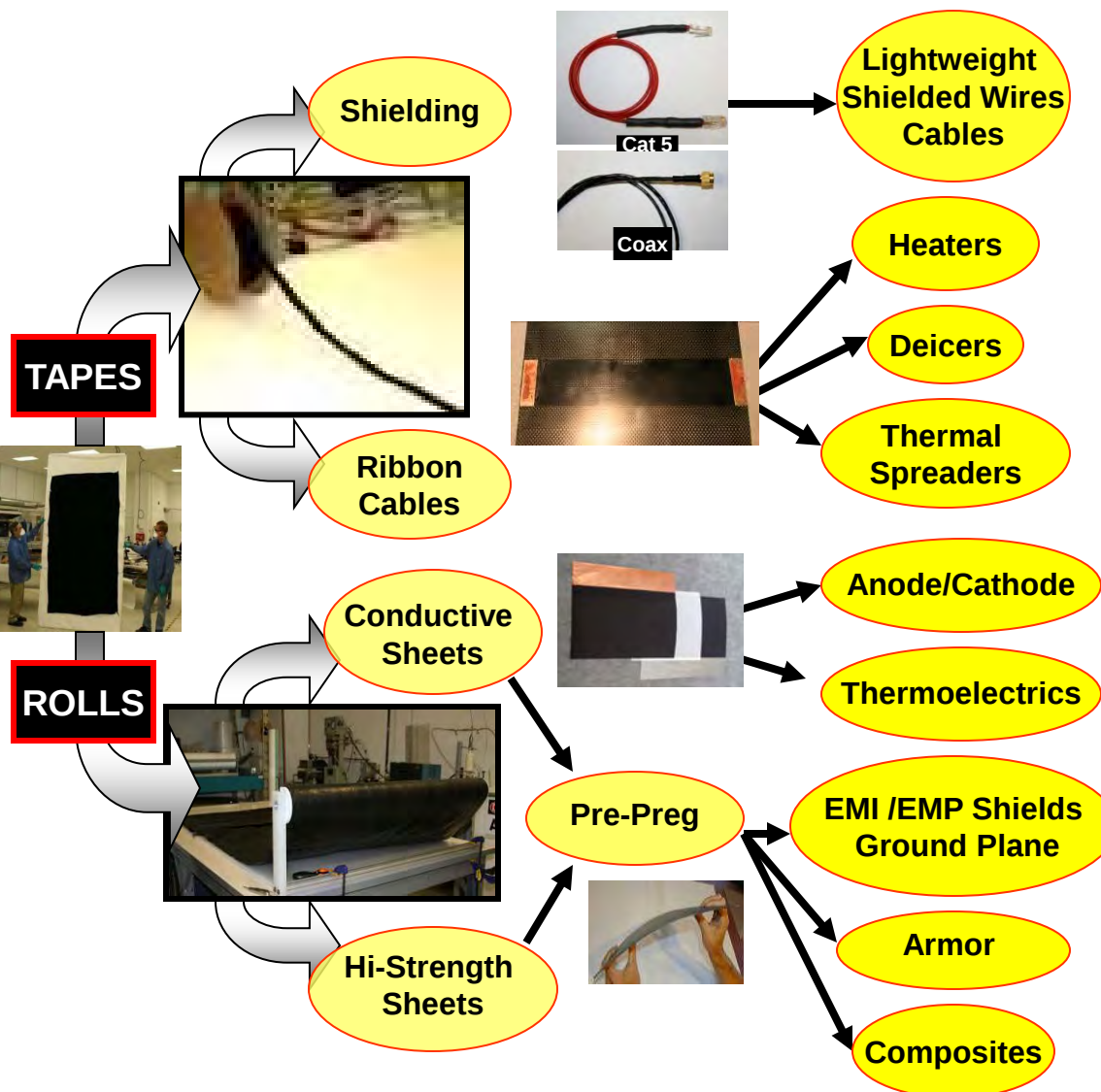


UC CEIN predictive model for hazard ranking and risk profiling

UC CEIN Predictive Multi-disciplinary Science Model



Expanded CNT sheet production with broad impact



Commercial and Defense Impact Multi-Industry Use



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

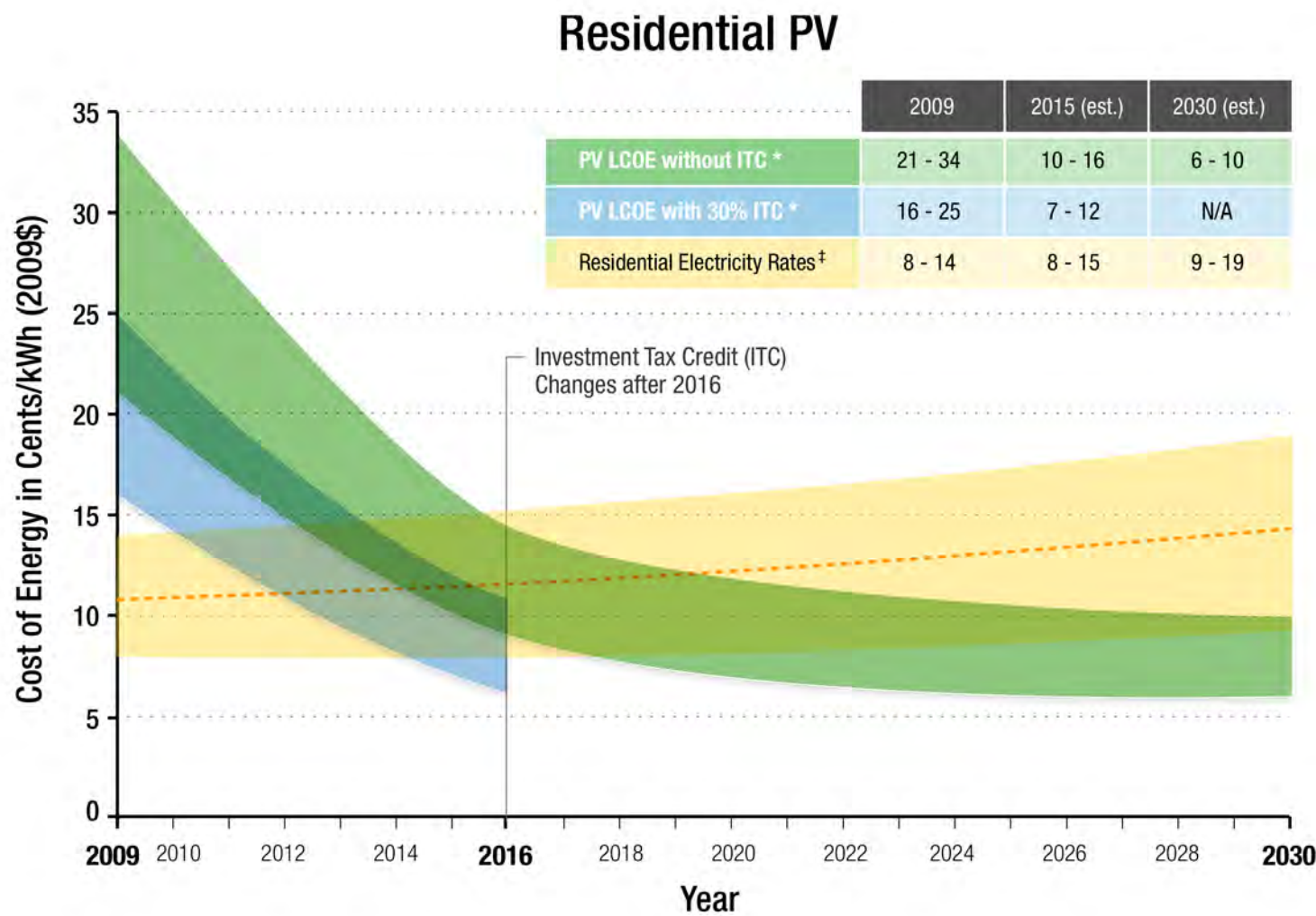
Design by NASA and MIT for a 354 passenger commercial aircraft that would be available for commercial use in 2030-2035 and would enable a reduction in aircraft fuel consumption by 54% over a Boeing 777 baseline aircraft

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)



Courtesy DOE, 2010

2010-2020: Key areas of emphasis

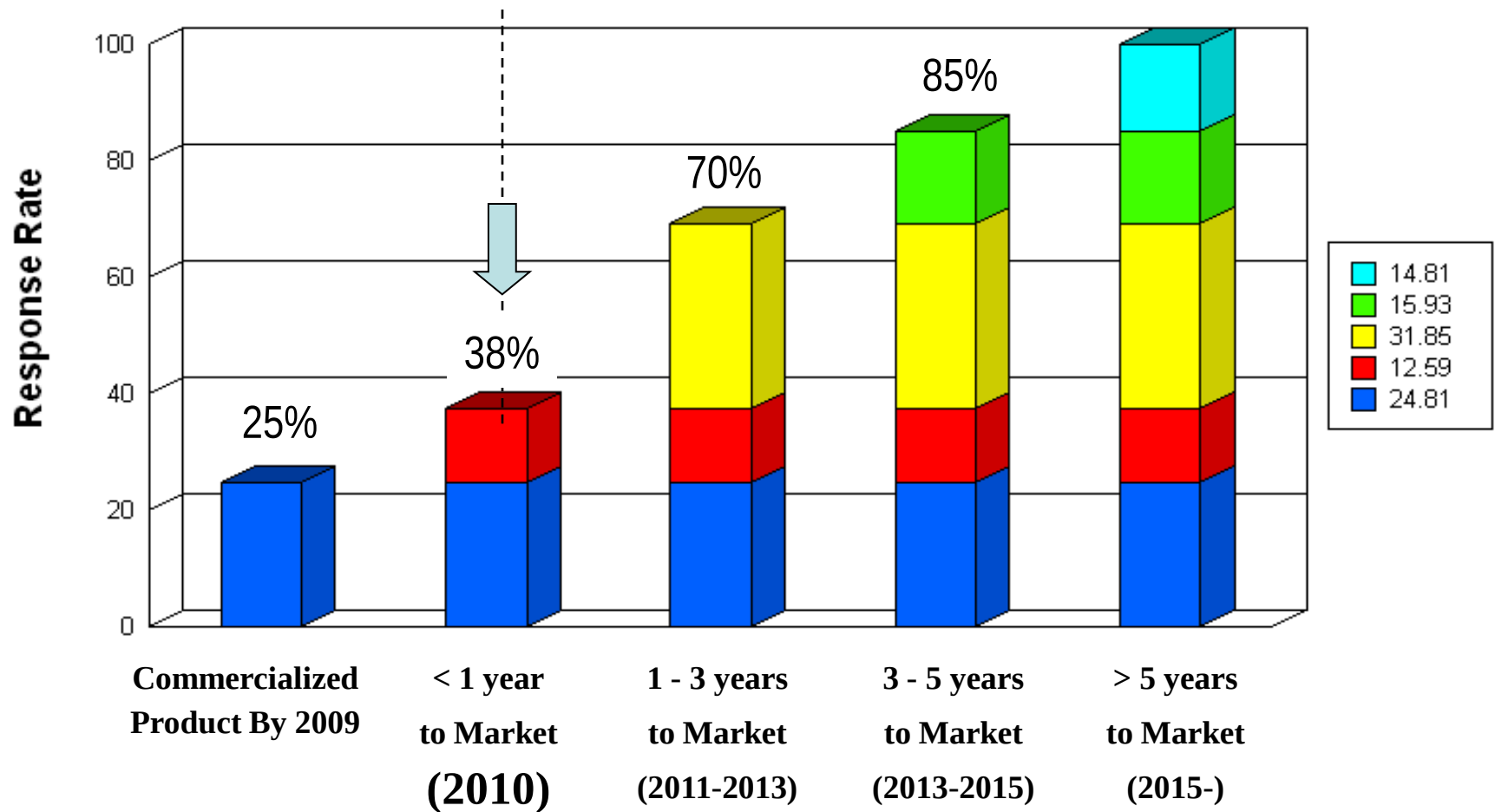
- Integration of knowledge at the nanoscale and of nanocomponents in nanosystems, aiming toward creating fundamentally new products
- Better experimental and simulation control of molecular self-assembly, quantum behavior, creation of new molecules, and interaction of nanostructures with external fields 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

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

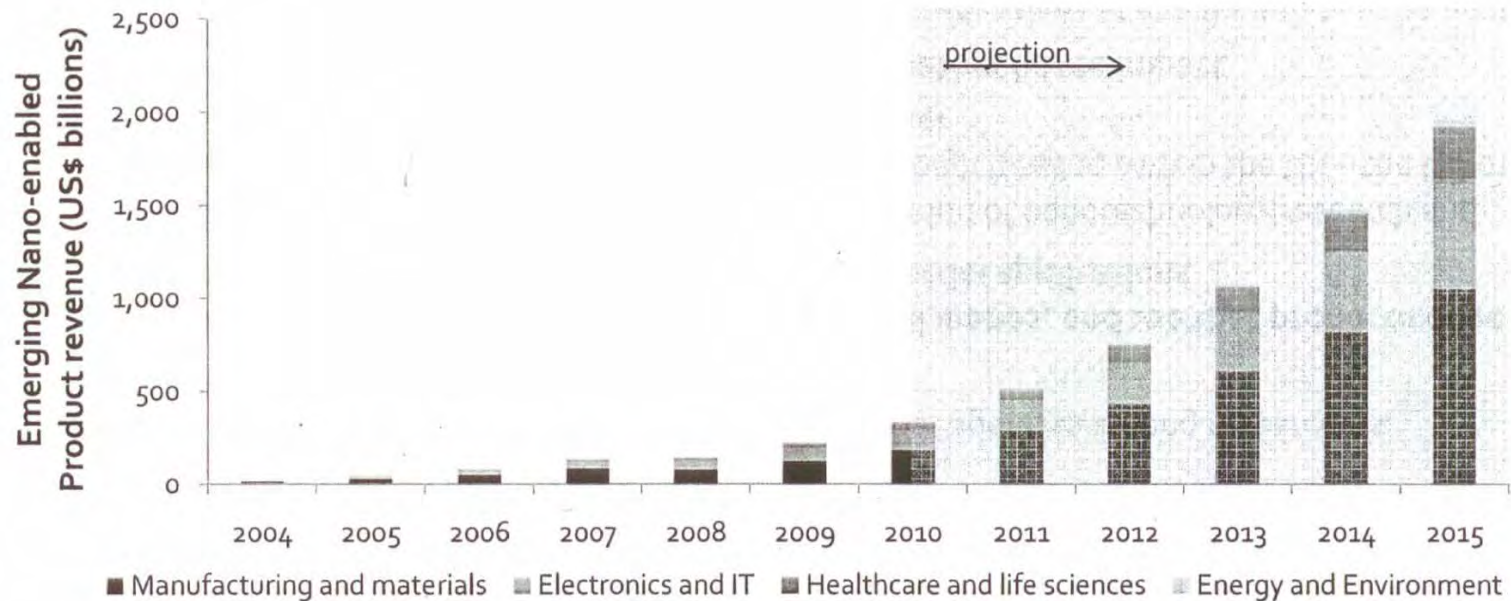
A shift to new nano enabled commercial products after 2010

Survey of 270 manufacturing companies



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

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

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”**