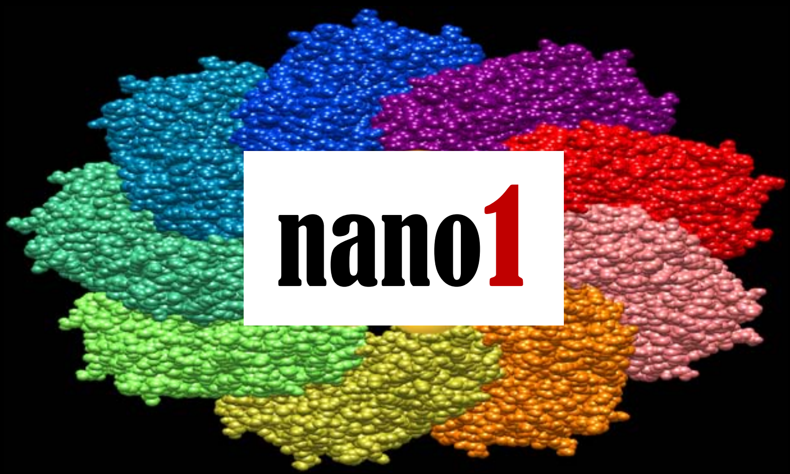
2000



2010

2020

Nanotechnology Research Directions to 2020: *Sustainable Nanomanufacturing*

Mike Roco
National Science Foundation and National Nanotechnology Initiative

AVS Conference, Nashville, October 31, 2011

Benchmark with experts in over 20 countries

"Nanostructure Science and Technology"

Book Springer, 1999

Nanotechnology

is creation of materials, devices and systems
by *control and restructuring of matter* **at dimensions of roughly 1 to 100 nanometers**,

⇒ at the transition from individual to collective behavior of atoms and molecules

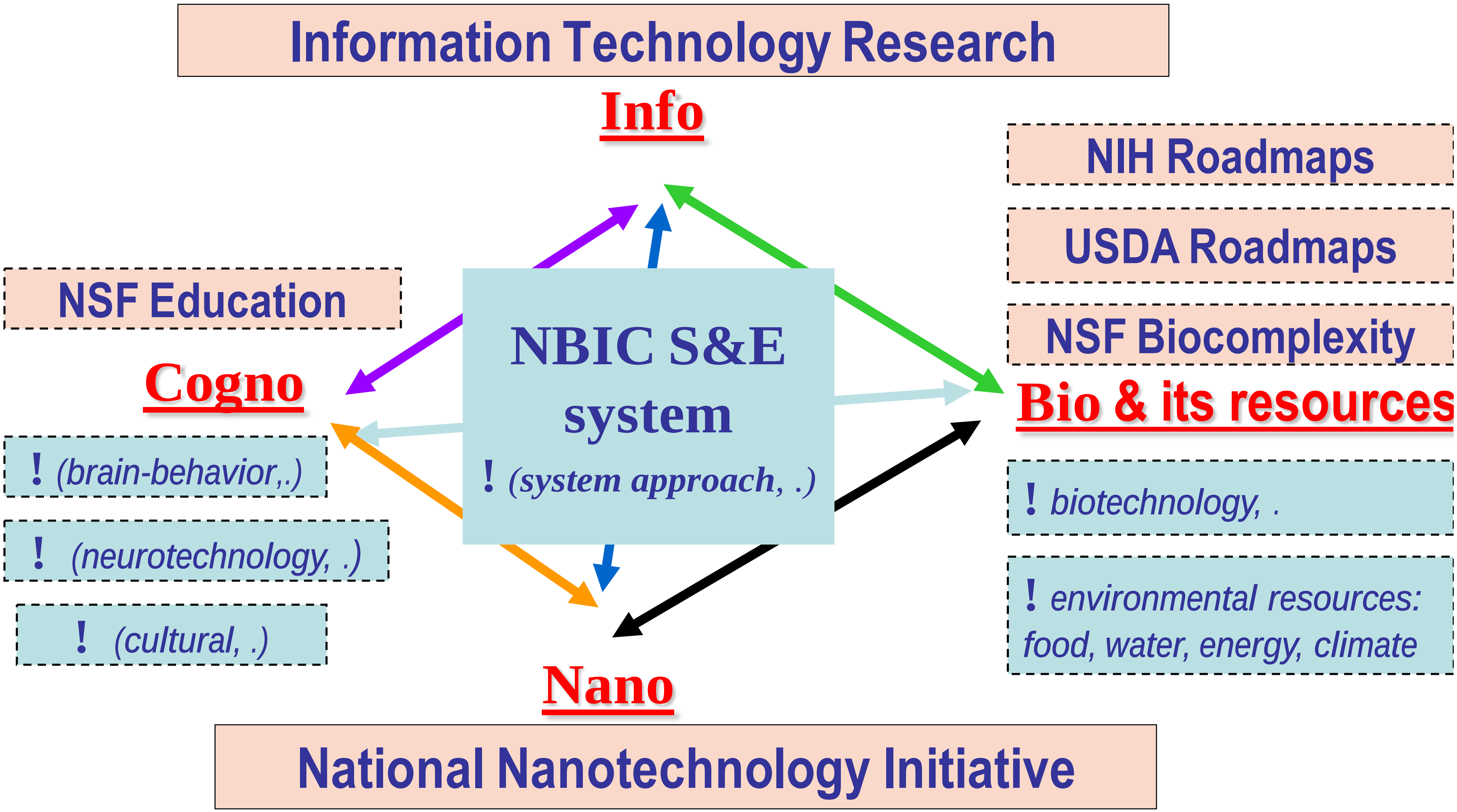
⇒ where new phenomena

⇒ enable new applications

Converging New Technologies transforming tools

("push"/ "pull" balance in U.S. 2000 - 2010)

	R&D		Broad Use
IT	1960	-	2000
BIO	1980	-	2010
NANO	2000	-	2020
NBIC	2010	-	2030



Five studies on convergence

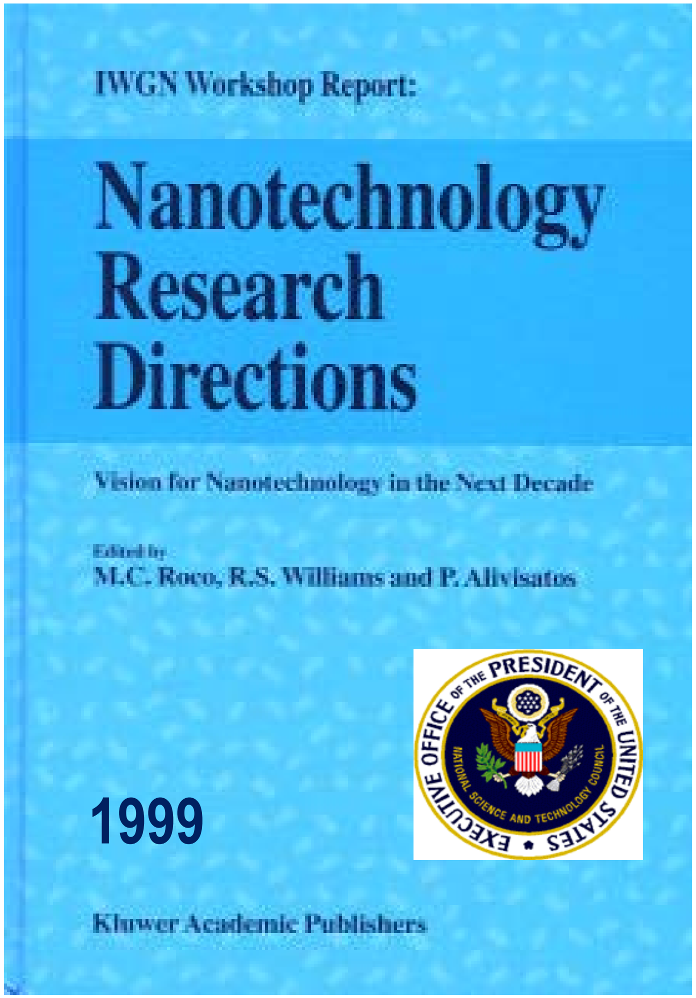
2003, 2006 and 2007 Springer; 2004 NYAS;
NSF 2004 (Organizations and Business)

NSF workshop, 2001
www.nsf.gov/nano
In Springer, 2003

November 2006

Long-term nanotechnology research directions (2000-2020)

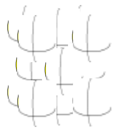
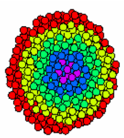
Nano1 (2000-2010) **nano2** (2010-2020)



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

TIMELINE FOR BEGINNING OF INDUSTRIAL PROTOTYPING AND NANOTECHNOLOGY COMMERCIALISATION:
FOUR GENERATIONS OF PRODUCTS AND PRODUCTION PROCESSES

Complexity and integration

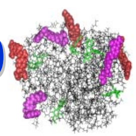
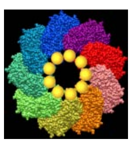



1st: Passive nanostructures (1st generation products)

a. *Dispersed and contact nanostructures* Ex: aerosols, colloids

b. *Products incorporating nanostructures* Ex: coatings; nanoparticle reinforced composites; nanostructured metals, polymers, ceramics

~ 2000

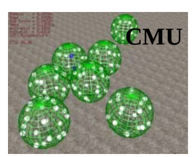



2nd: Active nanostructures

a. *Bio-active, health effects* Ex: targeted drugs, biodevices

b. *Physico-chemical active* Ex: 3D transistors, amplifiers, actuators, adaptive structures

~ 2005



3rd: Systems of nanosystems

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

~ 2010

4th: Molecular nanosystems

Ex: molecular devices 'by design', atomic design, emerging functions

~ 2015-2020

Converging technologies

Frame 1

Risk Governance Frame 2

Higher uncertainty & risk

MC Roco, Oct 31 2011

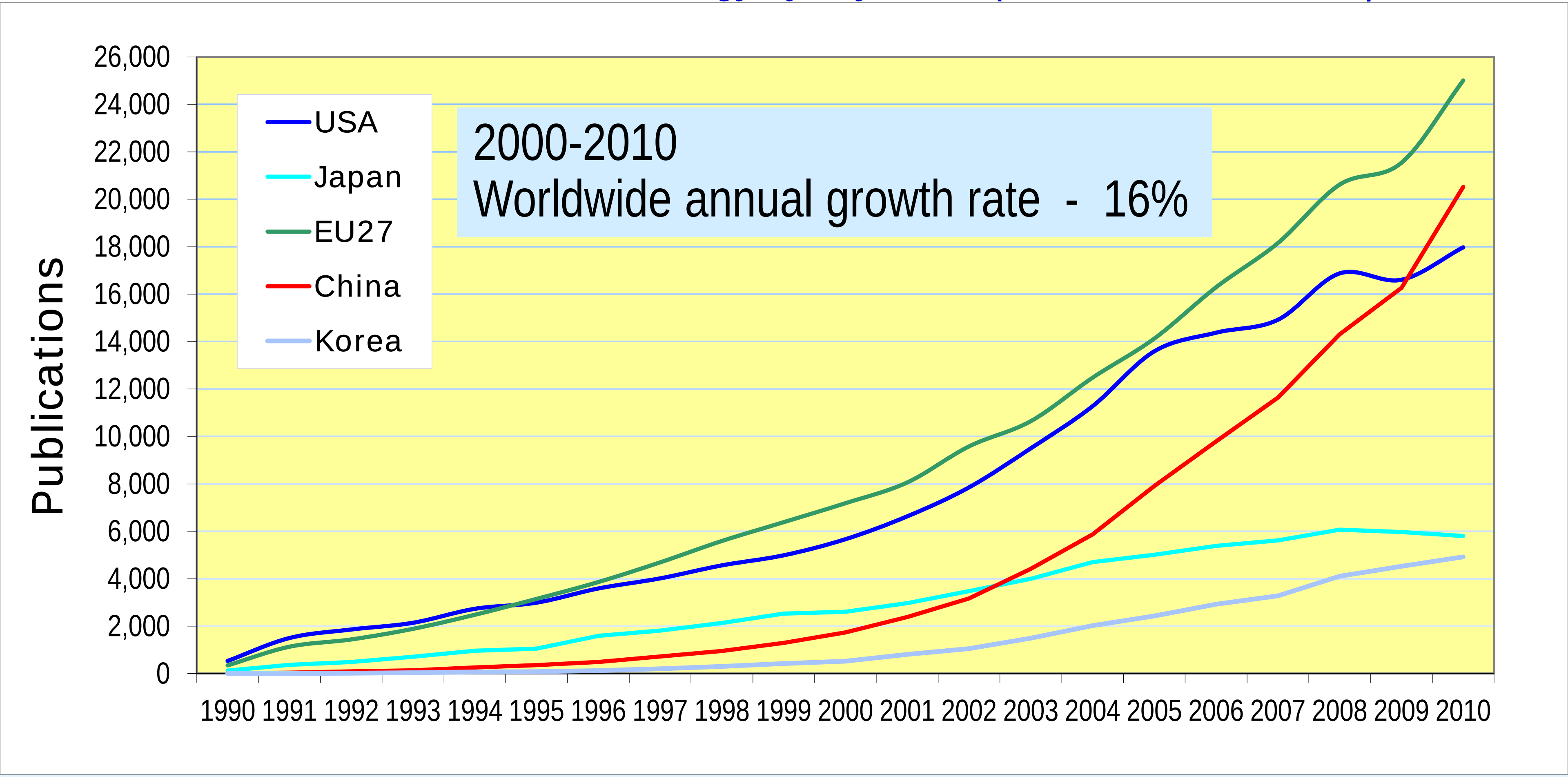
2000-2010
Estimates show an average growth rate of key nanotechnology indicators of 16% - 33%

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

MC Roco, Oct 31 2011

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

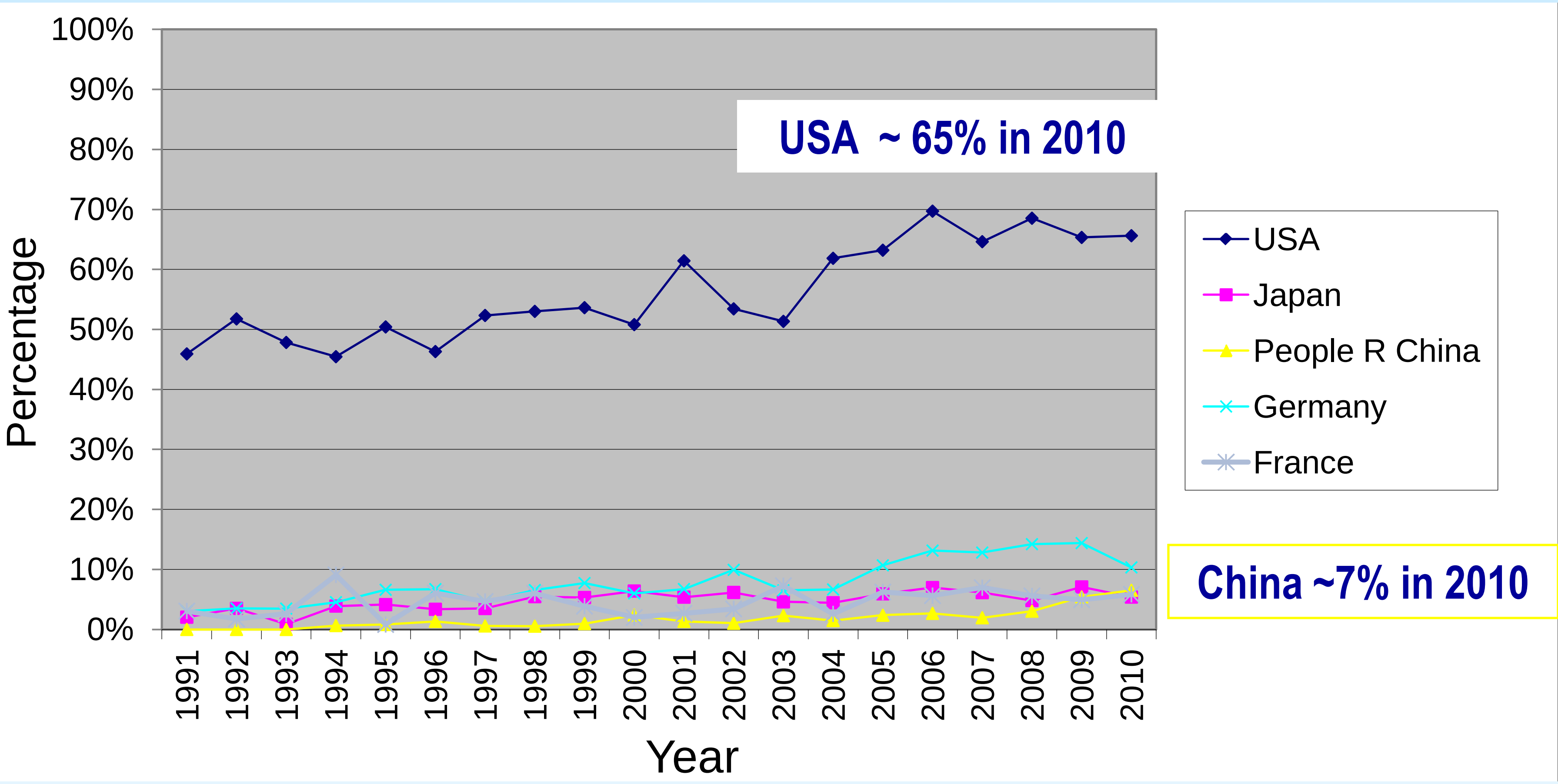
Data was generated from online search in Web of Science using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen and Roco, 2011)



Rapid, uneven growth per countries

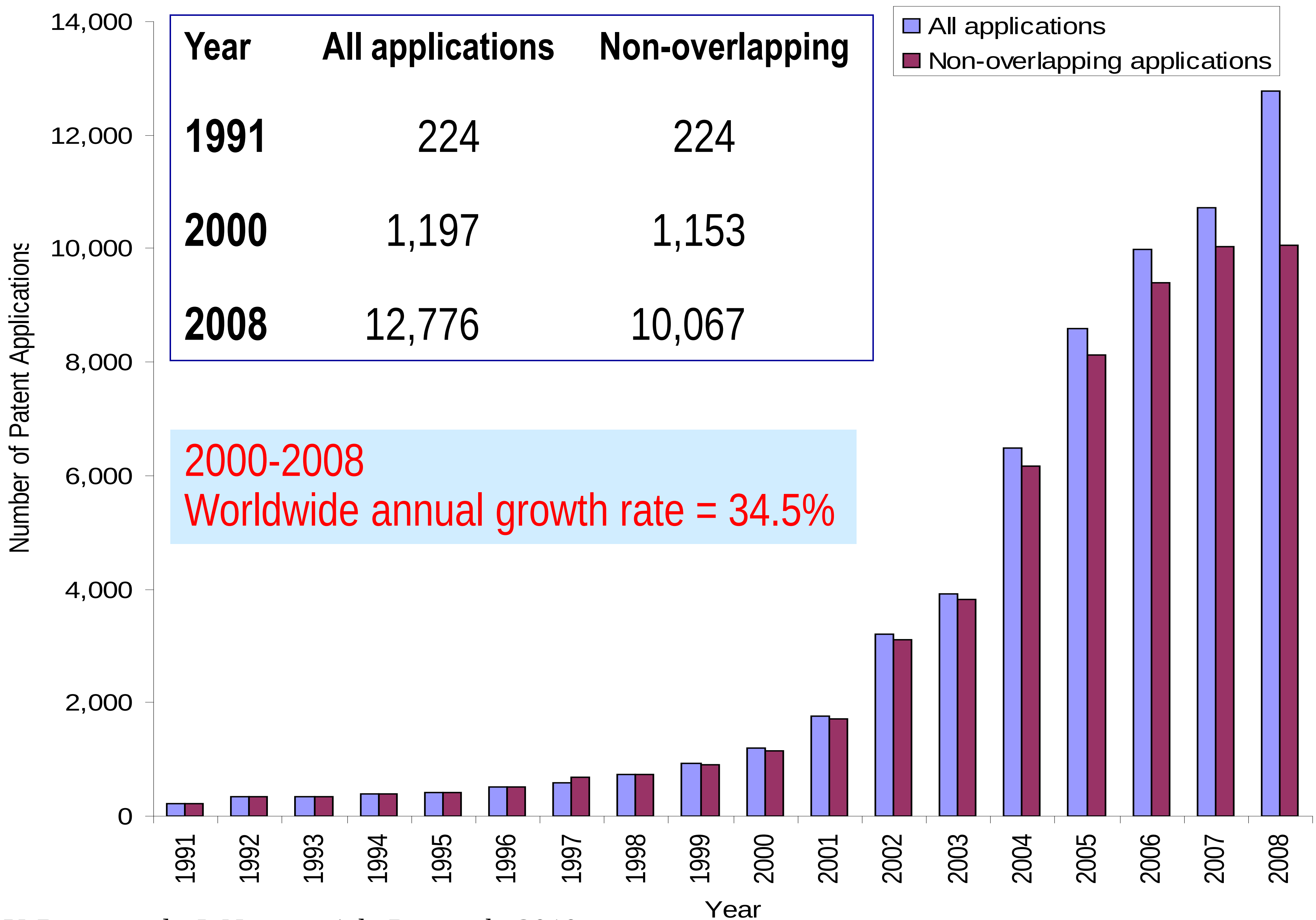
Percent contribution by country to nanotechnology publications in Science, Nature, and Proc. NAS

Title-abstract search (Chen and Roco, 2011)



U.S. maintain the lead in highly cited publications

WORLDWIDE NUMBER OF NANOTECHNOLOGY PATENT APPLICATIONS



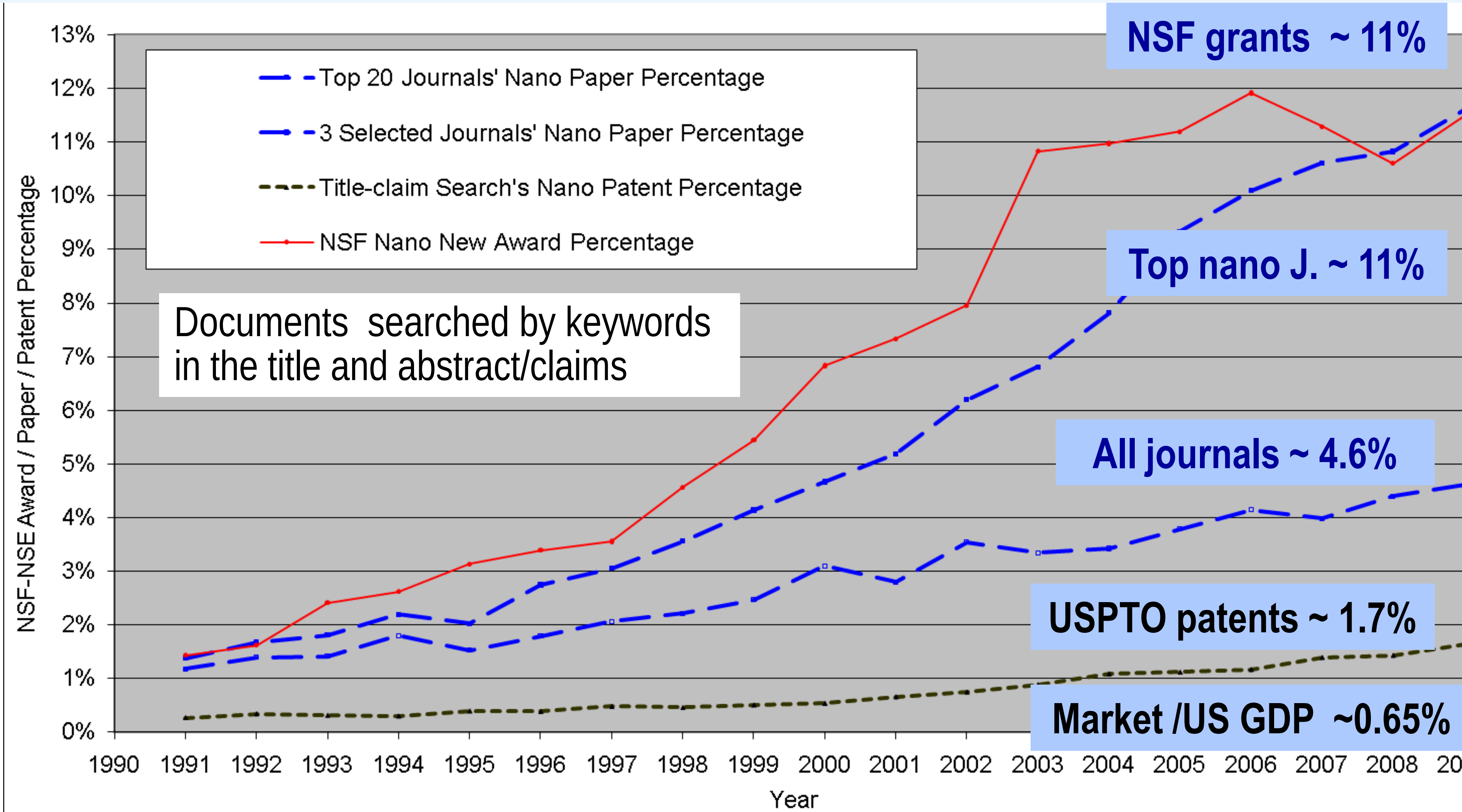
Year	All applications	Non-overlapping
1991	224	224
2000	1,197	1,153
2008	12,776	10,067

2000-2008
Worldwide annual growth rate = 34.5%

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

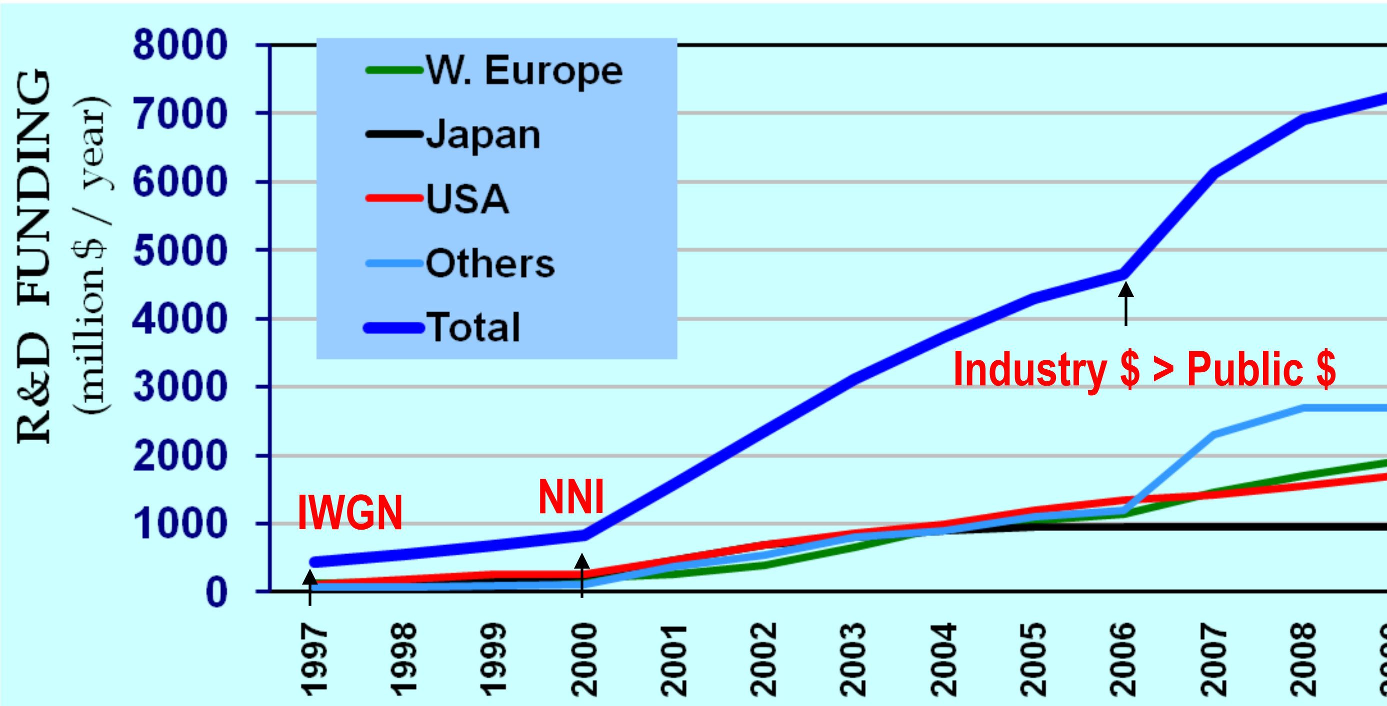
MC Roco, Oct 31 2011

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



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

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

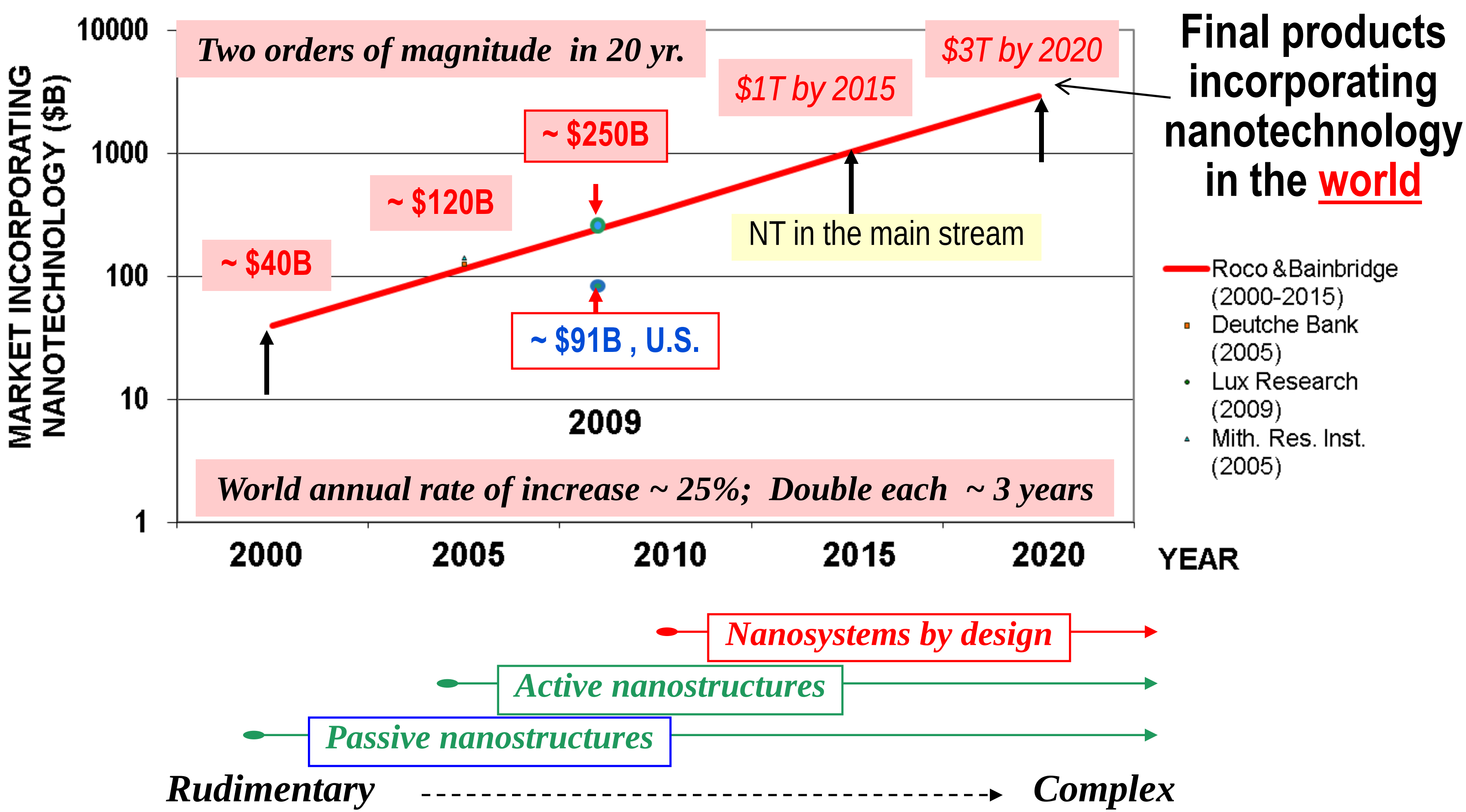
3rd Generation nanosystems

Rapid, uneven growth per countries

MC Roco, Oct 31 2011

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

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



Reference: Roco and Bainbridge, Springer, 2001

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

2001-2010

RE ~10,900 awards

by NSF's Principal Investigators

(patents searched by "title-claims" keywords at USPTO; examples)

Interval	2001-2010	NSF supported investigators with most patents - NNI at 10 years -	
Rank	Name NSF P.I.	Institution	# USPTO Patents (keyword search)
1	**Chad A. Mirkin**	Northwestern University	74
2	**Richard E. Smalley**	Rice University	70
3	**Bin Yu**	University of Albany	55
4	**Stephen R. Quake**	Stanford University	48
5	**Mark E. Thompson**	University of Southern California	43
6	**Moungi G. Bawendi**	Massachusetts Institute of Technology	42
7	**Andrew G. Rinzler**	University of Florida	40
8	**Ping Liu**	University of Texas at Arlington	37
9	**Joseph M. Jacobson**	Massachusetts Institute of Technology	36
10	**George M. Whitesides**	Harvard University	33
11	**Axel Scherer**	California Institute of Technology	31
12	**Thomas J. Pinnavaia**	Michigan State University	26
13	**Tobin J. Marks**	Northwestern University	23
14	**Charles M. Lieber**	Harvard University	23
15	**Nathan S. Lewis**	California Institute of Technology	22
16	**Hongjie Dai**	Stanford University	22
17	**Kerry J. Vahala**	California Institute of Technology	20
18	**Thomas W. Kenny**	Stanford University	20
19	**Michael N. Kozicki**	Arizona State University	19
20	**Tsu-Jae King**	University of California at Berkeley	19
21	**Robert Langer**	Massachusetts Institute of Technology	18
22	**Michael L. Simpson**	University of Tennessee	18
23	**Michael L. Roukes**	California Institute of Technology	17
24	**Jackie Y. Ying**	Massachusetts Institute of Technology	17
25	**Ting Guo**	University of California at Davis	16
26	**Stephen C. Minne**	Stanford University	15
27	**Nicholas L. Abbott**	University of Wisconsin-Madison	15
28	**Eric V. Anslyn**	University of Texas at Austin	14
29	**R. Stanley Williams**	HP	14
30	**Kenneth J. Klabunde**	Kansas State University	14
31	**Samuel I. Stupp**	Northwestern University	14

BRIC (country group) and China – largest growth rates in the last decade

- "**Nanotechnology Research Directions for Societal Needs in 2020**" (Roco, Mirkin and Hersam), 2010 (BRIC and China in the global context)
- "**Trends for Nanotechnology Development in China, Russia and India** " (Liu et al.), J. Nanoparticle Research, 2009, 1845-1866 (trends for papers and patents)
- "**Investor Status and Knowledge Diffusion in Nanotechnology: China, Russia and India**" (Liu et al.)J. of Am. Soc. for Information S&T, 2011, 1166-1176 (trends for innovation and networking)
- China's nano papers amount to **15% of its published research output** (Small, M. Grieneisen and M. Zhang, 2011)

Ten highly promising products incorporating nanotechnology in 2010

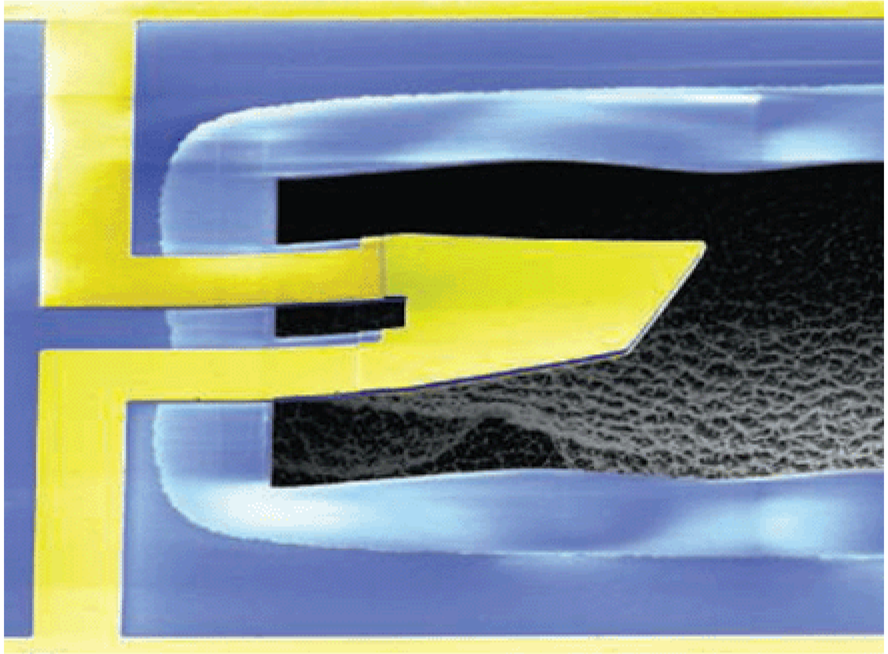
- Catalysts
- Transistors and memory devices
- Structural applications (coatings, hard materials, cmp)
- Biomedical applications (detection, implants,.)
- Treating cancer and chronic diseases
- Energy storage (batteries), conversion and utilization
- Water filtration
- Video displays
- Optical lithography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

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

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

The First Quantum Machine

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

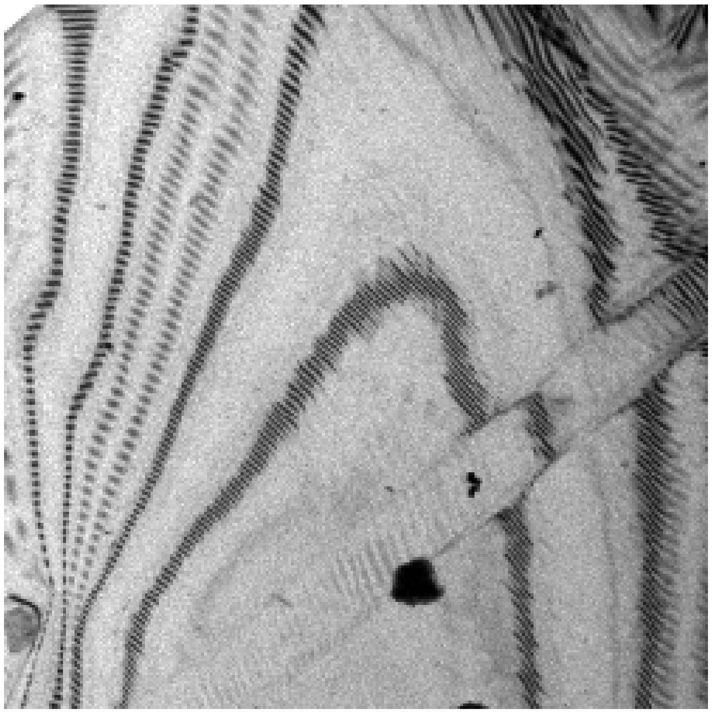


The simplest quantum states of motion with a vibrating device was measured (the board of aluminum is as long as a hair is wide)

Aaron O'Connell and Andrew Cleland, UCSB, 2010

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/

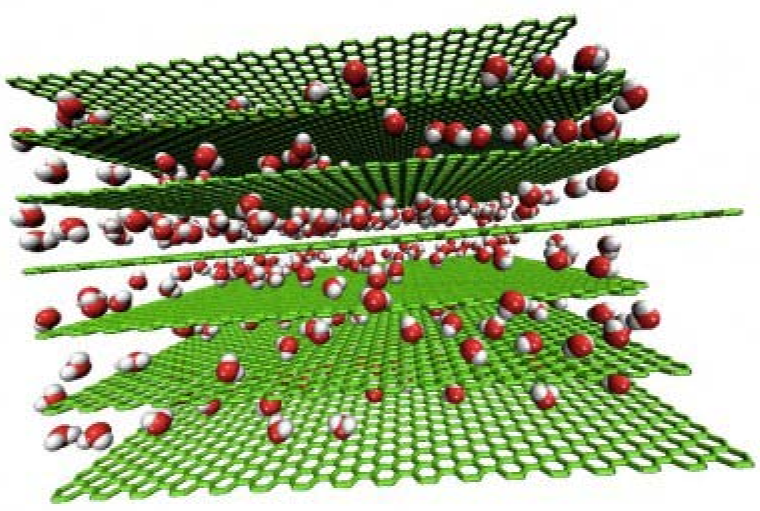
Use of ultra short laser flashes to observe fundamental motion and chemical reactions in real-time (timescale of a femtosecond, 10^{-15}s), with 3D real-space atomic resolution.

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

Graphite + water = the future of energy storage

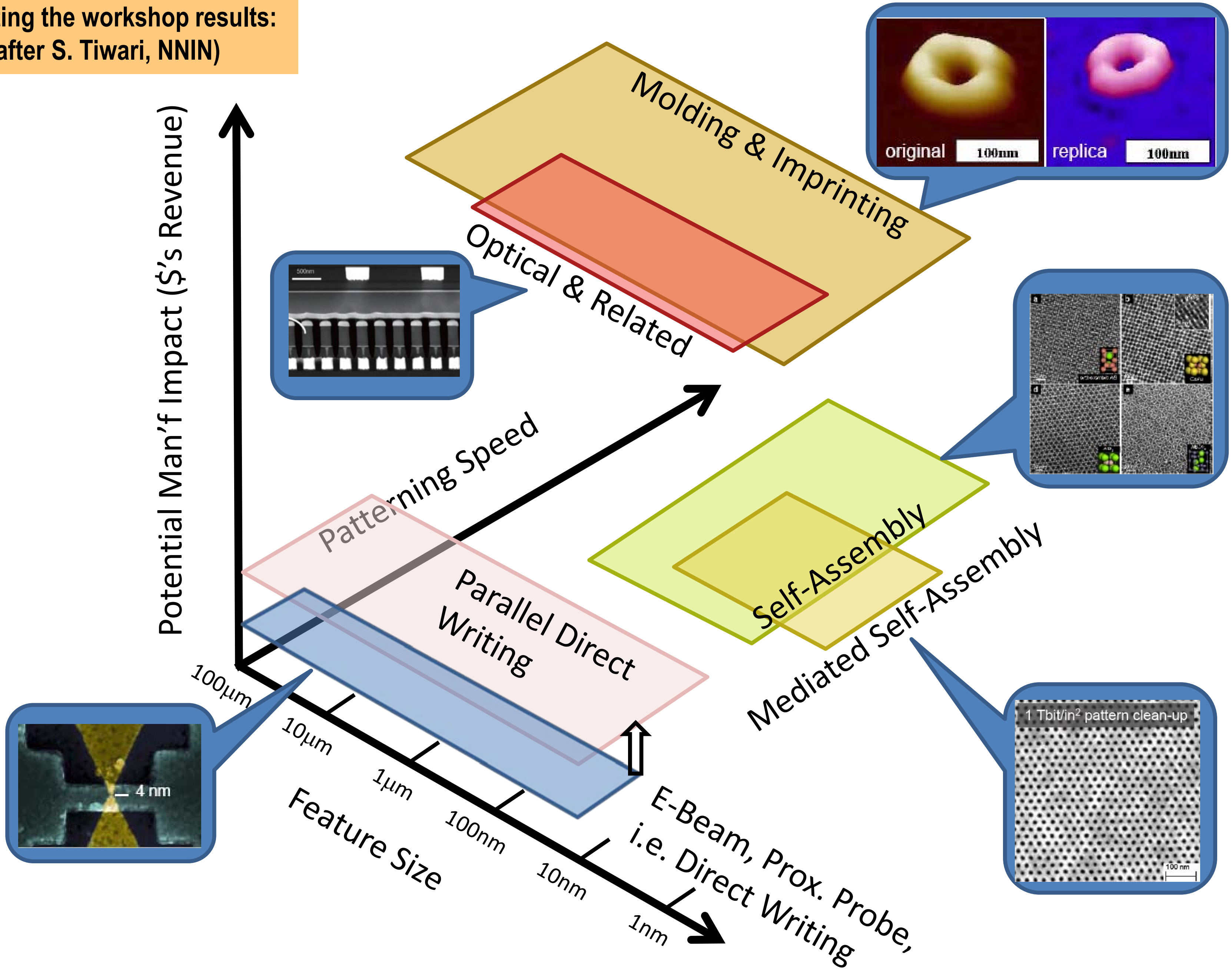
Monash University, July 2011

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



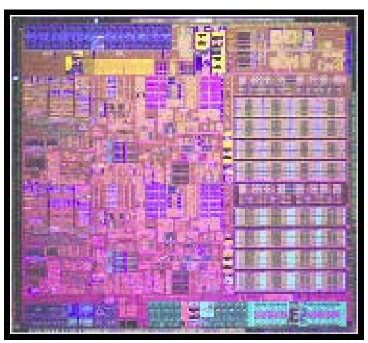
Graphene sheets. Credit: Gengping Jiang

Model for reporting the workshop results: synthetic view (after S. Tiwari, NNIN)

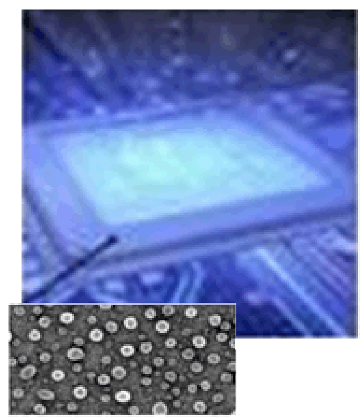


Nanopatterning on surfaces

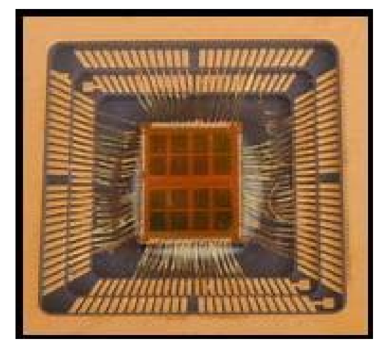
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



32 nm CMOS processor technology by Intel (2009)

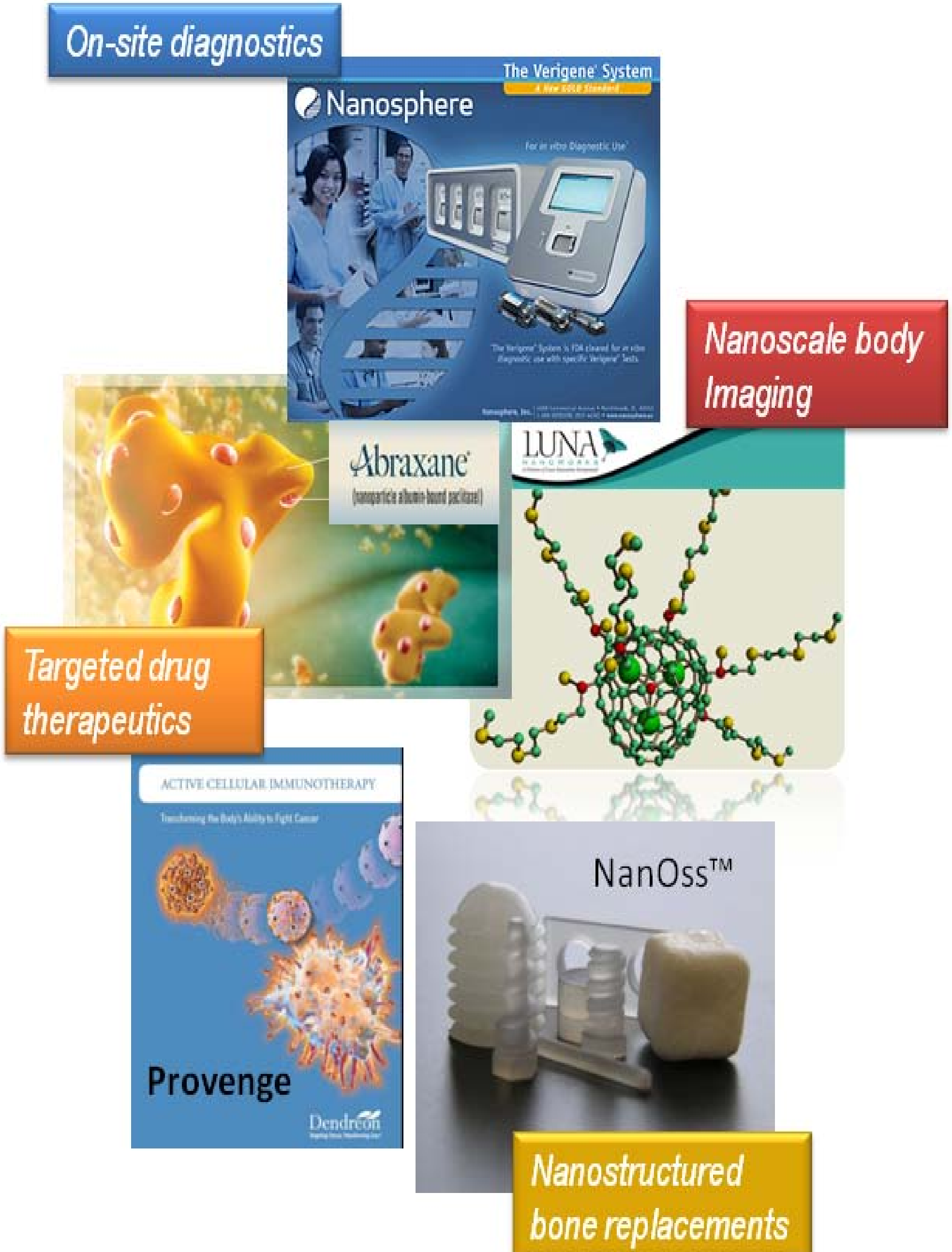


90 nm thin-film storage (TFS) flash flexmemory by Freescale (2010)



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

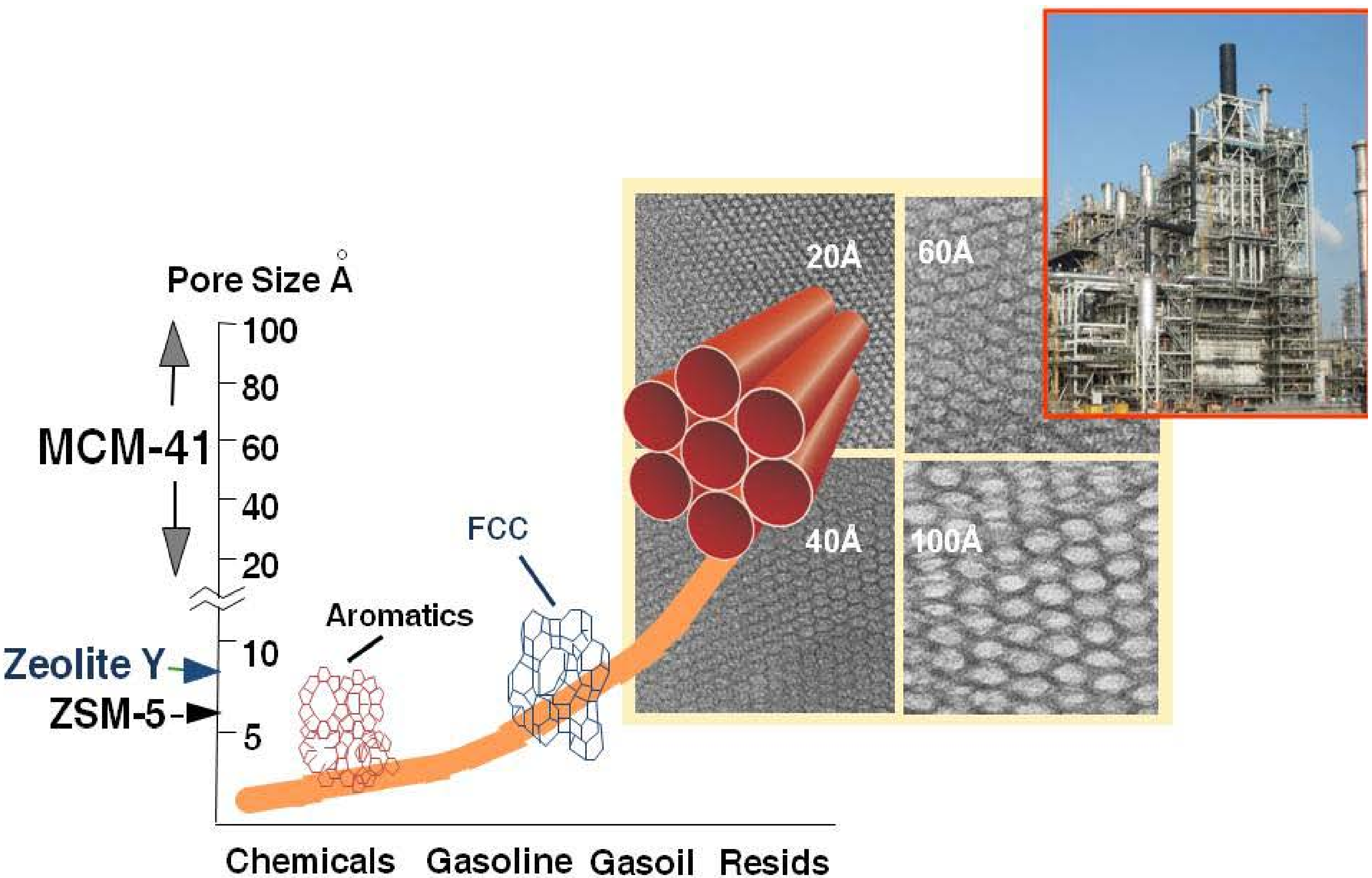
Nano2 Report, 2010, p. XII



Nano2 Report, 2010, p. XIV

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

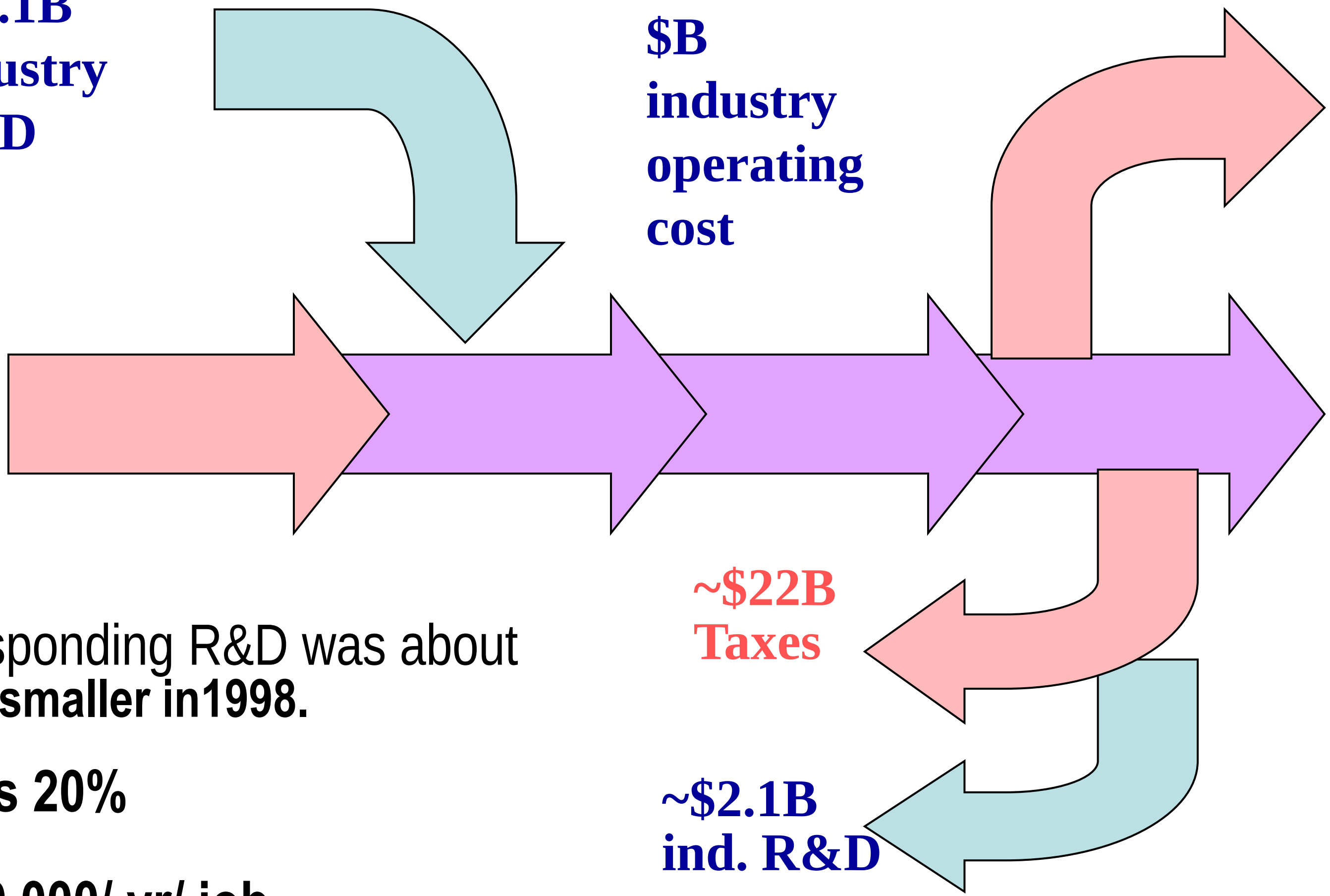
Examples of nanotechnology in commercial catalysis products for applications in oil refining, in production in 2010



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

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**

Examples of Penetration of Nanotechnology in Several Industrial Sectors

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

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

Nano2 Report, 2010, p. XXXVI

2000-2010: Sustainable Development

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

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

Manufacturing: **Transforming raw materials into products with desired properties and performance – generally in large quantities**

Defining Nanomanufacturing (1) :

Aims at building material structures, components, devices/ machines, and systems with nanoscale features in one, two and three dimensions. It includes

- **bottom-up directed assembling** of nanostructure building blocks (from the atomic, molecular, supramolecular levels),
- **top-down high-resolution processing** (ultraprecision engineering, fragmentation methods, positioning assembling),
- **engineering of molecules and supramolecular systems** (molecules as devices "by design", nanoscale machines, etc.),
- **hierarchical integration** with larger scale systems.

Atoms, molecules ⇨ **nanostructures** (intermediate) ⇨ **materials/ devices/ machines/ systems**

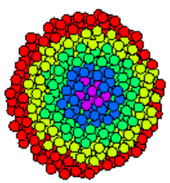
Defining Nanomanufacturing (2)

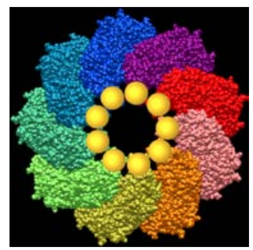
- Fragmentation
- Patterning
- Bulk restructuring
- Lithography, ..

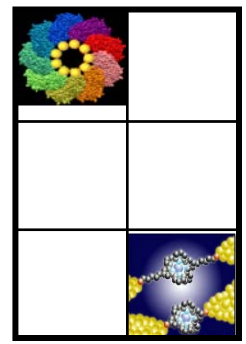
- Interfaces, field & boundary control
- Positioning parts
- Integration, ..

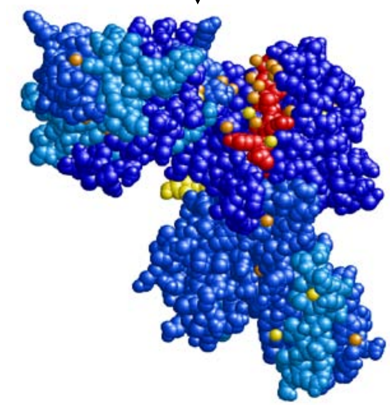
- System engineering
- Device architecture
- Integration, ..

- Nanosystem biology
- Emerging systems
- Hierarchical integration

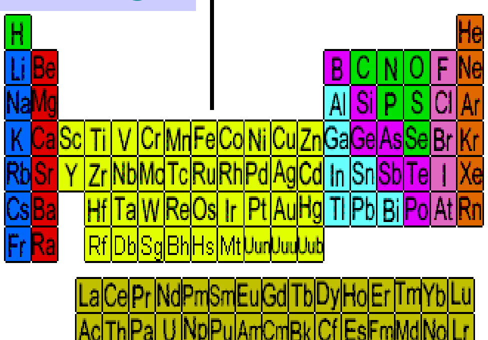








Assembling



- Directed selfassembling
- Templating
- New molecules

-Multiscale selfassembling,
- In situ process
- Fluidics ..

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

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

NANOPRODUCTS

Nanomanufacturing: typical bottom-up processes

- Controlled nucleation and growth
  - Aerosol and colloidal dispersions; deposition on surfaces
- Selfassembling
  - Natural process in living systems and biomimetics
  - Chemistry/chemical manufacturing
  - Guided by electric, magnetic, optical fields, DNA controlled ..
- Templating: Al and C nanotubes; by substrate; local reactors; . .
- Engineered molecules and molecular assemblies
  - Designed molecules as devices or for selfassembling
  - New molecular architectures by design
- Bio methods - Selectivity, selfassembling, synthetic biology, ..
- Bottom-up modular nanosystems
- Control replicating structures (ex: cellular approach)

Nanomanufacturing: other typical processes

- Lithography: optical, ultraviolet, electron-beam, SPM based (1-10 nm)
- Nano-machining
- Nano-manipulation of atoms, molecules, nanoparticles
- Fragmentation: mechanical milling, spark erosion, etc.
- Sintering of nano precursors
- Thermal treatment of metals, ceramics, composites
- Mixing of nanocomposites and their processing
- Fluidics
- Nanoscale robotics
- Bio-evolutionary approaches, ..

Nanotechnology Governance

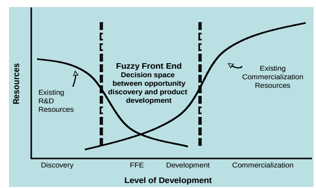
NANOTECHNOLOGY GOVERNANCE

- Investment policy
- Science policy
- Risk management
- Others . . . .

<u>Four key functions</u>:

Visionary → 1999: Outline 2000-2020
Nano1: Vision 2000-2010
Nano2: Vision 2010-2020

Transformative

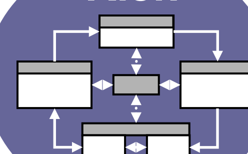


→ Invest in tools, infrastructure
Education, Innovation
Short and long term results

Responsible

Benefit society

Risk



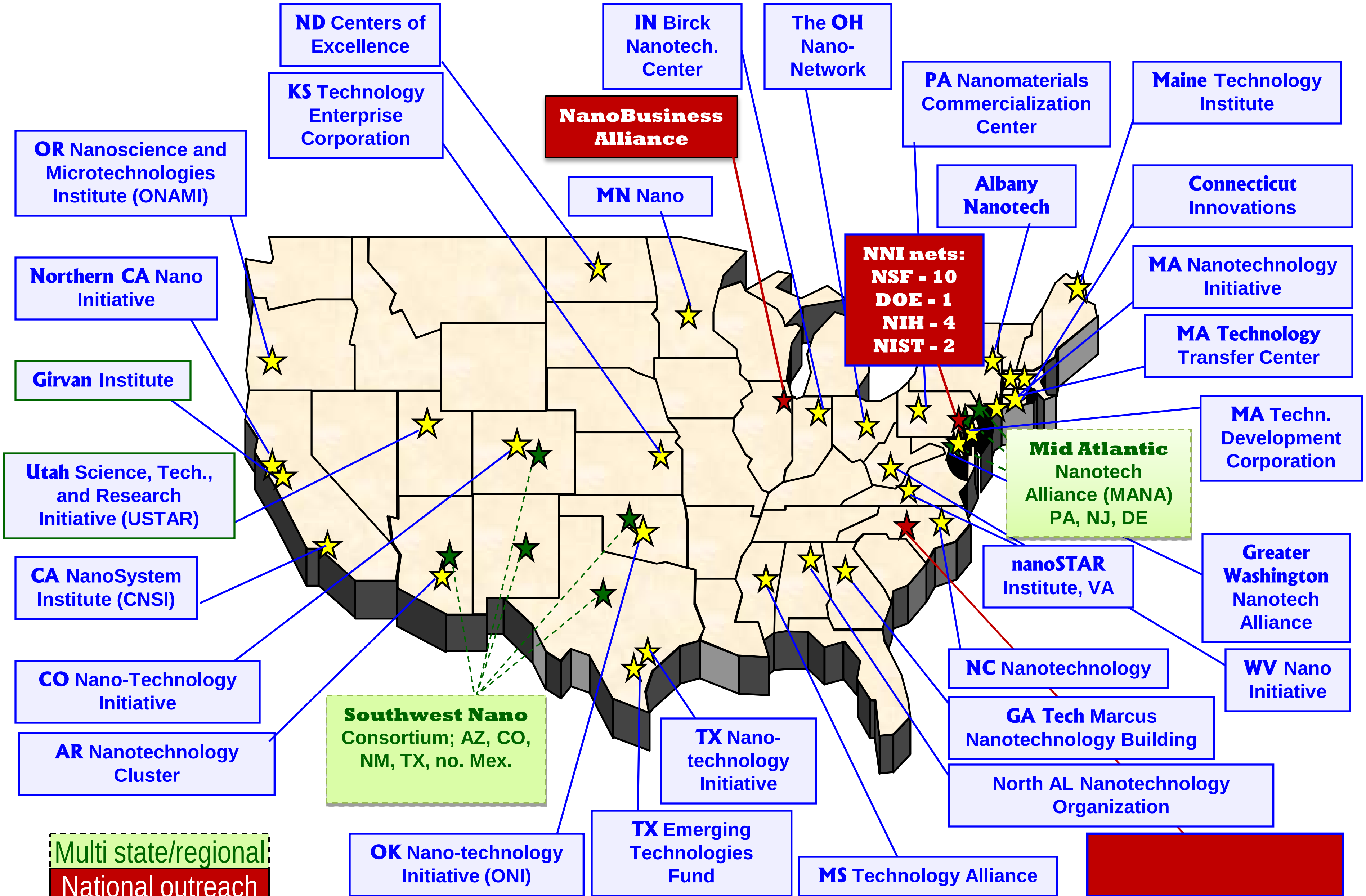
→ Risk Governance (EHS, ELSI,..)

Inclusive → Disciplines, Economy sectors,
Agencies,
International

Reference: Governance of Emerging Technologies (Roco 2008)

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

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



MC Roco, Oct 31 2011

Nanomanufacturing, Industry Liaison, and Innovation (NILI) Working Group

- **Purpose**: to advance and accelerate the creation of new products and manufacturing processes derived from discovery at the nanoscale.

- **Goals:**

1. Facilitate nanotechnology innovation, nanomanufacturing advancement, and technology transfer in and by Federal agencies

2. Exchange information and stimulate interactions relating to nanotechnology among Federal agencies, academe, industry, professional societies, and State and local organizations

3. Create innovative methods for transferring techn. to industry

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

Sustainable Nanomanufacturing

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

Nanoelectronics for 2020 and Beyond

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

Nanotechnology for Solar Energy

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

2001-
2012

Changing national investment

FY 2012 NNI Budget Request ~ $2,130 million

Fiscal Year	NNI	MANU	% MANU	
2000	$270M			
2001	$464M			
2002	$697M			
2003	$862M			
2004	$989M			
2005	$1,200M			
2006	$1,351M			
2007	$1,424M			
2008	$1,555M	$47.1M	3.01%	
2009	$1,702M	$63.9M		+ $140M (ARRA/stimulus) = $1,842M
2010	$1,912M	$84.8M		
CP 2011	$1,850M	$70.3M	3.80%	
Request 2012	$2,130M	$122.5M	5.75%	

2001-
2012

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

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

FY 2012 Budget Request $455.9M

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

Fiscal Year	NSF	MANU	% MANU
2000	$97M		
2001	$150M		
2002	$199M		
2003	$221M		
2004	$254M		
2005	$338M		
2006	$344M		
2007	$373M		
2008	$389M	$20.7M	5.30%
2009	$397M	$21.9M	
2010	$428.7M	$21.4M	
CP 2011	$412.1M	$22.4M	5.40%
Request 2012	$455.9M	$57.2M	12.60%

+ $108M (ARRA / stimulus) = $505M

NNI increase focus on nanomanufacturing Ex.: FY 2011 at NSF

- Nanomanufacturing. The FY 2011 effective investment includes an increase of about $10 million to $32.20 (8% of total NNI budget at NSF)

  - Nanomanufacturing program (2002-) ~ $9M

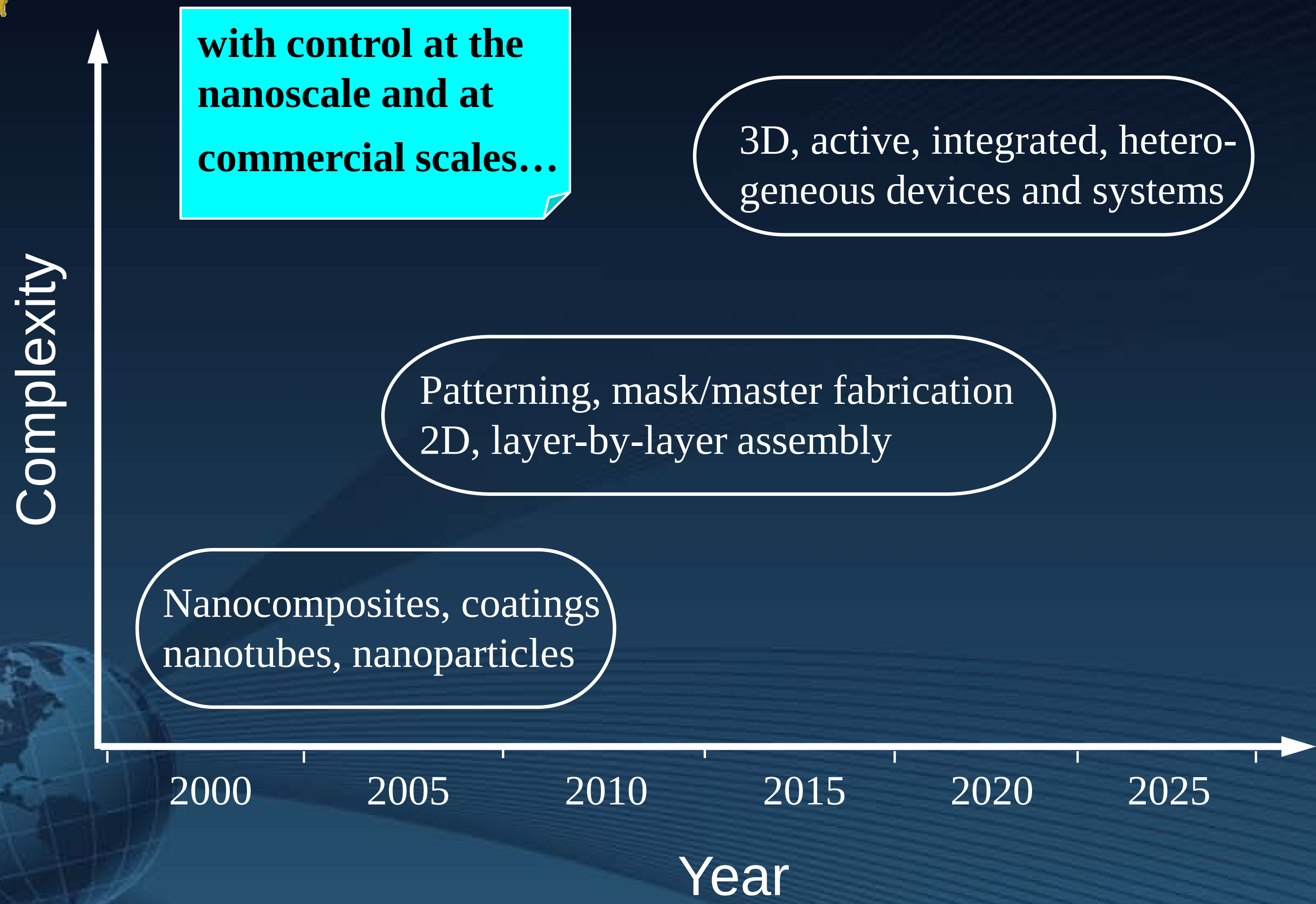
  - Signature initiative on scalable nanomanufacturing ~ $11M (interdisciplinary teams, NIRTs)

  - National Nanomanufacturing Network (2004/2005 -) composed of four Nanoscale Science and Engineering Centers ($15M, partly from nanomanufacturing program)

  - Single investigator awards , other "core" NSF programs (2001-)

  - IUCRC, GOALI, PFI , SBIR/STTR

Changing NanoManufacturing Challenges



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

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

CHM
Center for Hierarchical Manufacturing
University of Massachusetts Amherst

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

Center for High-rate Nanomanufacturing

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

SINAM
CENTER FOR SCALABLE AND INTEGRATED NANOMANUFACTURING

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

Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems

National Nanomanufacturing Network

Open-access network
www.nanomanufacturing.org

Director: Mark Tuominen
beta.internano.org

In FY 2012 Request:
a new system oriented nano centers

- **Nanosystems Engineering Research Centers**

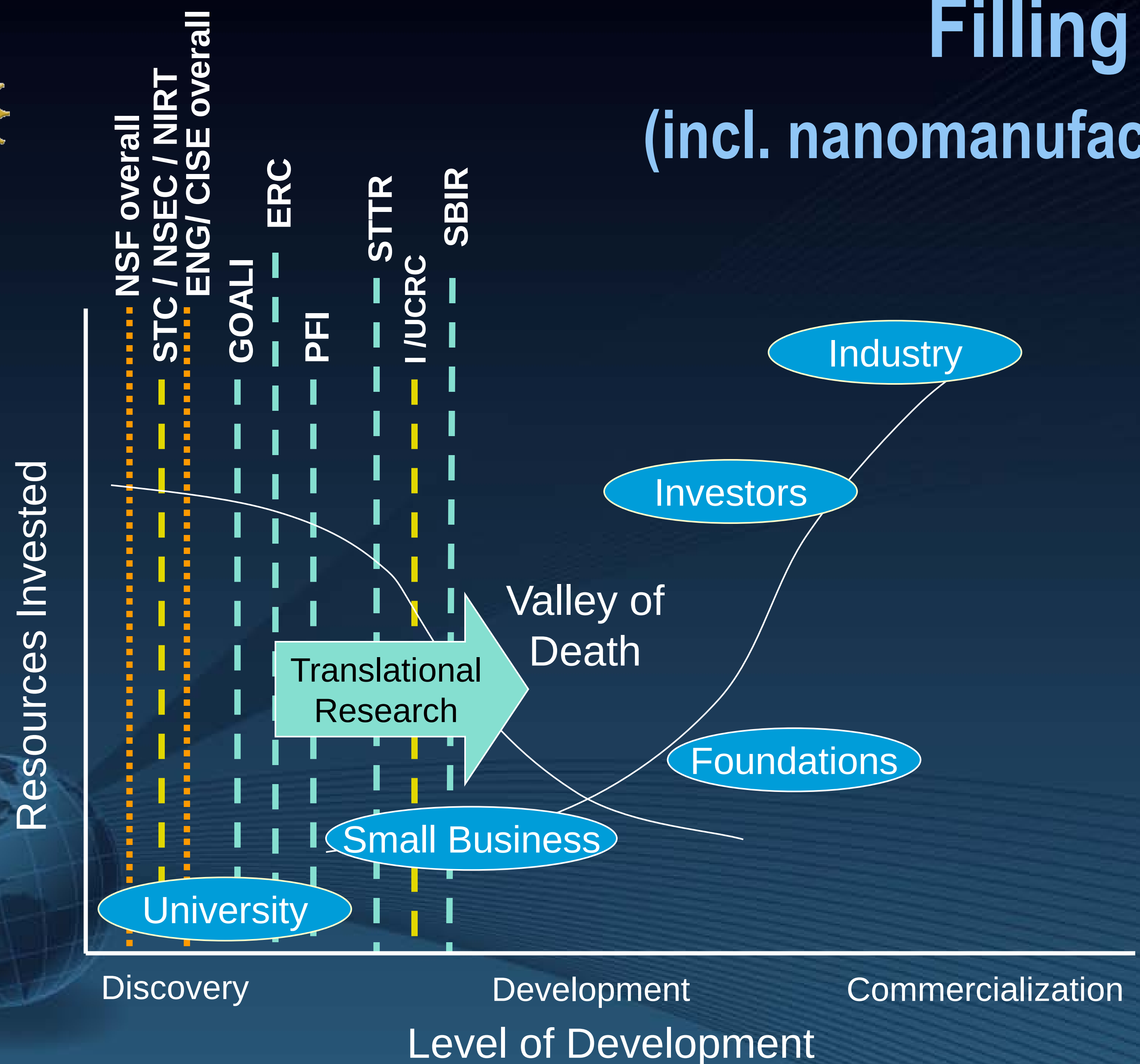
  for 5 + 5 years ($3-4 M/year per center)

  Pre-proposal in September 2011 … awards in 2012

  Address major topics **from discovery to innovation**

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

Filling Gaps
(incl. nanomanufacturing)



NSF Investment in Nanotechnology Implications for Safety and Society

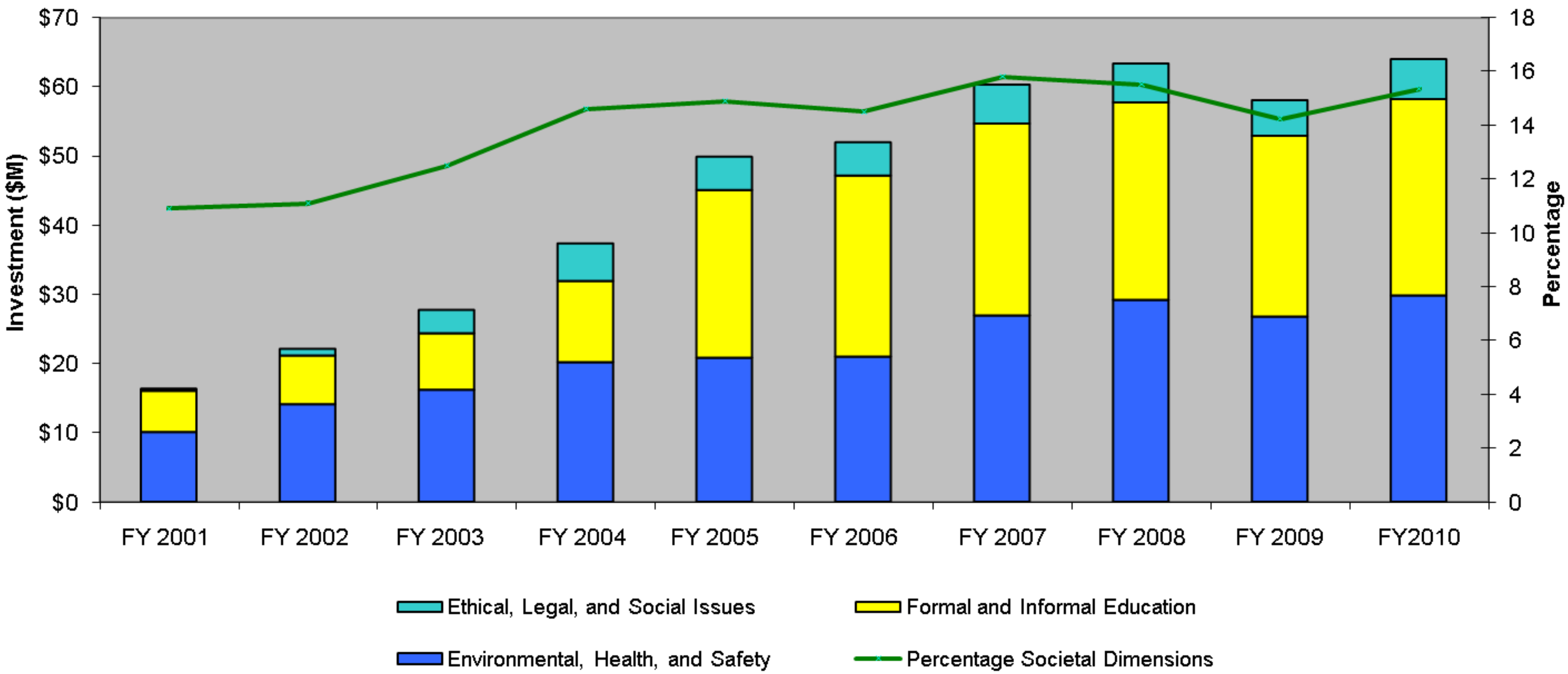
Nano-manufacturing safety added in 2003

Focus on future nano-generations added in 2006

New CEIN in 2008

Focus on nanosystems >2010

EPA NIEHS DOE, FDA



The Risk Management Escalator and Stakeholder Involvement

(from Simple via Complex and Uncertain to Ambiguous Phenomena) with reference to nanotechnology

	Naturally nanostructured materials	Engineered nanostructured materials	Active nanostructures and systems	Large and molecular nanosystems
Risk Problem	Simple	Component Complexity induced	System uncertainty induced	Ambiguity induced
Type of Discourse	Instrumental	Epistemological	Reflective	Participative
Actors	• Agency Staff • External Experts	• Agency Staff • External Experts • Stakeholders	• Agency Staff • External Experts • Stakeholders - Industry - Directly affected groups	• Agency Staff • External Experts • Stakeholders - Industry - Directly affected groups - General public
Type of Conflict		Cognitive	• Cognitive • Evaluative	• Cognitive • Evaluative • Normative
Remedy	Statistical Risk Analysis	Probabilistic Risk Modelling	Risk Balancing Necessary + Probabilistic Risk Modelling	Risk Trade -off Analysis & Deliberation necessary + Risk Balancing + Probabilistic Risk Modelling

Frame 1 (Naturally nanostructured materials; Engineered nanostructured materials) — Frame 2 (Active nanostructures and systems; Large and molecular nanosystems)

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

nano2

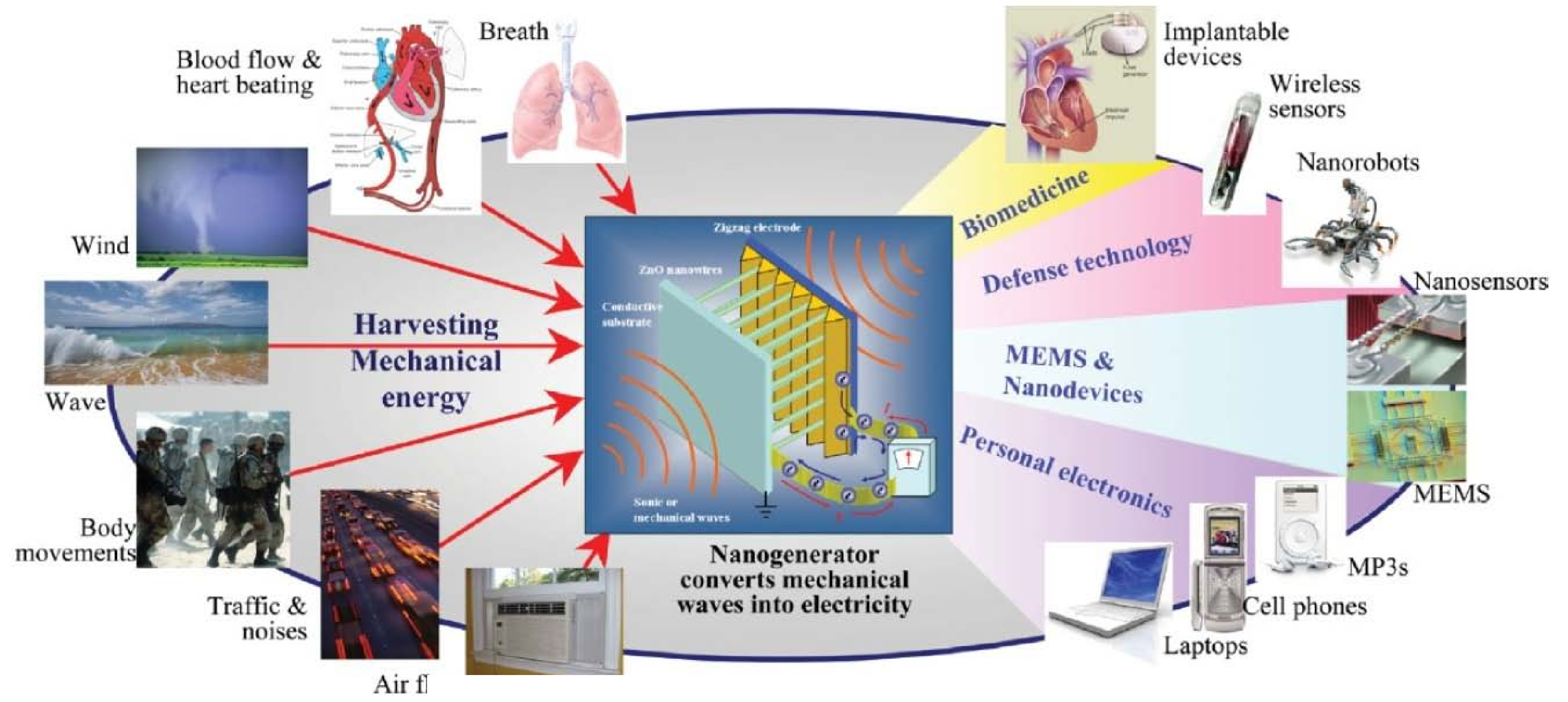
Twelve trends to 2020

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

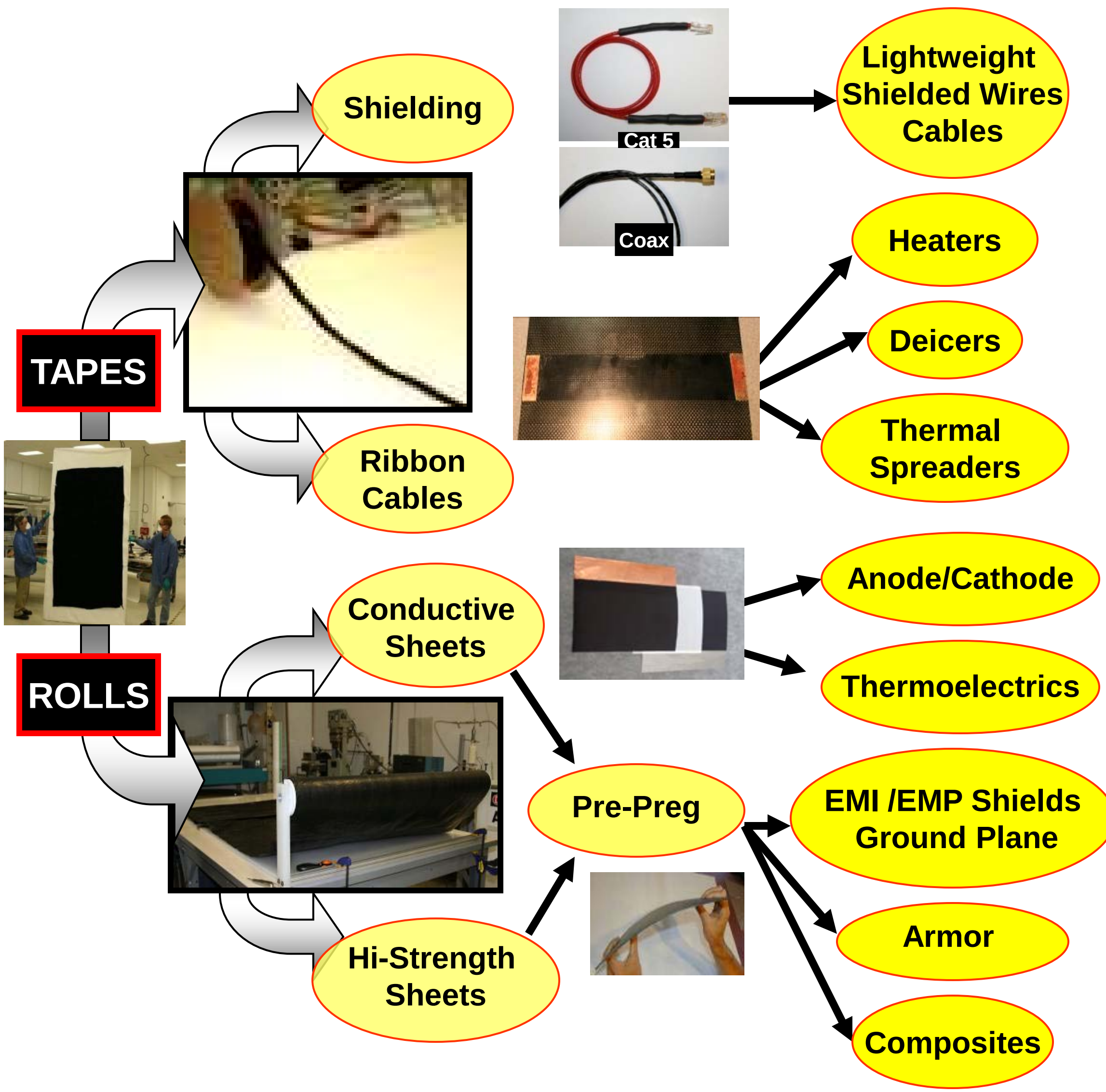
Ex: Self-powered nanosystems

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



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

Expanded CNT sheet production with broad impact



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

Twelve opportunities for pre-competitive nanomanufacturing R&D

1. Guided molecular assembling on several length scales (using electric and magnetic fields, templating, imprinting, chemical methods, etc.)
2. Modular and platform-based nanomanufacturing for nanosystems
3. Use micro/nano environments: microreactors, microfluidics, deskfactories
4. Designing molecules with new structures and functionalities

5. Nanobio-manufacturing - harnessing biology for nanomanufacturing (using living cells directly, borrowed, or taken as inspiration)
6. Manufacturing by nanomachines - advances catalysts, DNA machines, ..
7. Hierarchical nanomanufacturing - integrate in 3D, diff. materials, functions
8. Scale-up and high-rate production of manufacturing processes

9. Standardized tools for measurements and manufacturing
10. Predictive simulation of nanomanufacturing processes
11. Predictive approach for toxicity of nanomaterials (ex: oxidative stress)
12. Development and use of nanoinformatics and intellectual property

2. Modular and platform-based fabrication of nanosystems

- **Modules for measuring nanoscale processes** (SNL)
- **Biotic-abiotic nanomodules** (ex: with parts of viruses and bacteria) for sensors, energy conversion, nanomachines (Ex: Cornell U., Carnegie Mellon U.)
- **Platforms for nanomanufacturing processes** with various applications in larger companies
- **Platforms by relevance of R&D**: energy, water, sustainability, food, cancer research, forestry, concrete
- **Combinatorial approaches for new architectures and nanoscale networks**

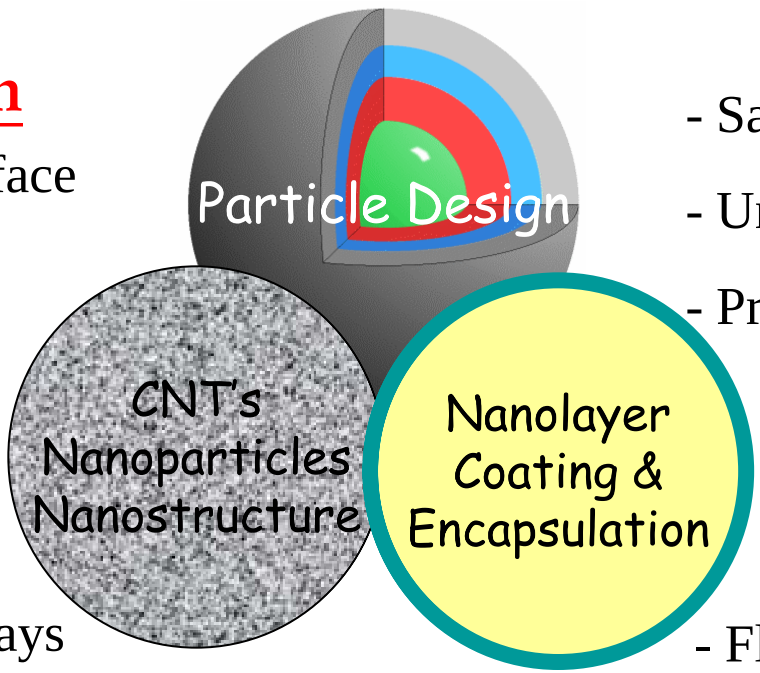
DuPont: Process Engineering & Manufacturing

for synthesis (CVD, Aerosol, Crystallization, precipitation), size reduction, surface treatment, coating, encapsulation, dispersion, incorporation

Nanotechnology platform for various particle technologies

Characterization

- PSD, morphology, surface
- Defects
- End-use performance



Manufacturing

- Safety
- Unit operations & Scale up
- Process integration

Applications

Films, Electronics, Displays

EP, Coatings, Personal care, Sensors, N&H

Assembly

- Fluid dynamics
- Field (E&M)
-Molecular template
- Biomolecule assisted

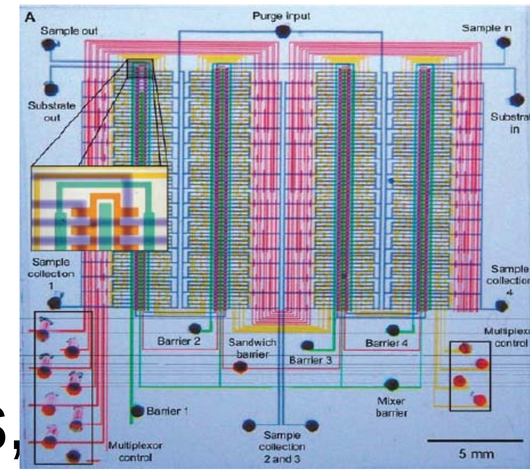
Modeling&Simulation

Molecular, Meso, Macro, CFD,

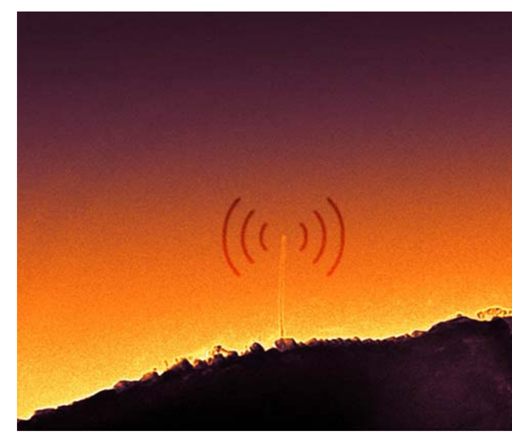
Example 3rd generation

Platforms for systems nanotechnology

- Create controllable systems built from nano components: unifying principles that enable control of emergent behavior in complex nanosystems
- Wide application: revolutionary new products, petascale computing, organ regeneration, sensors for health monitoring
- Enable other goals for: nanomanufacturing, efficient use of energy; sensor capabilities
- Development of a new framework for risk assessment



Ex UIUC: Microfluidics systems incorporating nanocomponents



Ex UCB: nano radio = antenna, filter, amplifier

3. Use nano/micro-environments:

microreactors, microfluidics, deskfactories

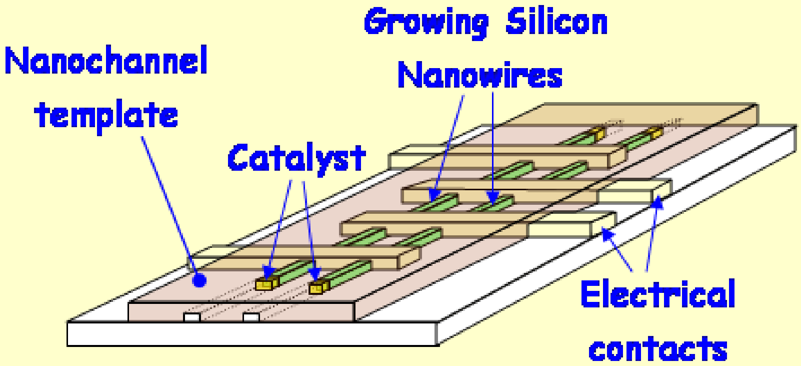
For process control, process intensified, with less waste, parallel production, potentially continuous, at the point of use

- <u>Microchannels for reactors</u> (for large specific surface area; for precise manufacturing larger macromolecular yield and controlled nanoparticle size distribution)
- <u>Microfluidic devices</u> for nanoscale assembling
- <u>Desk size factories</u> for processing nanomaterials
- <u>In-situ synthesis of nanostructures</u> (ex. Nanoscale channels for in-situ manufacturing, Fonash, Penn State)
- <u>Simultaneous, multiple processes</u> in same environment

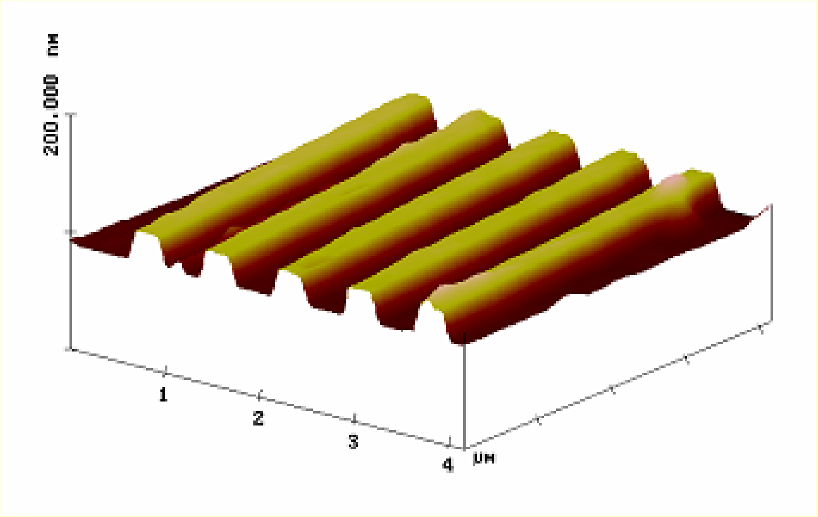
Example 1st generation

"Grow in place" for Nanowire Devices

(S. Fonash, Penn State)



(a)



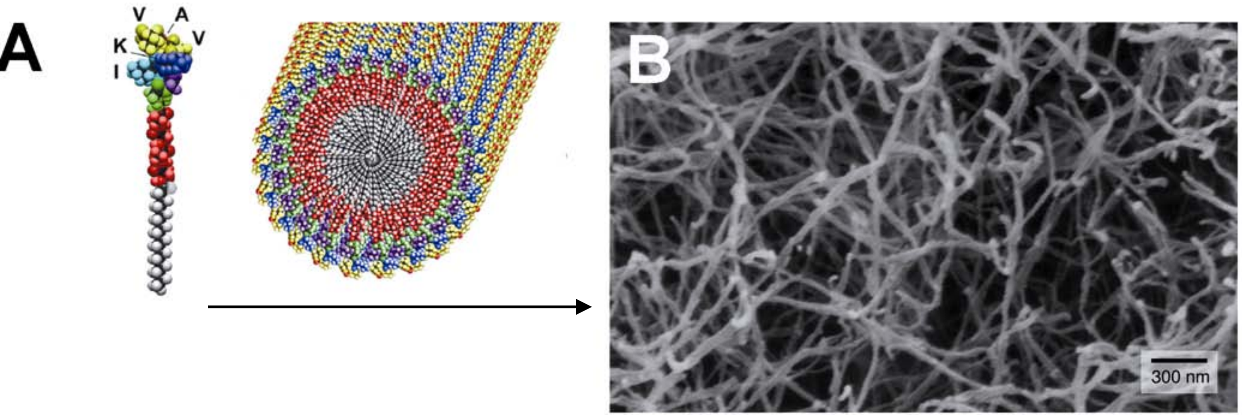
(b)

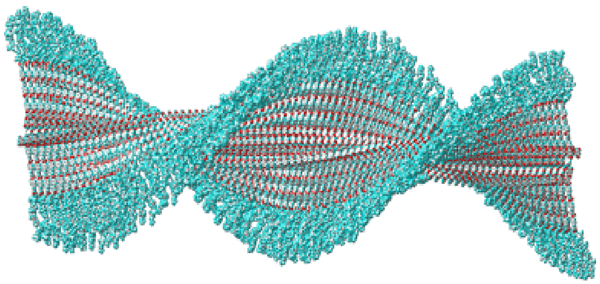
a. Manufacturing nanowire "in situ". "Grow-in-place" method developed at Penn State, keeps assembled together all nanostructured materials during processing (Shan et al., 2004)

b. AFM image of grown silicon nanowires

4. Designing molecules
with new structures and functionalities
Example for hierarchical selfassembling - 4th NT generation (in research)

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)

Need for nanomanufacturing in the U.S.

- **Service work alone is not sufficient for a modern economy**
- **Nano - broad based technology** to enhance or replace mature technologies in order to maintaining high paying jobs
- **Better opportunities for nanomanufacturing in US when**:
  - Need of advanced infrastructure and multidisciplinary teams
  - Highly automated processes
  - Linked to biotechnology, medicine and overall converging technologies
  - Adapting existing manufacturing infrastructure
  - Requiring an ecology of innovation

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

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

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 job creation and return to society** - high-added value nanomanufacturing
- *Nanotechnology governance will be **institutionalized*** , with increased globalization and a co-funding mechanism

Several background references

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Taylor and Francis 2007

“Nanotechnology Risk Governance”
in Global Risk Governance Framework, Springer 2007

“Possibilities for Global Governance of Converging Technologies”,
J. Nanoparticle Res. 2008

"Mapping Nanotechnology Innovations and Knowledge"
Springer 2009

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

Information items

- NSF Nanoscale Science and Engineering Grantees Conference

  Dec. 5-7, 2011

  Westin Hotel, Arlington, VA

  www.nseresearch.org

- Position of Program Director for Nanomanufacturing (NSF/ENG/CMMI): open

  www.nsf.gov