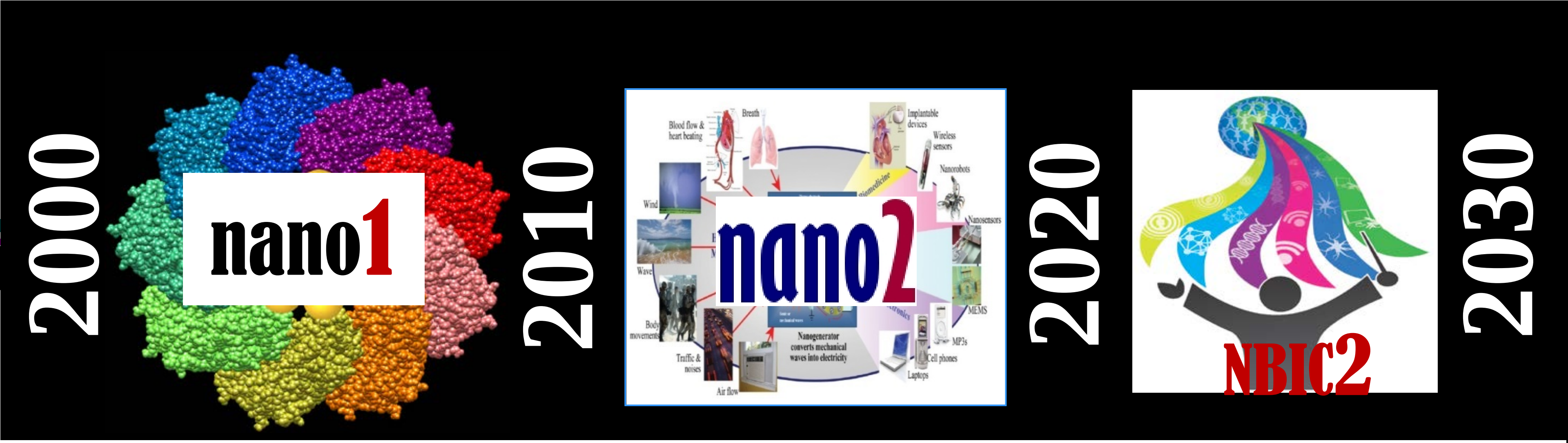


Nanotechnology Path to Sustainable Society

Mihail C. Roco
National Science Foundation and National Nanotechnology Initiative

SUN-SNO-GUIDENANO Sustainable Nanotechnology Conference
Venice, March 9, 2015

Topics

- Sustainable society

- Long-view of nanotechnology affirmation
  US & international perspective

- Paths to sustainable society
  Nano – a general-purpose technology

Sustainable society

Social (population growth and needs, governance, enduring democracy),
economic (knowledge, technology, materials, water, energy, food, climate), and
environment (clean, renewable, biodiverse)
sustainability in planetary boundaries

Nanotechnology Governance

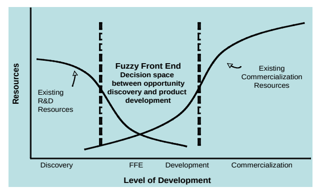
NANOTECHNOLOGY GOVERNANCE

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

Four key functions:

Visionary

Transformative

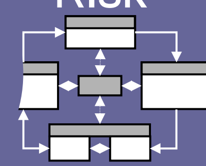


Responsible

Benefit society

Sustain

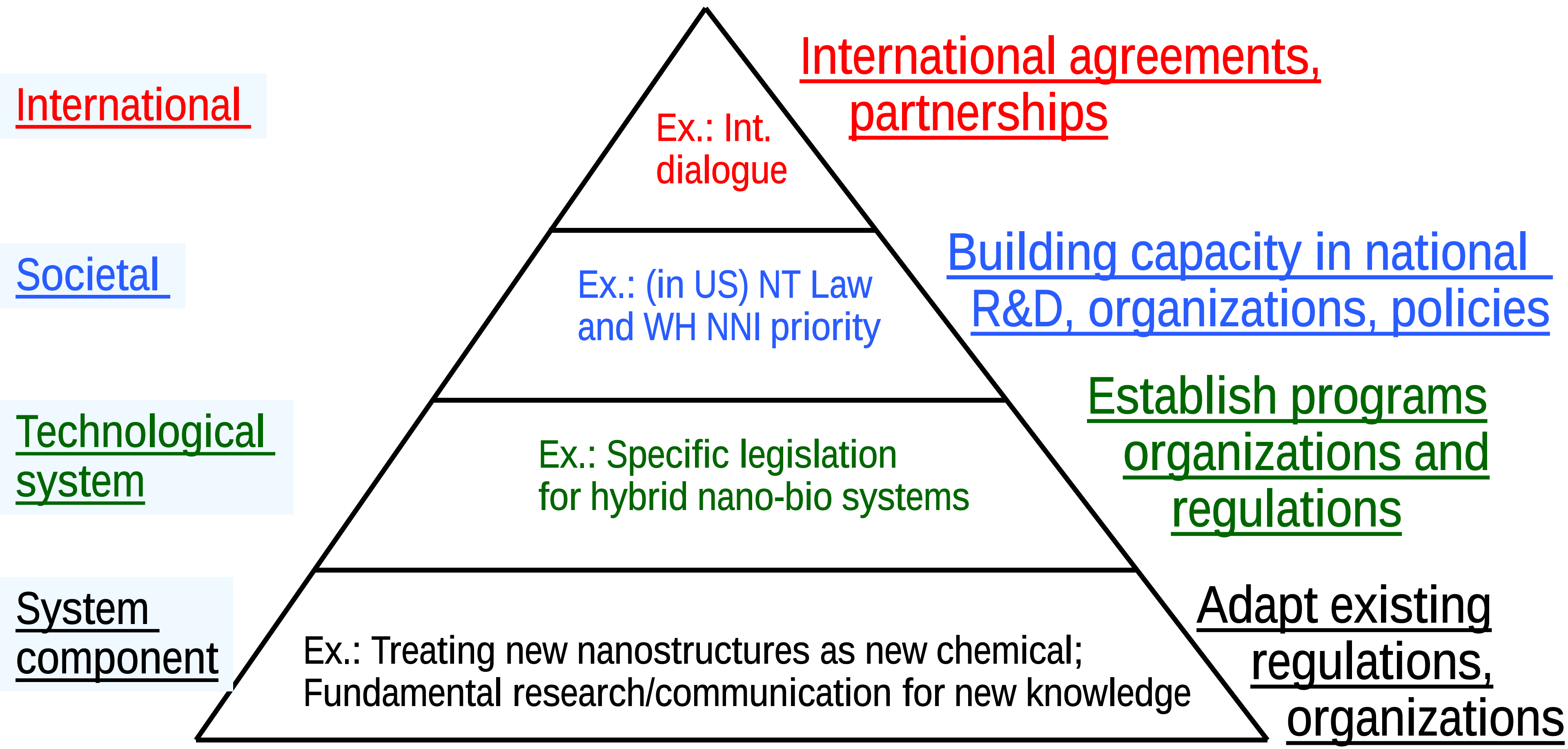
Risk



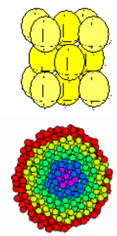
Risk Governance

Inclusive

The functions of good governance are applied to SEVERAL GOVERNANCE LEVELS



The functions of good governance are applied to
FIVE GENERATIONS OF NANOTECHNOLOGY

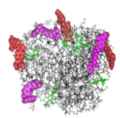


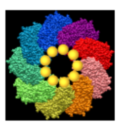
1st: Passive nanostructures (1st generation products)

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

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

~ 2000



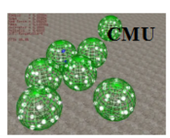


2nd: Active nanostructures

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

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

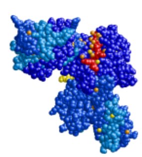
~ 2005



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

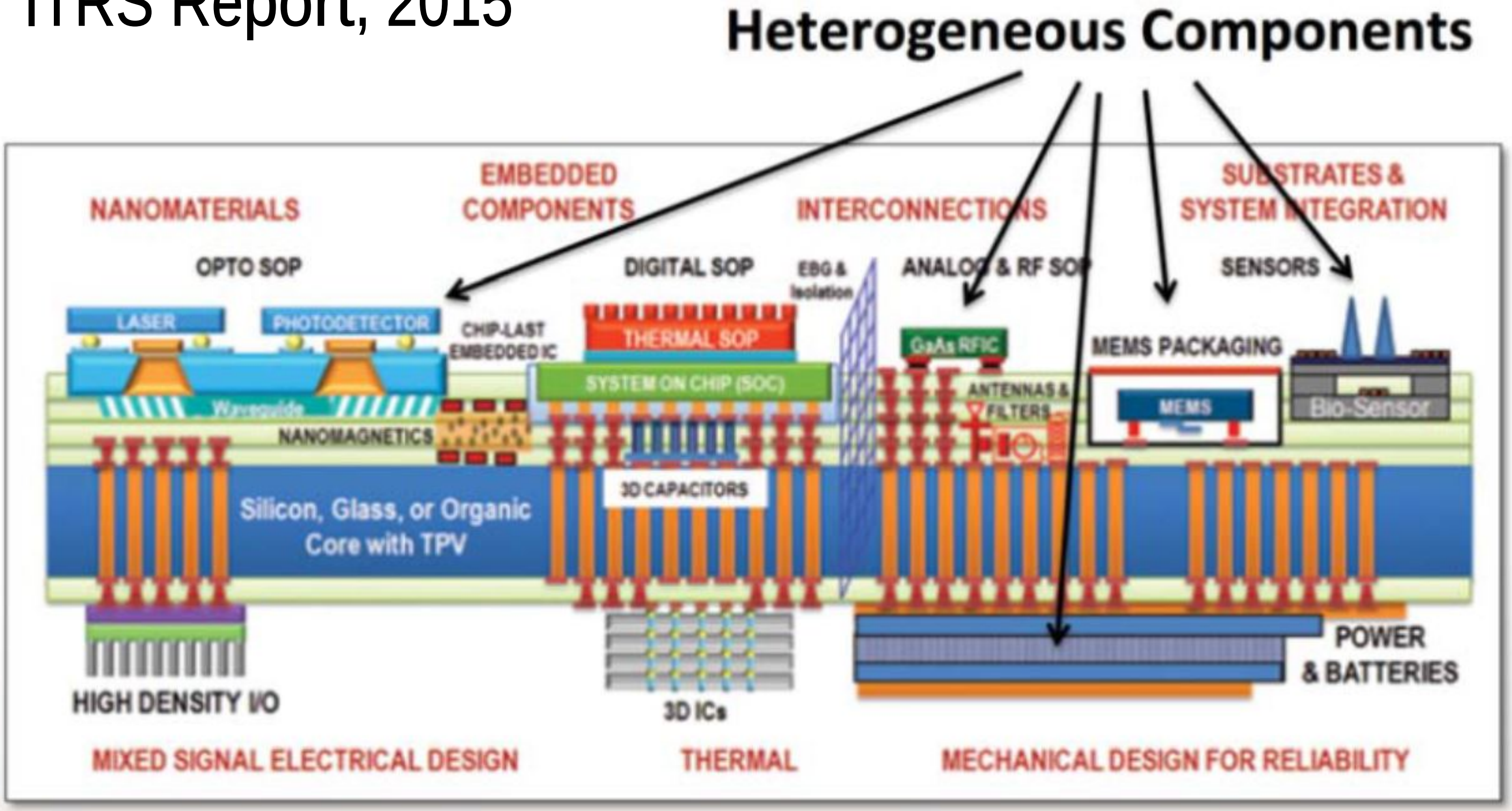
5th Converging technologies

Frame 1

Risk Governance Frame 2

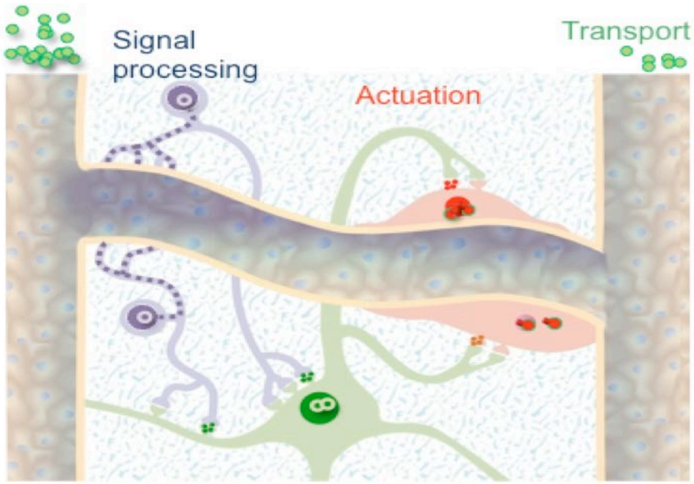
Illustration of new challenges for integrated architectures

ITRS Report, 2015



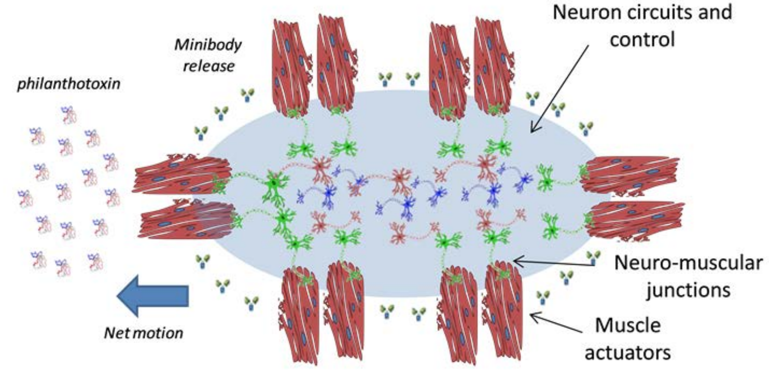
Source: Georgia Tech PRC, http://www.prc.gatech.edu/overview/images/etpc.jpg

Illustration of new challenges: Emerging Behaviors in Integrated Cellular Systems and their Boundaries



Controlling the complex functional behaviors of interacting cell clusters, and their interaction with the surroundings

Understand cellular behaviors guided by integrated biological, biochemical, and physical processes, and their interaction with the surrounding systems

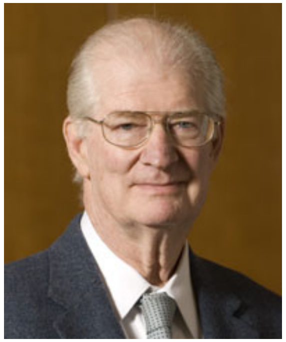


NSF STC: MIT (Kamm); GA Tech, Illinois, Morehouse, UC Merced, City College

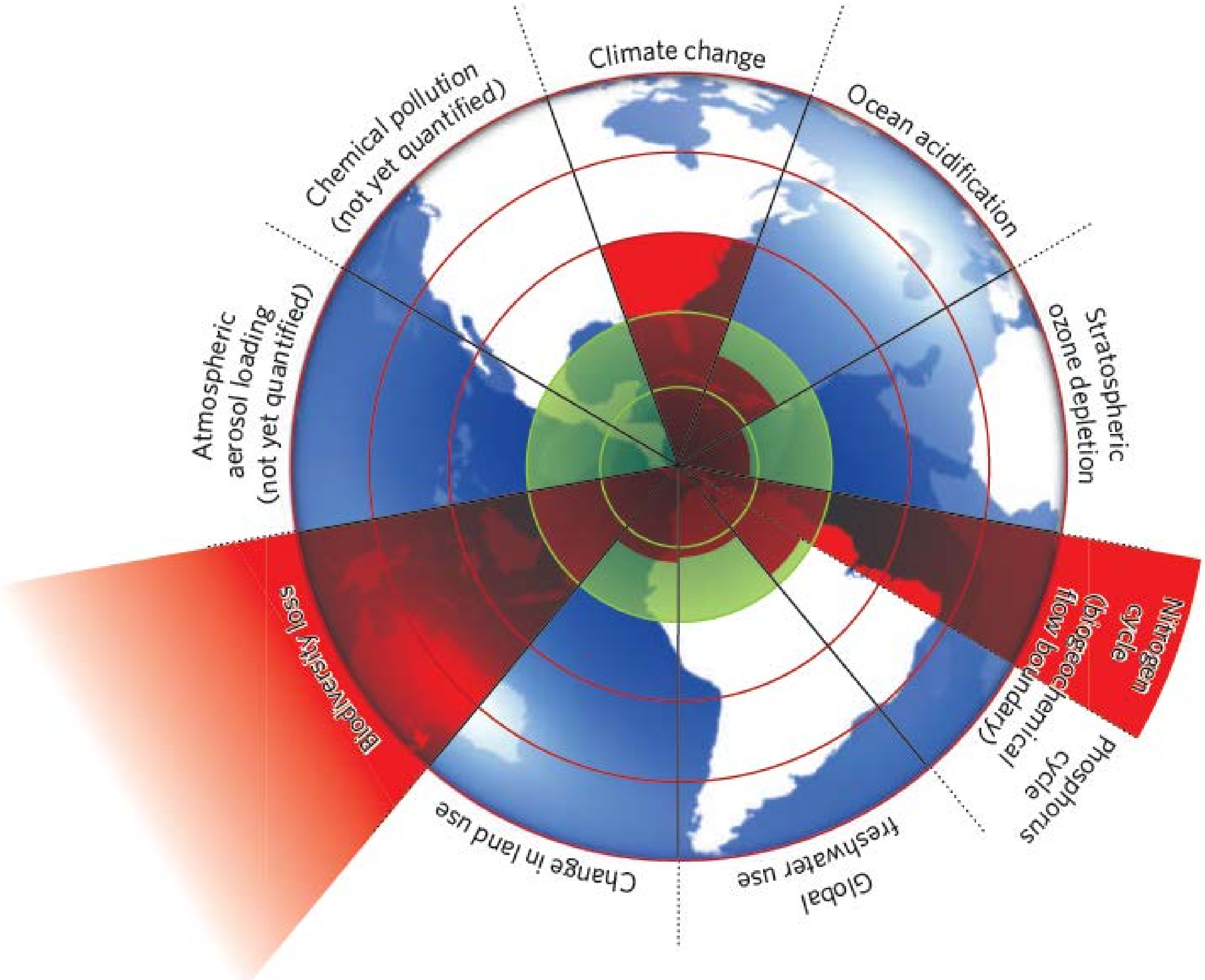
What is Sustainable Development?

- **Bruntland Commission (1987)**
  Development that would meet the needs of the present without compromising the ability of future generations to meet their own needs

- **Herman Daly**
  - Non-renewable resources should not be depleted at rates higher than the development rate of renewable resources
  - Renewable resources should not be exploited at a rate higher than their regeneration level
  - The absorption and regeneration capacity of the natural environment should not be exceeded



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



Current critical planetary boundaries are

- biodiversity
- nitrogen cycle
- climate change

(Rockström et al. 2009)

Nano2 Report, 2010, p. 147

Sustainability has emerged as the key driver for addressing global problems facing the world, including:

– Energy and Water
– Agriculture, Food and Natural Resources
– Human Health and Well-Being
– Urban and rural communities
– Materials and Manufacturing
– Environment and Climate Change
– Societal Engagement and Public Benefits

Possible targets for nanotechnology and convergent technologies

- Infinitely Recyclable, Re-usable, and Renewable Industrial Ecosystems (IR^3)
  - Reduce demand for virgin materials, reduce carbon emissions
- Community, buildings and household self-sufficiency
  - Focus on low-income communities and households

Long view

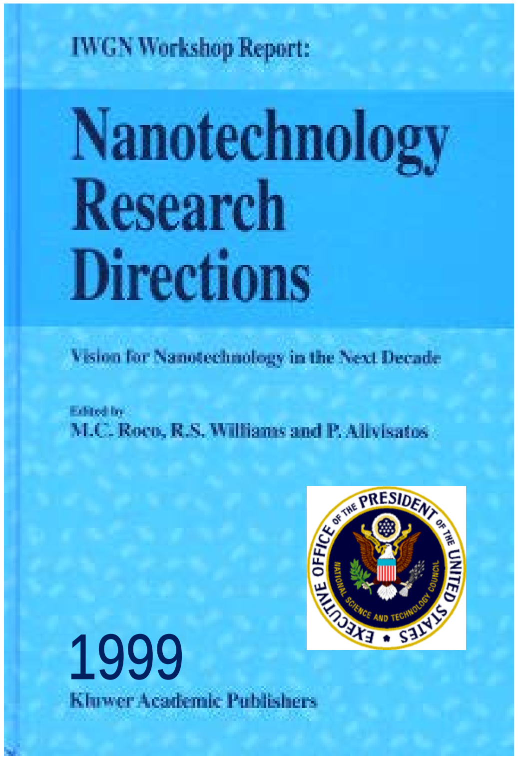
- Since 2000, nanotechnology is an essential megatrend in S&E, the most exploratory field as a general foundation as compared to IT and BIO

- Nanotechnology today continues exponential growth by vertical science-to-technology transition, horizontal expansion to areas as agriculture/ textiles/ cement, and spin-off areas (~20) as spintronics/ metamaterials/…

- After 2020, nanotechnology promises to become the primary S&T platform for investments & venture funds once design & manufacturing methods, and respective education & physical infrastructure are established

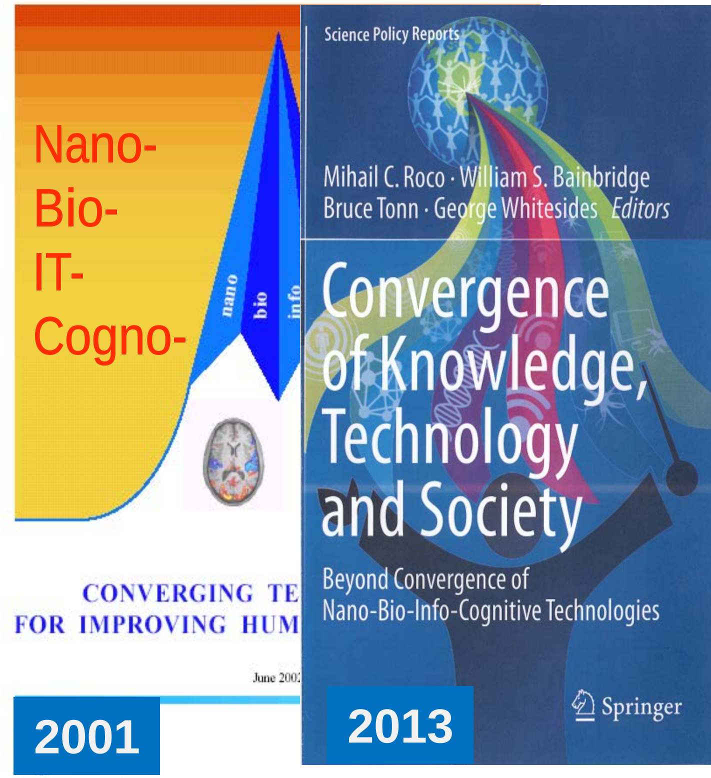
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects

nano1 (2001-2010)



nano2 (2011-2020)

NBIC1 & 2 (2011-2030)



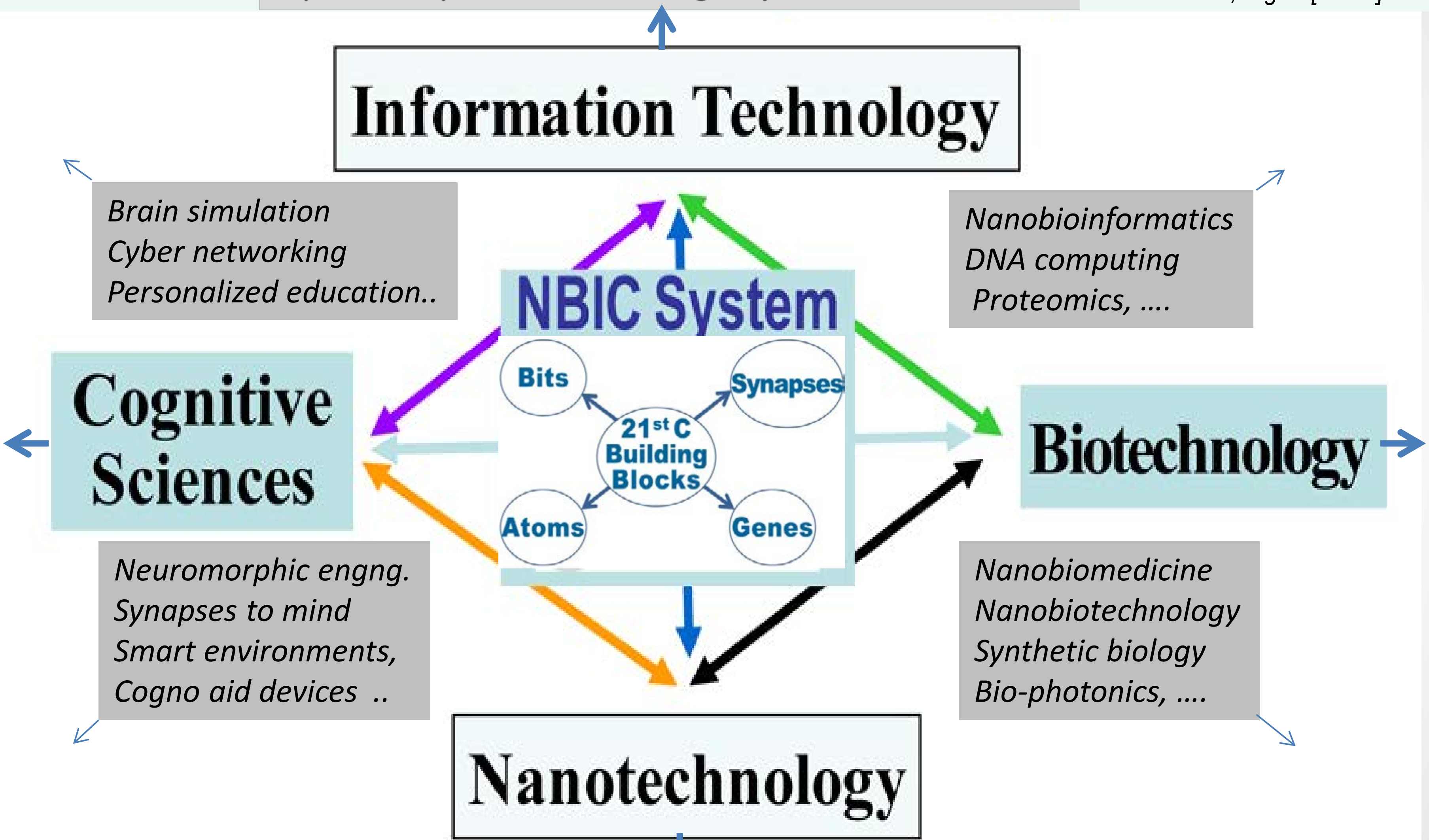
30 year vision to establish nanotechnology: changing focus and priorities

Reports available on: www.wtec.org/nano2/ and www.wtec.org/NBIC2-report/ (Refs. 2-5)

Converging foundational technologies - NBIC

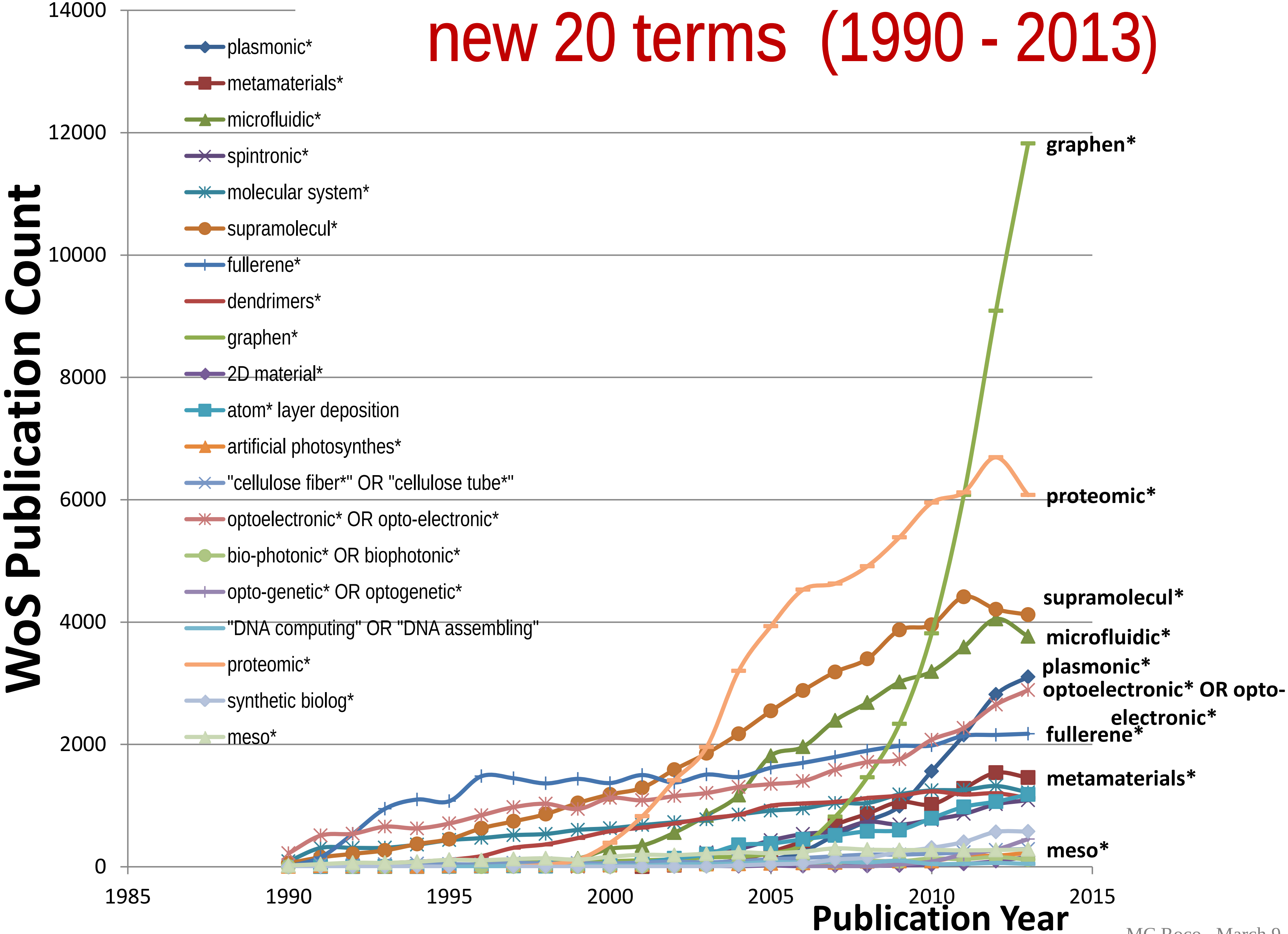
Information Technology Spin-offs : Large-data bases, topical computer-aided –design, cyber networks, .. .

Roco and Bainbridge, 2013 , Fig 2 [Ref 1]



Nanotechnology Spin-offs : Nanophotonics, plasmonics, materials genome, mesoscale S&E, metamaterials, nanofluidics, carbon electronics, nanosustainability, wood fibers, DNA NT, ..

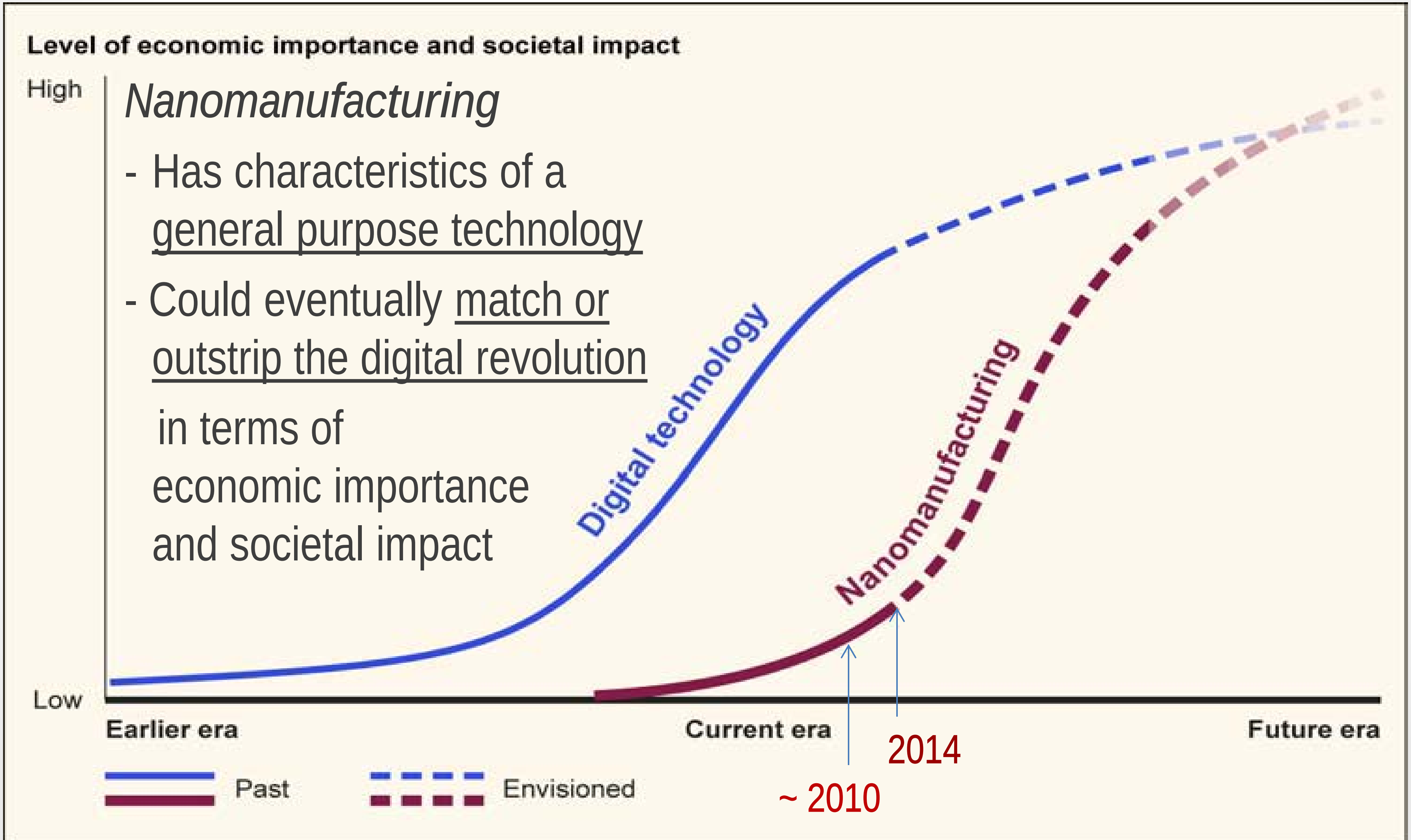
WoS publications on nano-extended new 20 terms (1990 - 2013)



MC Roco, March 9 2015

Conceptualization of "Nanomanufacturing" and "Digital Technology" megatrends: S-curves

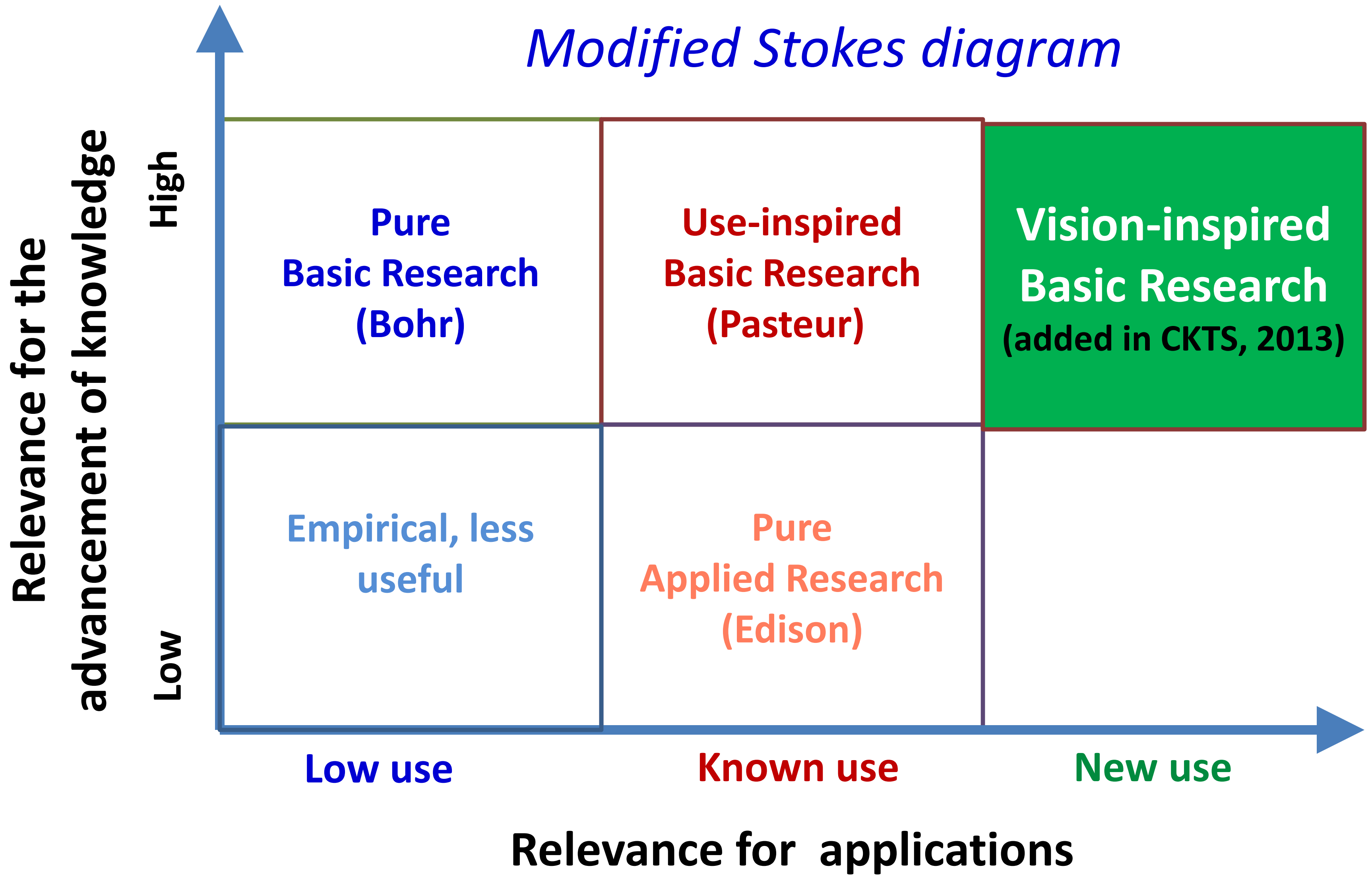
(GAO-14-181SP Forum on Nanomanufacturing, Report to Congress, 2014)



Nanomanufacturing

- Has characteristics of a general purpose technology
- Could eventually match or outstrip the digital revolution in terms of economic importance and societal impact

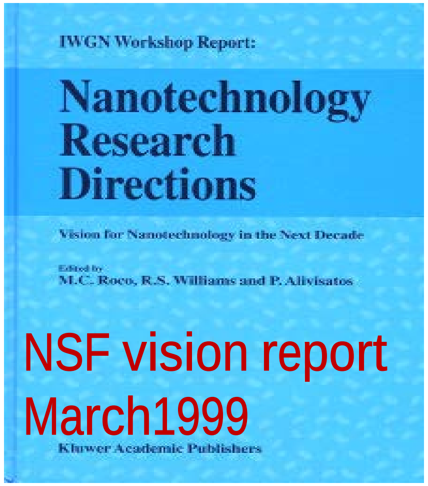
Vision inspired research is essential for the long-term view of nanotechnology



Roco and Bainbridge, 2013 , Fig 9 [1]

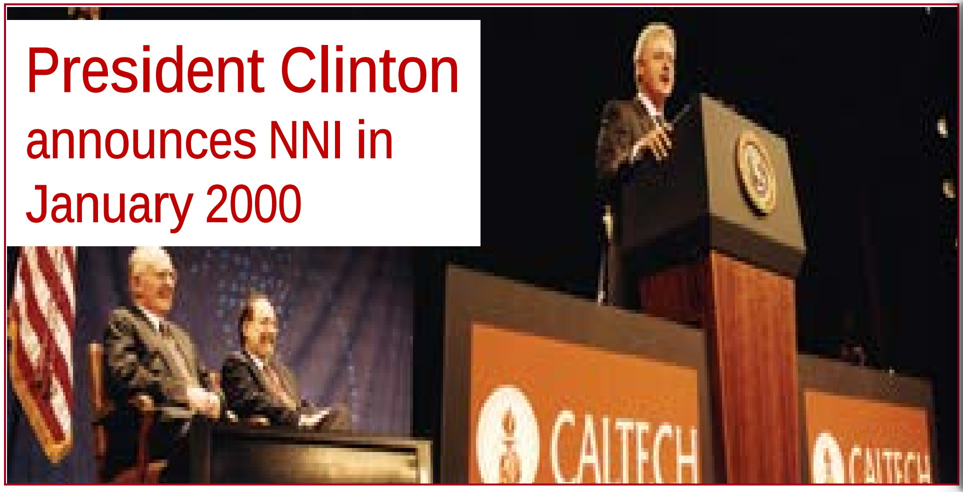
Implementing the 30 year vision in U.S.

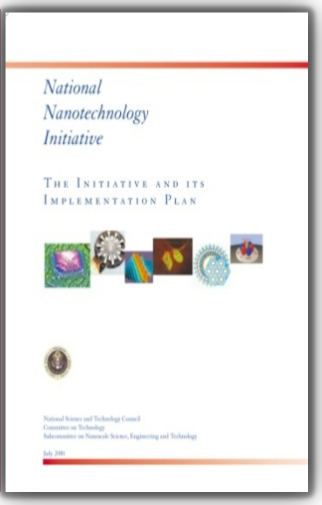
NNI in three administrations: Clinton, Bush and Obama



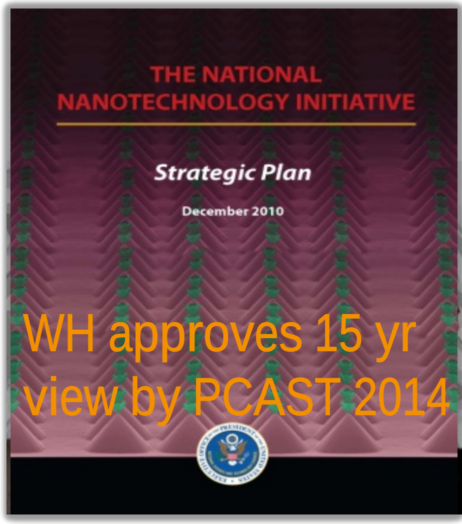
NSF vision report March1999

President Clinton announces NNI in January 2000





President Bush Signing 21st Century Nanotechnology R&D Act – December 2003



WH approves 15 yr view by PCAST 2014

President Obama

Three overarching goals for nanotechnology development

- Increase productivity
  (in industry, agriculture, transportation, ..)
- Quality of life
  (health, culture, security, aging, ..)
- Societal sustainability
  (physical Surroundings, resources, biodiversity, economic, social, cultural, ..)

DOC/NIST
DOE
HHS/NIH
OSTP
OMB
NSF
DOD
HHS/FDA
NASA
USDA/NIFA
USDA/ARS
HHS/CDC/
NIOSH
USDA/FS

National Nanotechnology Initiative, 2000

(Vision: control of matter at nanoscale will bring a revolution in technology; see www.nano.gov)

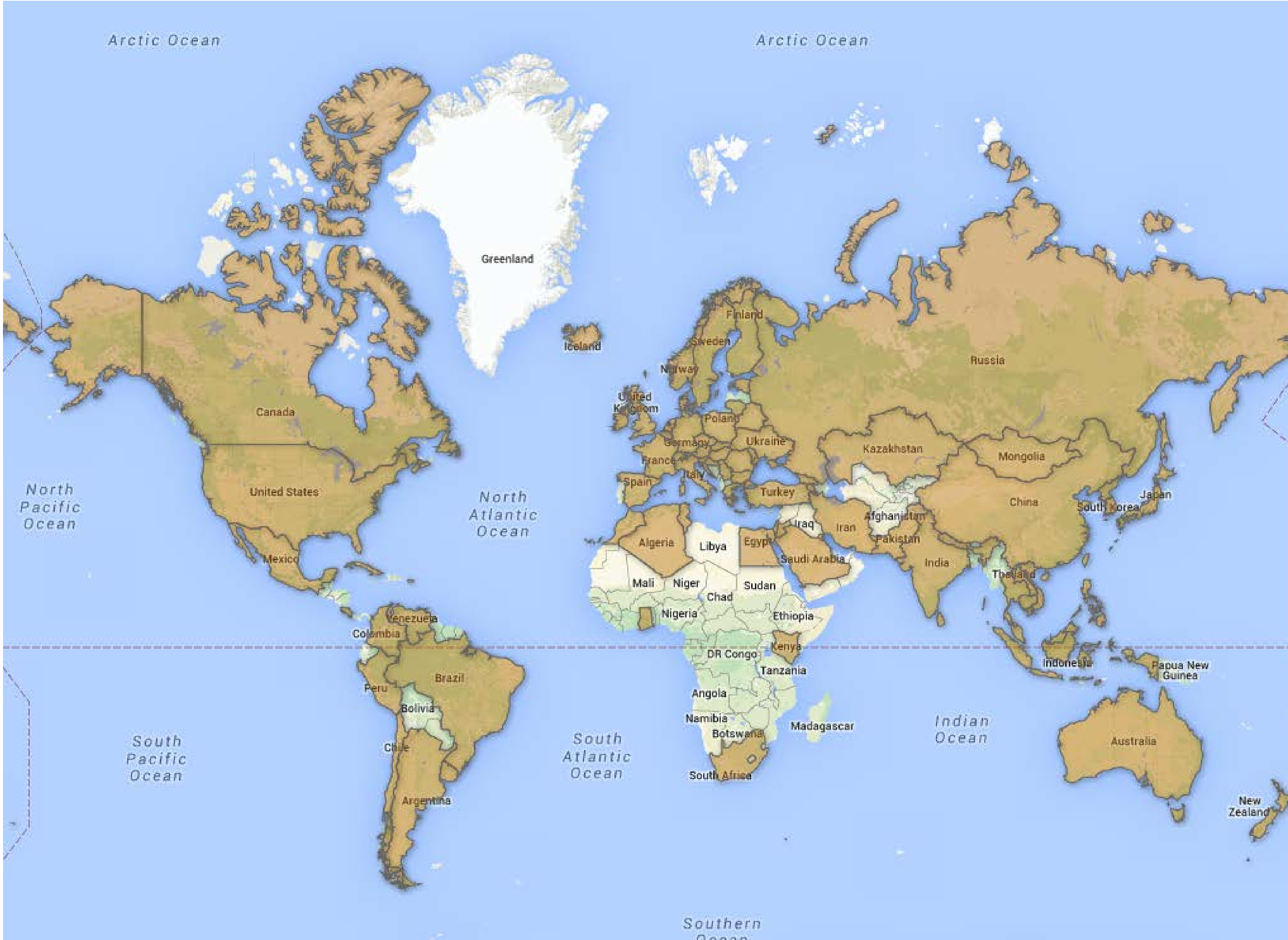
DOS
EPA
DOTr
NRC

PCAST Report on NNI, 2014:

Recommends New Grand Challenges

DOT
DOC/
USPTO
IC/DNI
DOI/
USGS
DOJ
DOC/EDA
DOC/BIS
DHS
CPSC
ITC
DOEd
DOL

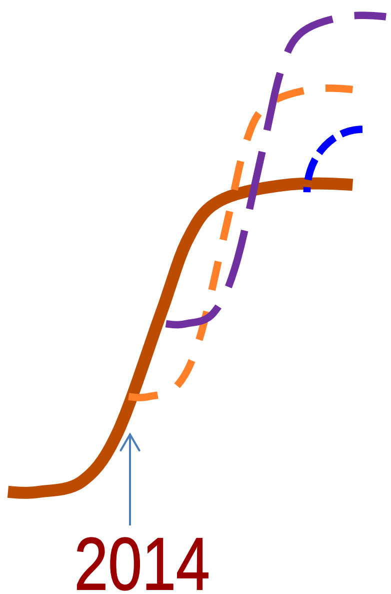
Over 80 countries with nanotechnology R&D



2013 industry survey (Lux Res.): global revenues $1 trillion

Global Nanotechnology future

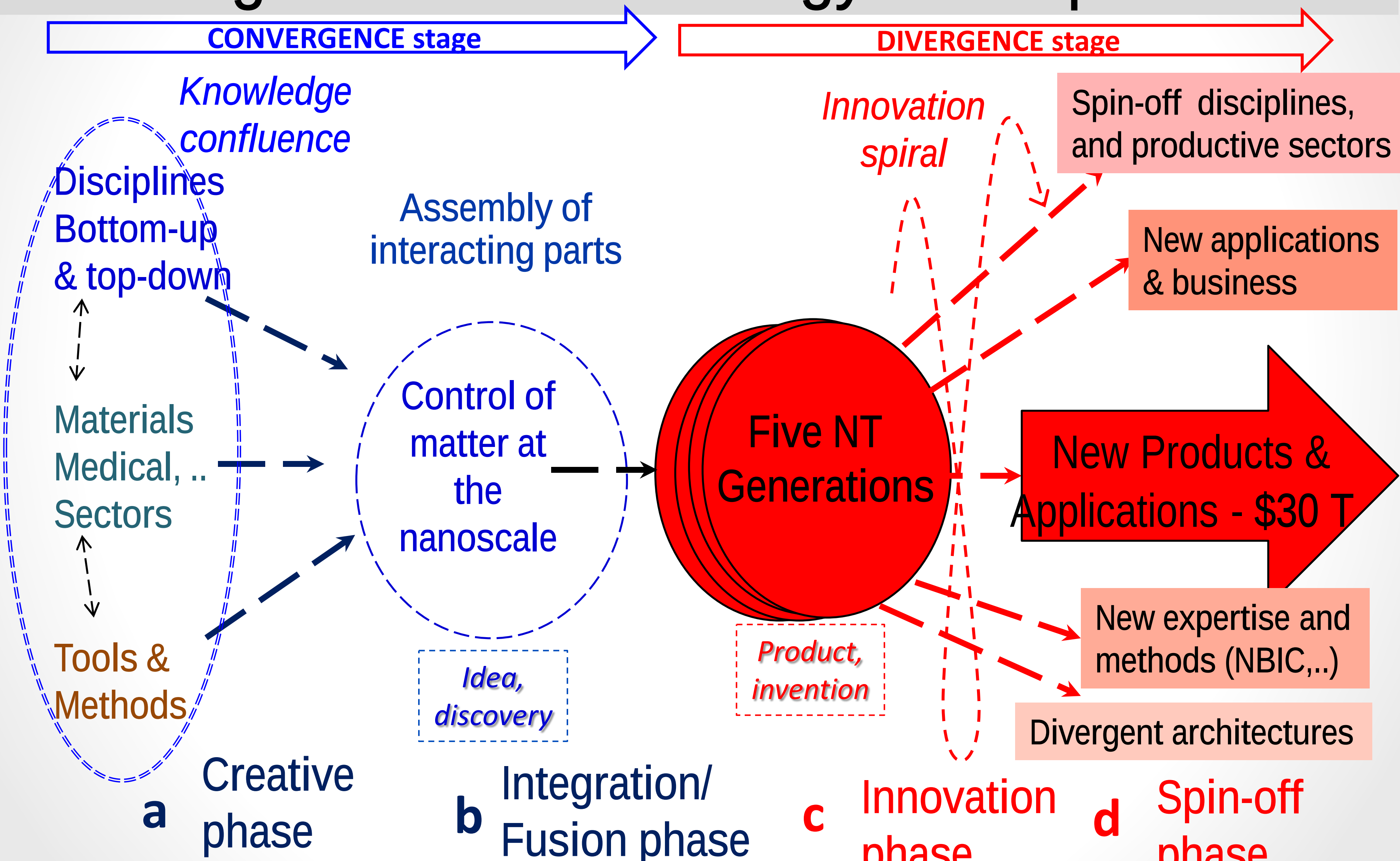
Breakthroughs in novel system architectures and nano-bio-info-cognitive convergence are expanding and leading to emergence of novel technology platforms



S – development curve for foundational nanoscale science and technology

- amplified return on investment/ multiple branches
- revenue growth ~ 43% per year in 2011-2014
- nanotech products est. to reach >10% GDP in most developed countries by 2030

2000-2030 Convergence-Divergence Cycle for global nanotechnology development



Based on Roco and Bainbridge, 2013 ,Fig. 8 [1]

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

FIVE GENERATIONS NANOPRODUCTS

2030

DIVERGENCE

New convergence platforms & economy immersion

~ 2021 ← **nano3** **technology divergence** → ~ 2030

Create spin-off nano-platforms
in industry, medicine and services;

NS&E integration for general purpose technology

~ 2011 ← **nano2** **system integration** → ~ 2020

Create nanosystems by science-based
design/processes/technology integration

CONVERGENCE

Foundational interdisciplinary research at nanoscale

~ 2001 ← **nano1** **component basics** → ~ 2010

Create passive and active nanocomponents
by semi-empirical design

2000

6. Nanosystem Conv. Networks

5. NBIC Techn. Platforms

4. Molecular Nanosystems

3. Systems of Nanosystems

2. Active Nanostructures

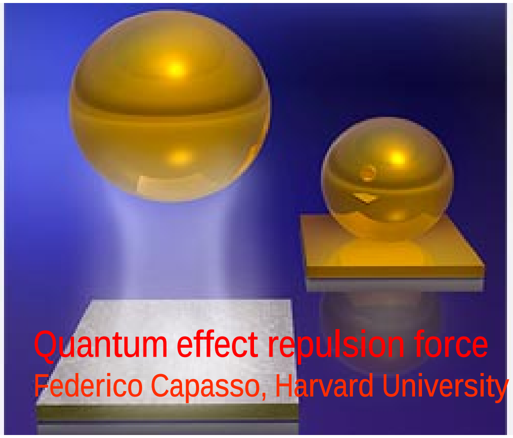
1. Passive Nanostructures

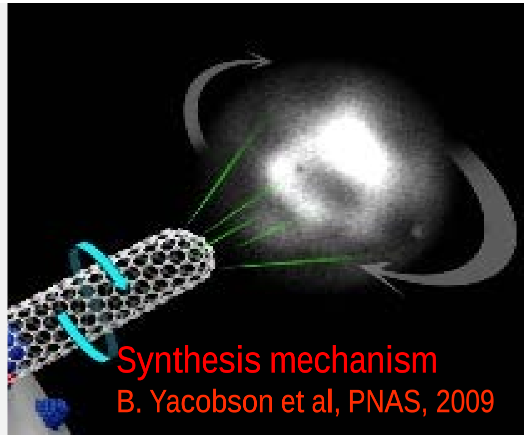
(Refs. 2-5)

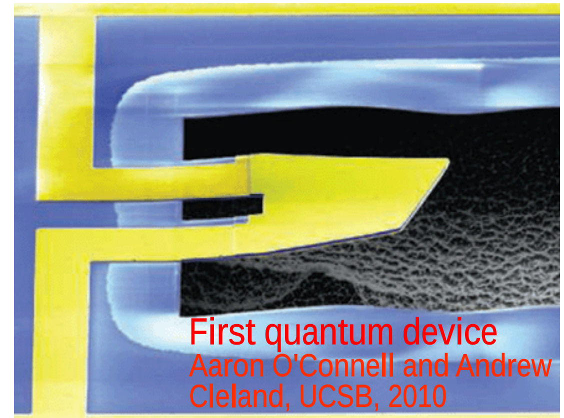
MC Roco, March 9 2015

Examples for Nano 1 (2001-2010)

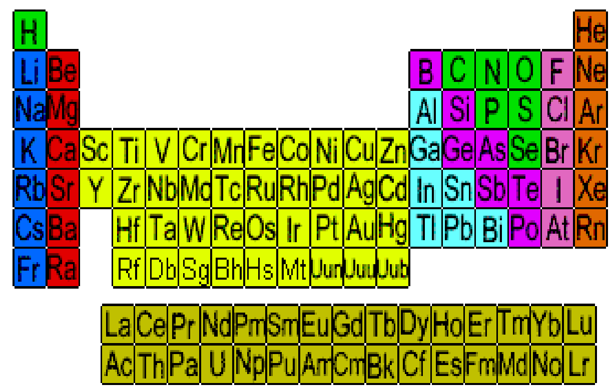
- New individual phenomena, processes, structures



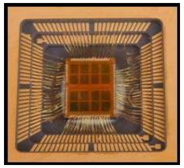




- Semi-empirical synthesis of nanocomponents (particle, quantum dots, tubes, coatings,..) over all the periodic table

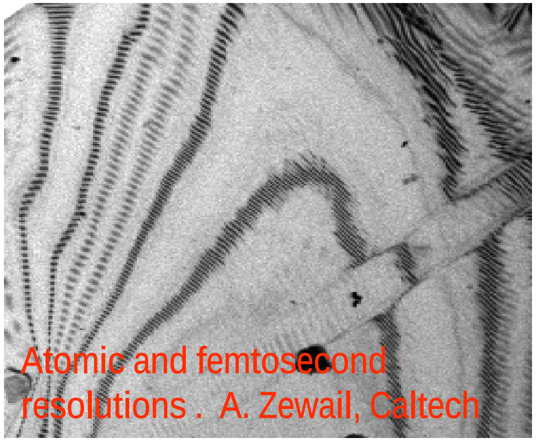


- Nanocomponents have extended semiconductor's Moore's law since 2000



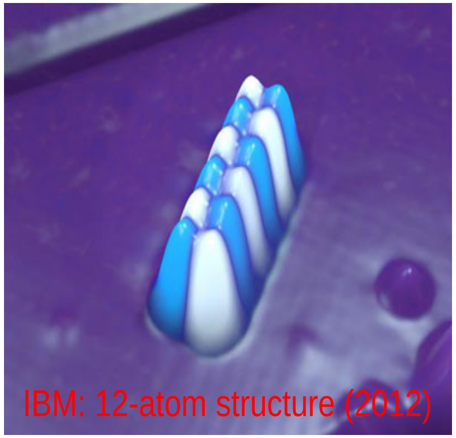
Examples for Nano 2 (2011-2020)

- Direct measurements & simulations (at femtosecond, N↑ interacting atoms) for domains of biological and engineering relevance

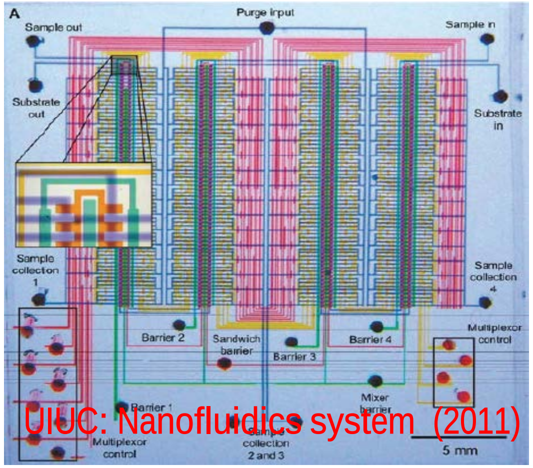


Atomic and femtosecond resolutions . A. Zewail, Caltech

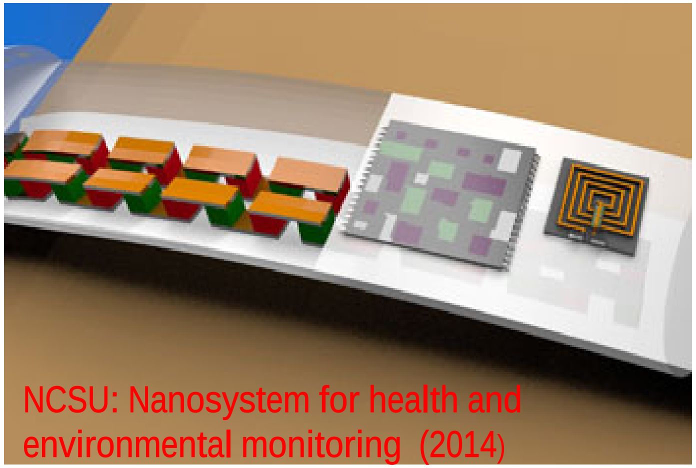
- Science based integrated nanosystems by design



IBM: 12-atom structure (2012)



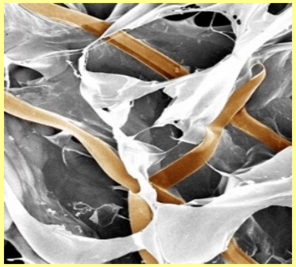
UIUC: Nanofluidics system (2011)



NCSU: Nanosystem for health and environmental monitoring (2014)

Examples for Nano 3 (2021-2030)

- **New system architectures**: guided self-assembling structures, evolutionary architectures, biomimetics--based, biorobotics-based, neuromorphic, adiabatic switching and reversible logic for IT, … to be invented.



- **Nano-Bio-Info-Cognition technology platforms**
- **Service and molecular medicine** individualized
- Genetic – neurotechnologies – robotics - .. **to improve human potential**
- High productivity - high return **new industry sectors**

Perception

"Nanotechnology" is not:

- Not "a buzz word" – corresponds to the transition in nature and technology from individual atomic properties to their collective effects enabling diversity on the Earth
- Not "a polluant technology" – aims at non-covalent assembling, low (p,T) & pollution, "how molecules like"
- Not "a mature field" – going beyond the 1st generation of passive nanoparticles toward complex nanosystems
- Not "limited to unsolicited research" - it needs new tools, infrastructure, unifying concepts in education, focus R&D efforts on emerging and bottleneck research

2000-2010 (data from Nano2 Report, NSF/WTEC)

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*					

updated Nano2 Report, 2010, p. XXXIII (Ref. 3)

2010-2013 (data from Lux Research world industry survey, Jan 2014)

Global and US revenues from Nano-enabled products

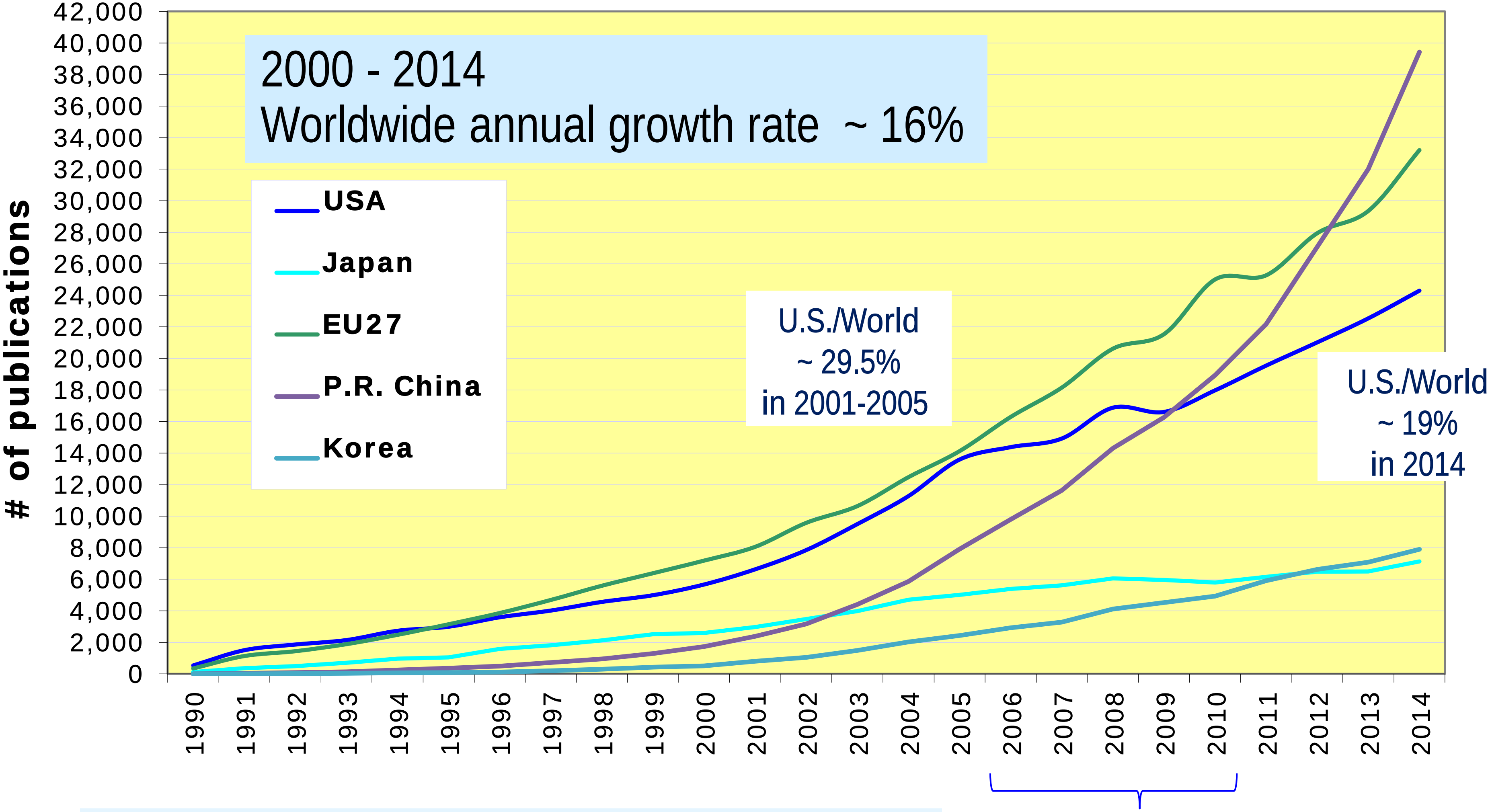
(All budgets in $ billion)	2010	2011	2012	2013	2010-2013
Total world revenues	*339* *(10 yr ~ 25%)*	*514*	*731*	*1,014*	*+ 676*
US revenues	109.8 (10 yr ~ 24%)	170.0	235.6	318.1	+ 208
World annual increase	10 yr ~ 25%	52%	42%	39%	44%
US annual increase	10 yr ~ 24%	55%	39%	35%	43%
US / World	32.4% 10 yr ~ 35%	33%	32%	31%	32%

MC Roco, March 9 2015

Total nano product revenues annual growth > 40% in 2010-2013. “S – curve”

Nanotechnology publications in the WoS: 1990 - 2014

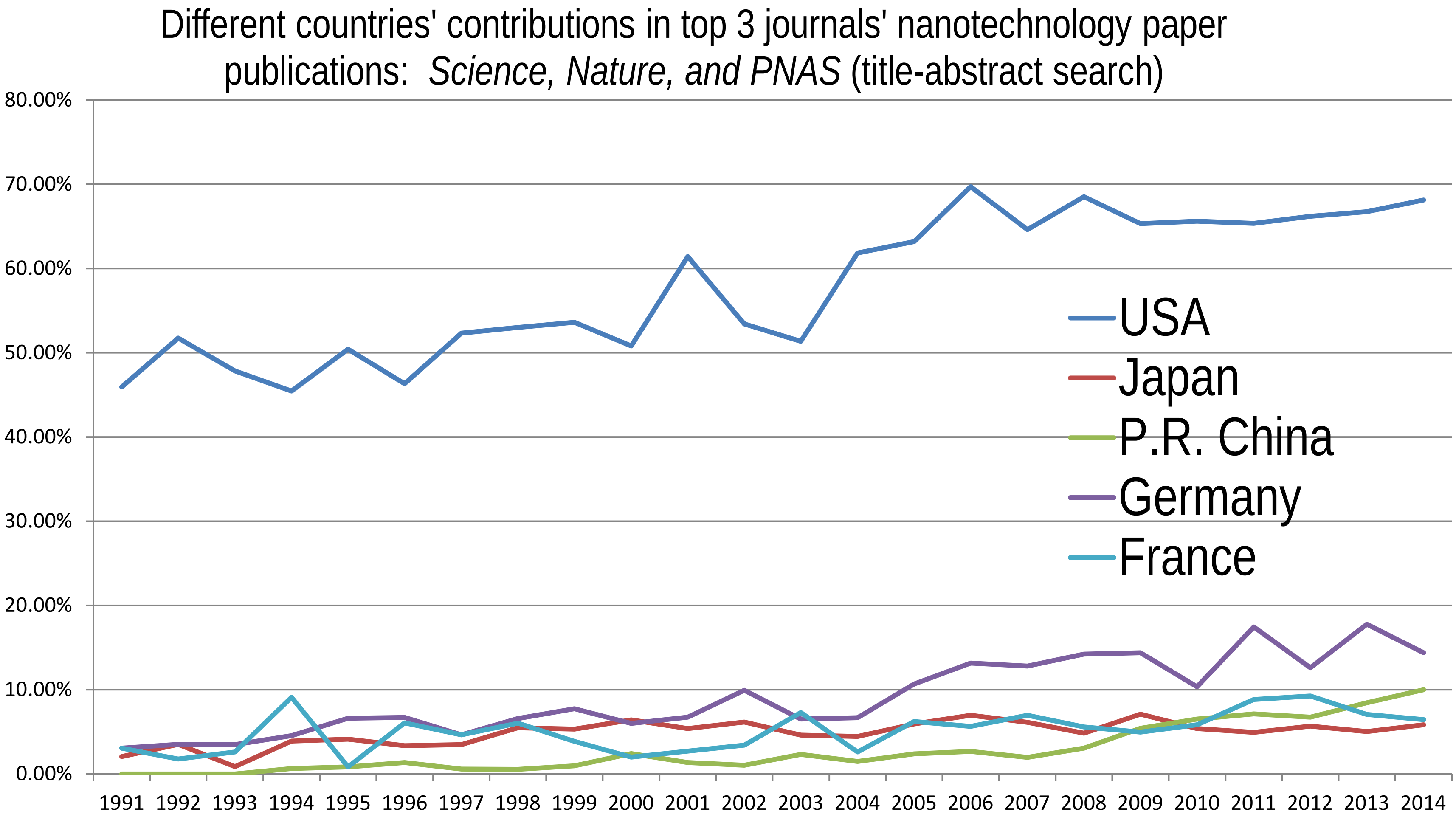
"Title-abstract" search for nanotechnology by keywords for six regions (update of NANO2, Fig 1 (Ref. 3) using the method described in (Ref. 7))



Rapid, uneven growth per countries

MC Roco, March 9 2015

Five countries' contributions to Top 3 Journals (Nature, Science, PNAS) in 2014, by individual journals



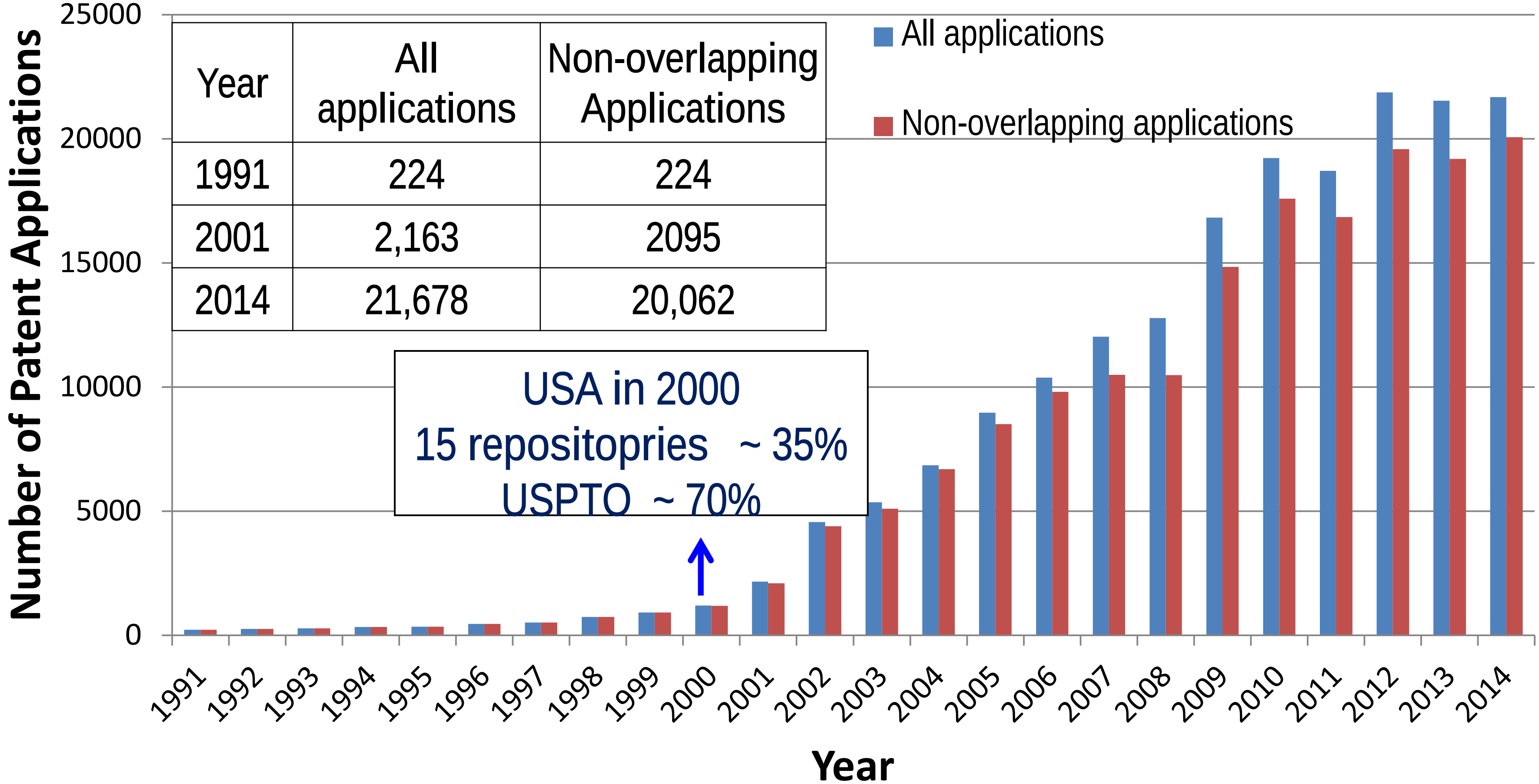
U.S. leads with about 66% (at least one author from US)

MC Roco, March 9 2015

Number of nanotechnology patent applications per year published annually (1991-2014)

"Title-abstract" search for nanotechnology by keywords (Chen and Roco 2013, based on [4]))

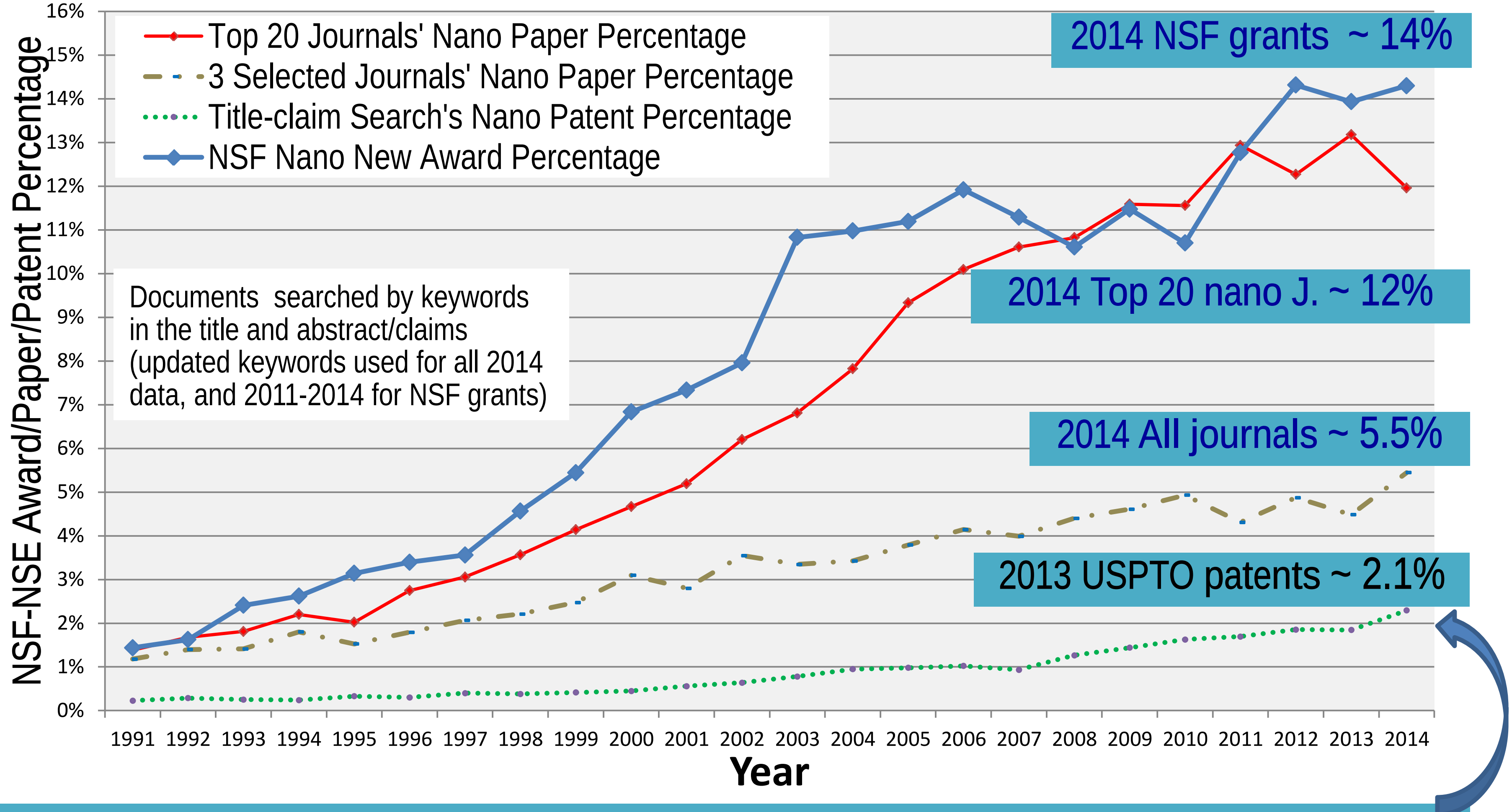
Year	All applications	Non-overlapping Applications
1991	224	224
2001	2,163	2095
2014	21,678	20,062



Longitudinal evolution of the total number of nanotechnology patent applications in the 15 repositories per year ("title-abstract search by keywords" 1991–2014). Data was obtained from UA's NSE database (crawled from Espacenet).

Percentage rate of penetration of nanotechnology in NSF awards, WoS papers and USPTO patents (1991-2014)

(update Encyclopedia Nanoscience, Roco, 2015)



Est. Market / US GDP: 2014 ~ 2% ; 2016 ~ 3% ; 2020 ~ 7% (if 25% market growth rate)

Nanotechnology penetration in economy

(Nano 2020, Lux Research)

U.S.	2000	2010	Est. in 2020
Semiconductor industry	0	60%	100%
New nanostructured catalysts	0	~ 35%	~ 50%
Pharmaceutics	0	~ 15%	~ 50%
Wood	0	0	~ 20%

PENETRATION Nanotechnology	Low	Medium	High
Catalysts			X
Coatings			X
Insulation	X		
Filtration		X	
Transportation			X
Robotics		X	
Mobile electronics			X
Displays			X
Packaging (electronics)	X		
Thermal management	X		
Batteries		X	
Supercapacitors		X	
Paint			X
Diagnostic and monitoring sensors		X	
Cosmetics			X
Food products and packaging	X		
Personal care products		X	
Sunscreen			X
Packaging (medical)	X		
Surgical tools			X
Implantable medical devices		X	
Contrast agents (medical)	X		
Lab supplies		X	
Fuel cells			X
Hydrolysis		X	
Solar cells			X
Grid storage		X	
Water treatment and purification		X	
Air purification			X
Environmental monitoring	X		

Nanotechnology-enabled products by sectors in 2014

Materials and manufacturing: Fiber reinforced plastics, nanoparticle catalysts, coatings, insulation, filtration, transportation (cars, trucks, trains, planes, ships), robotics (actuators and sensors)

Electronics and IT: Semiconductors, mobile electronics and displays, packaging, thermal management, batteries, supercapacitors, paint

Health care and life sciences: Diagnostic and monitoring sensors (cancer), cosmetics, food products and packaging, personal care products, sunscreen, packaging, surgical tools, implantable medical devices, filtration, treatments (cancer radiation therapies) and medications formulations, contrast agents, quantum dots in lab supplies like fluorescent antibodies

Energy and environment: Fuel cells, hydrolysis, catalysts, solar cells, insulation, filtration, supercapacitors, grid storage, monitoring equipment (sensors), water treatment and purification

(from industry sources, Lux Research)

2001-
2014

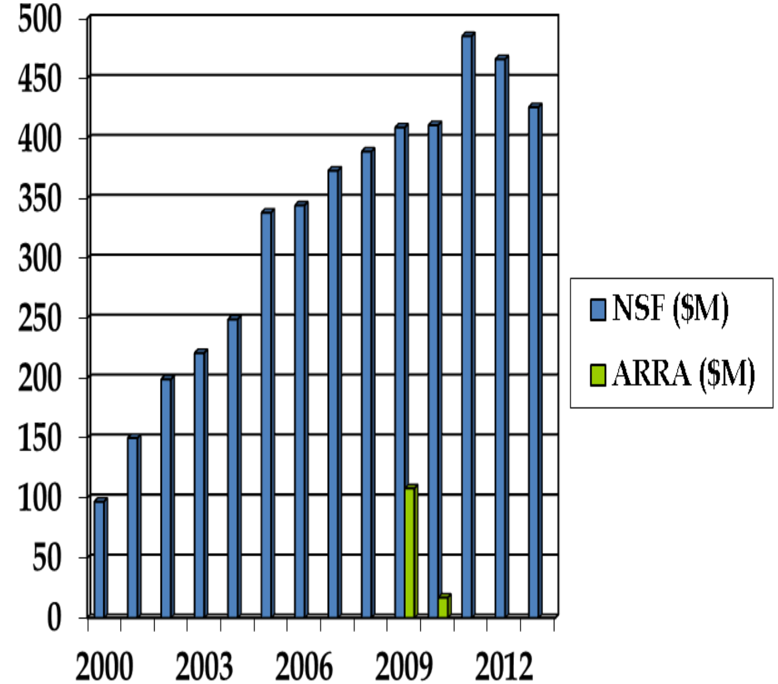
NSF – discovery, innovation and education in Nanoscale Science and Engineering (NSE)

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

FY 2015 Budget Request - $412 million

Interval FYs 2000-2013: U.S. average - $23.5 / capita

– Fundamental research
  ~ 5,000 active projects
  in all NSF directorates

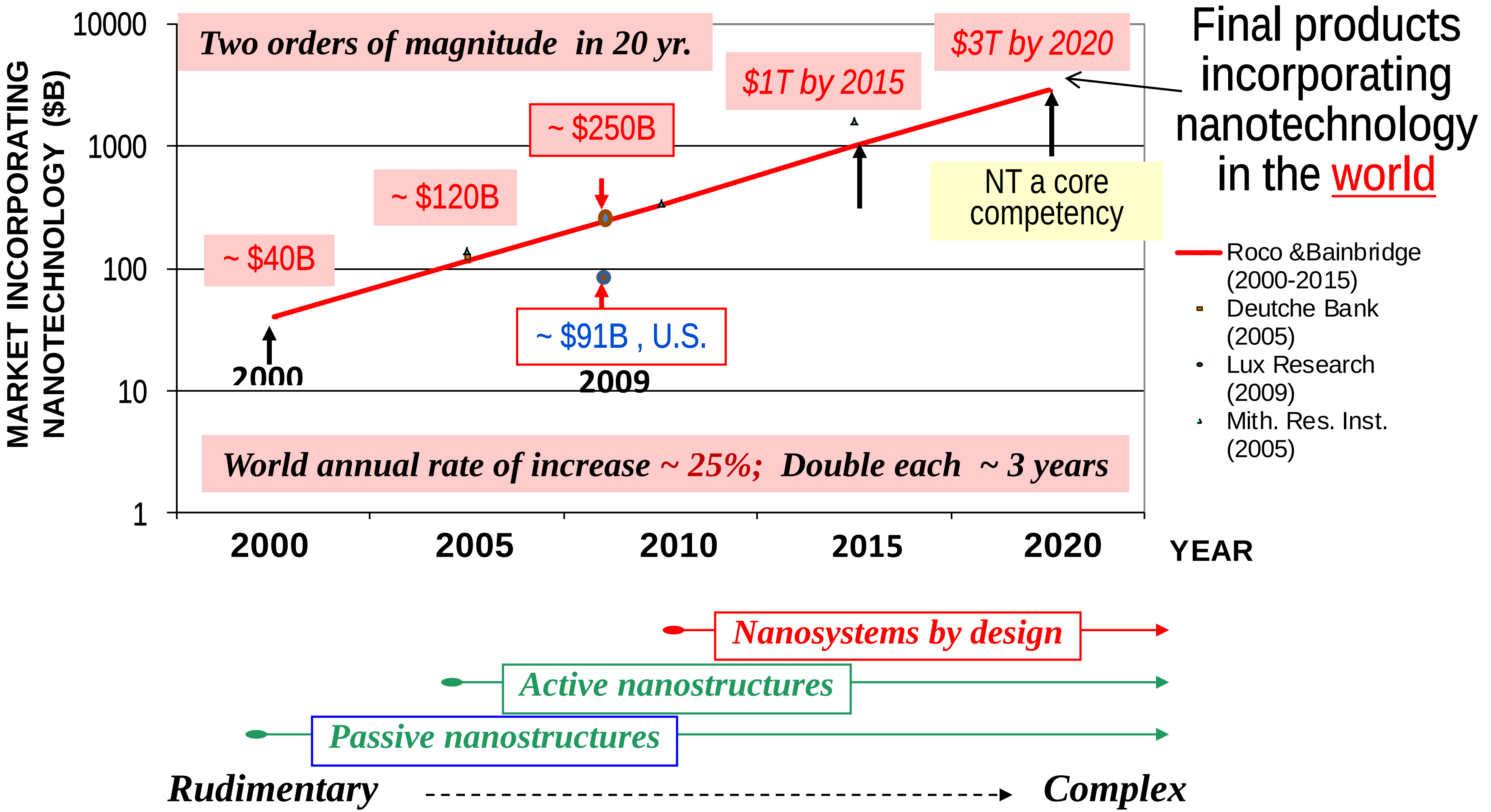


– Establishing the infrastructure
  26 large centers, 2 general
  user facilities, teams

– Training and education
  > 10,000 students and teachers/y; ~ $30M/y

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

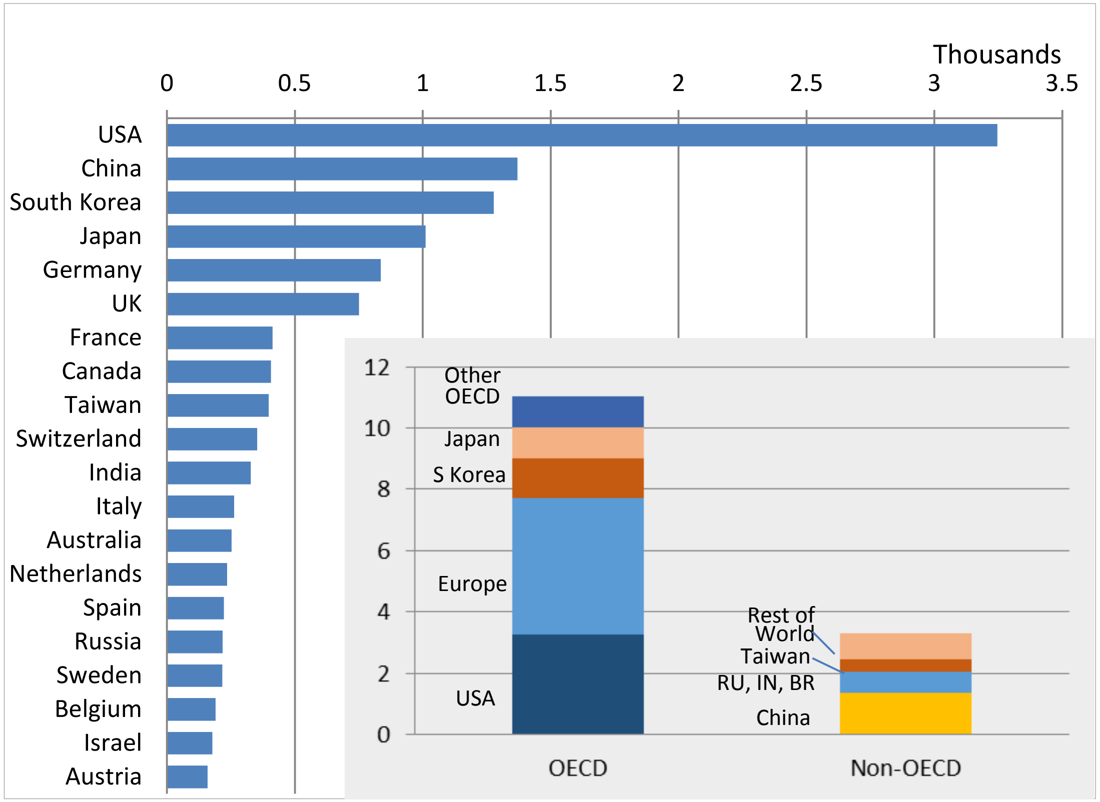
- Estimation made in 2000 after international study in > 20 countries
- THE ESTIMATIONS ARE IN AGREEMENT WITH SURVEYS UNTIL 2010; then, LUX surveys larger in 2012 (world $731B, US $235B; ~40% annual increase)



Ref: Roco and Bainbridge, "Societal Implications.." 2001; and NANO2, Fig 3 [3]

Corporate entry into nanotechnology

Leading countries, 2011-2014*



*Corporate entry in the nanotechnology domain through patent applications (1990-Spring 2014) or publications (1990-2014), by corporate organizations.
Source: P. Shapira, J. Youtie, and Y. Li (Georgia Institute of Technology and Center for Nanotechnology in Society CNS-ASU), analysis of records (January 2015) in the EPO Worldwide Patent Statistical Database (PATSTAT) and Thomson Reuters Web of Science. PATSTAT data was provided by L. Kay (CNS-UCSB).
Notes: Analysis of corporate organizations (N=12,495). Organizations matched where possible to reduce most apparent duplicated variations of corporate names. Universities and non-profits excluded. OECD = 34 member countries as of January 2015. Europe = 25 European countries that are OECD members.
Nanotechnology search terms based on S. Arora, A. Porter, J. Youtie & P. Shapira (2013).

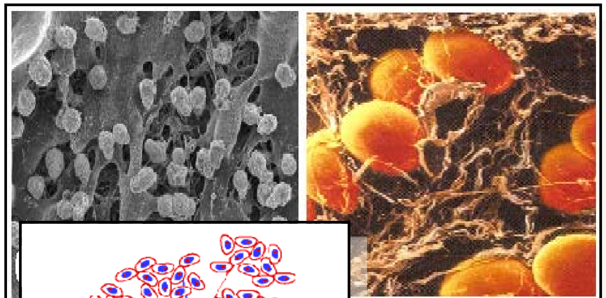
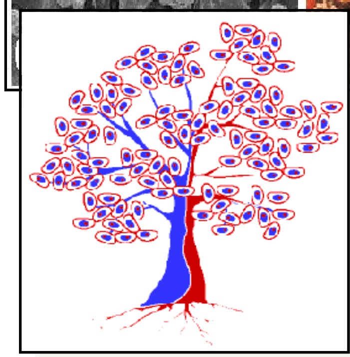
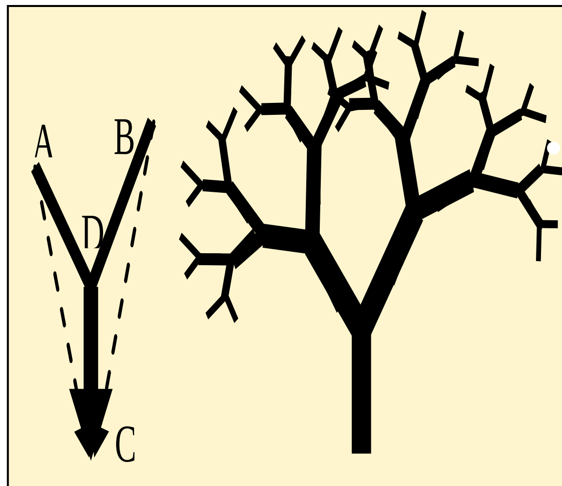
Paths to sustainable nanotechnology

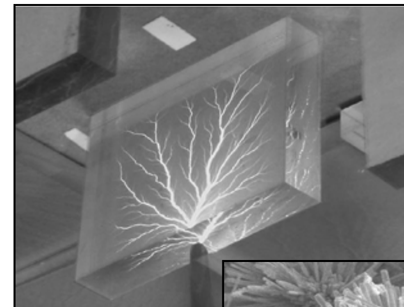
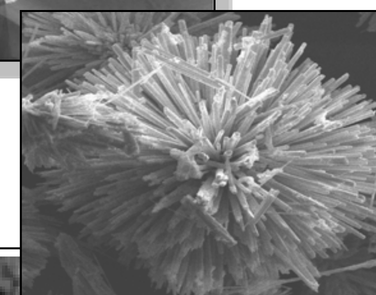
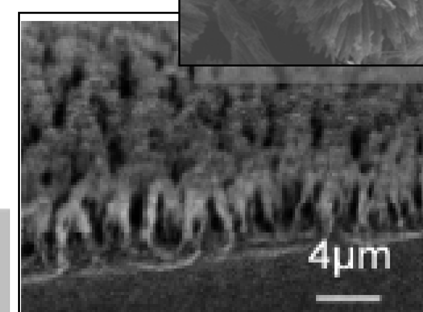
- Nanotechnology (less material, energy, water and waste) immersion in socio-economic projects
- Transformative and responsible S&T governance: sustainable nanotechnology development and societal sustainability (economic, social, cultural, for communities) using nanotechnology
- Convergence with other fields to create new S&T platforms
- Establish sustainability research & educ. programs

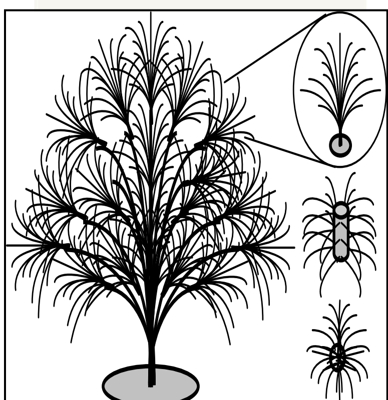
Leave molecules and nanostructure to do what they do well

preference to non-covalent bonds (lower energy, pressure, temperature)

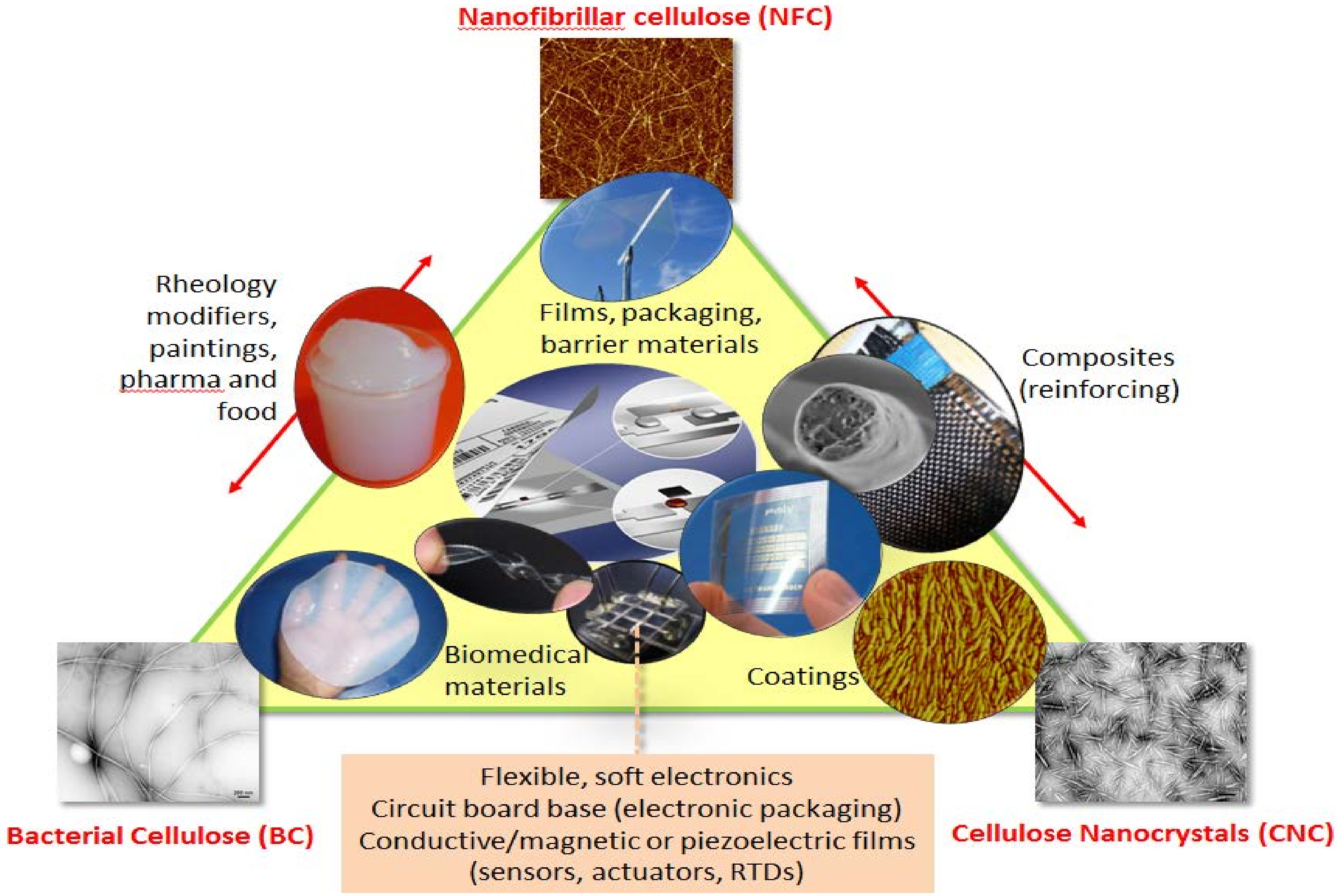
Ex: Bioinspired Random Fractal Structures



Cellulose Nanomaterials



O.J. Rojas, NCSU, 2014

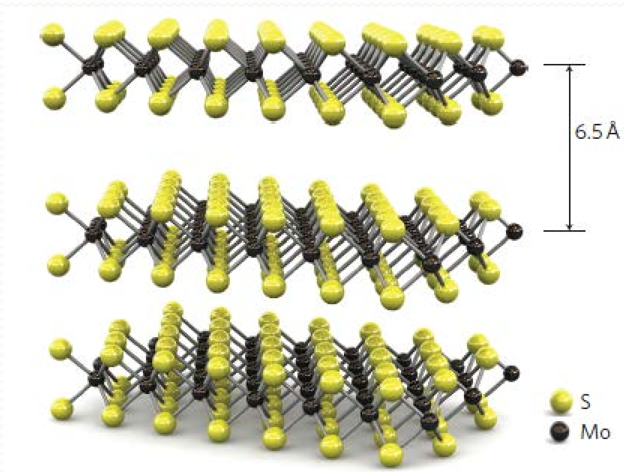
Nanocomposite 2D materials beyond graphene – for sustainable & safe manufacturing

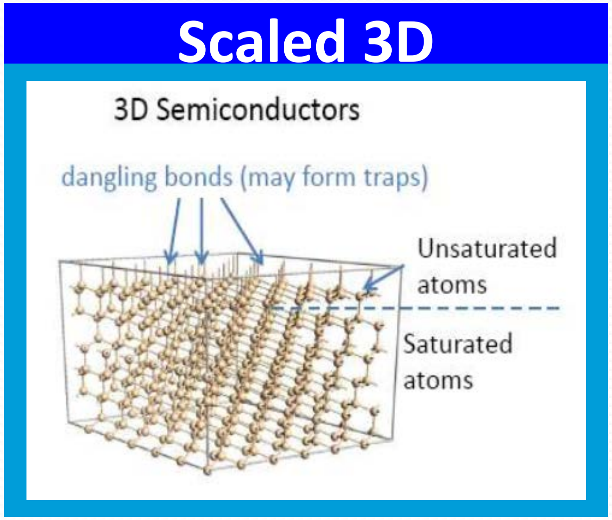
- Various layered 2D materials exist: oxides, nitrides, sulfides
- Van der Waals solids: e.g. 2D MoS2
- MoS2 turns from indirect band-gap semiconductor to direct band-gap

➢ Bulk MoS2 crystal, like graphite – Molybdenite – earth abundant

➢ Modular materials and systems

➢ 3D assembling

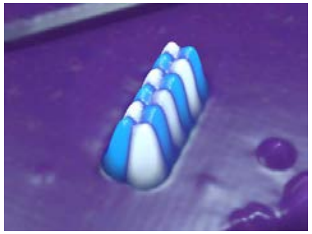




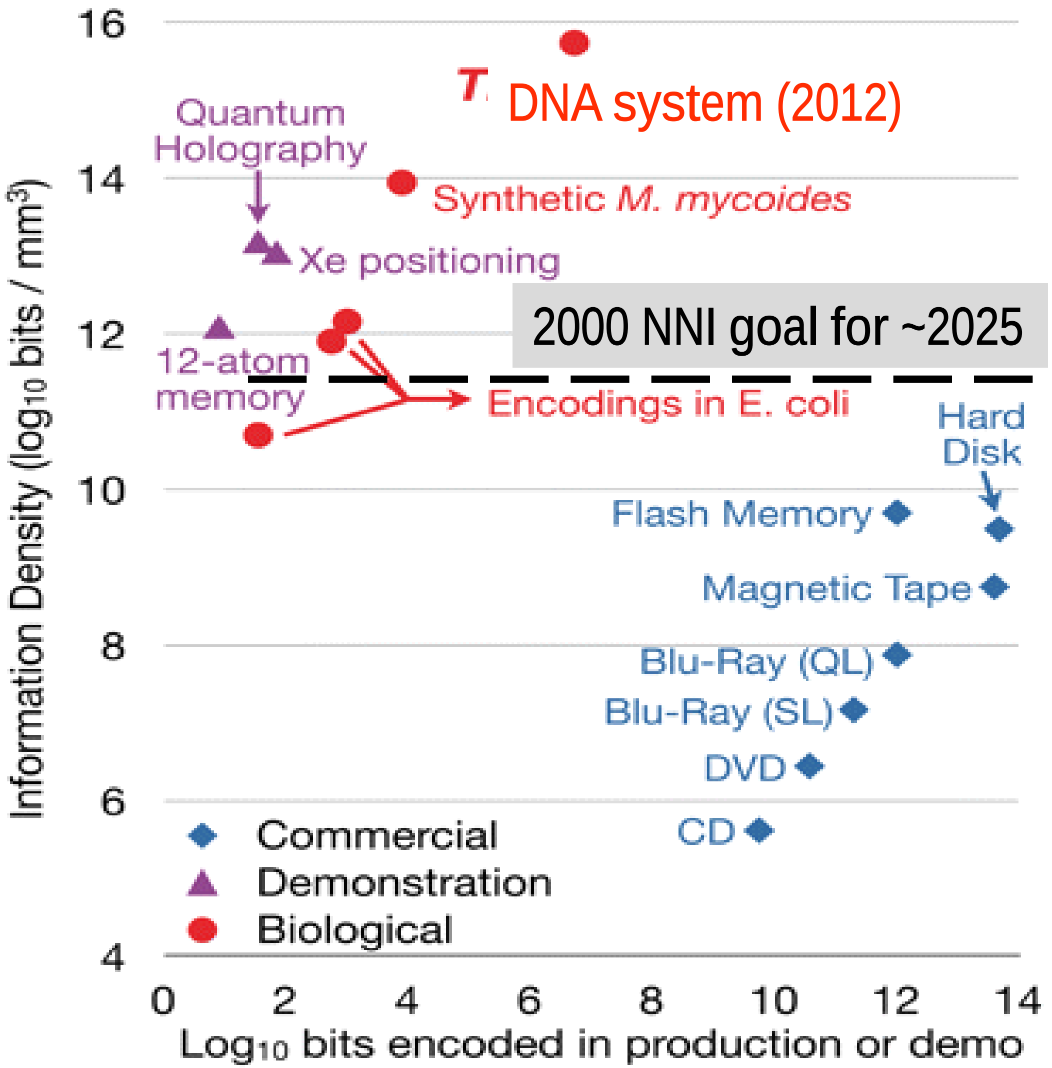
12-atom and DNA data memory systems

2000: NNI goal for ~2025 that all information from Library of Congress in a device of size of sugar cube **1cm cube** (Pres. Clinton) – was then labeled as too ambitious.

Jan 2012: 12 atom structure, store it in **1cm cube**
(Science, 2012)
IBM



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

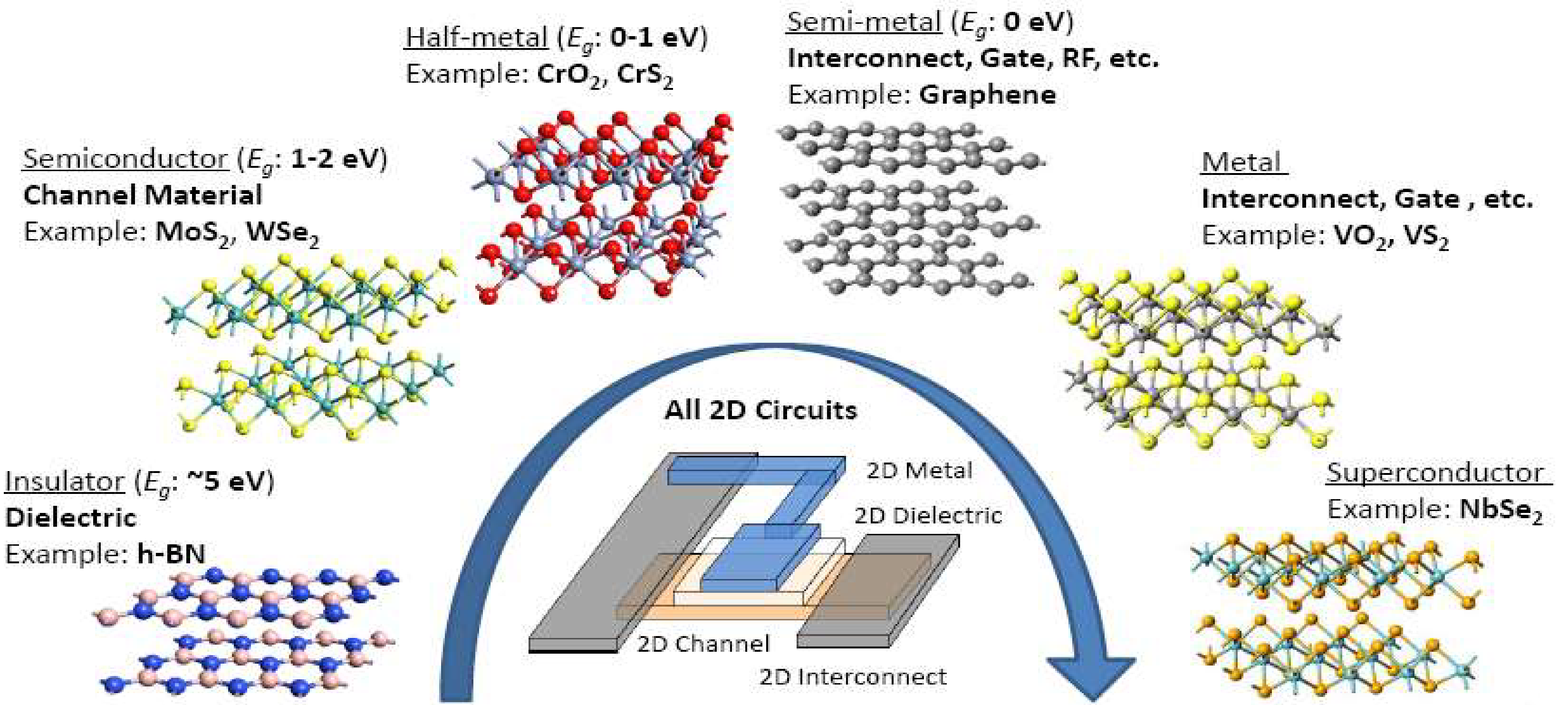


Modular Nanosystems

Example: using 2D electronic materials

- A Broad Range of Choices:
  - From Insulator to Superconductor
  - Provide Possibility for 2D Circuits

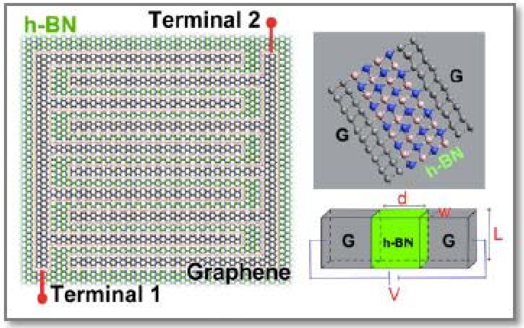
Graphene Family (C, Si, BN)
MX_2 (TMD) Family (>88 members)

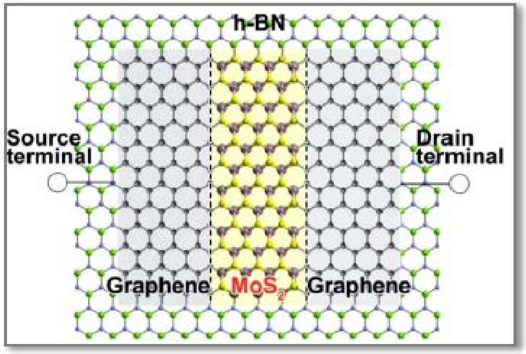


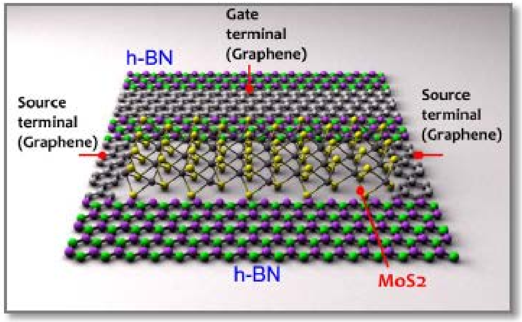
Courtesy Kaustav Banerji (UCSB)

Nanomodular 2D/3D structures for devices

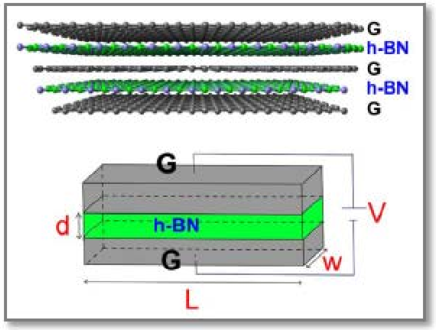
In-Plane 2D Devices

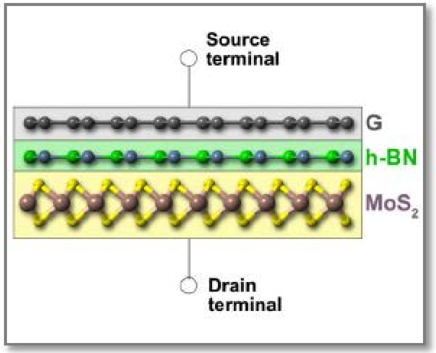


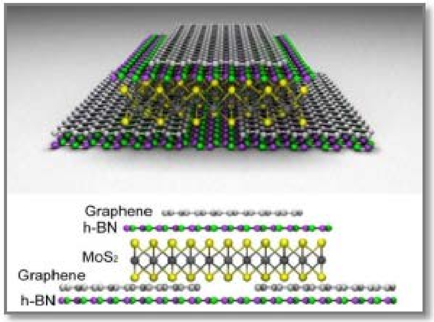




Stacked 2D Devices







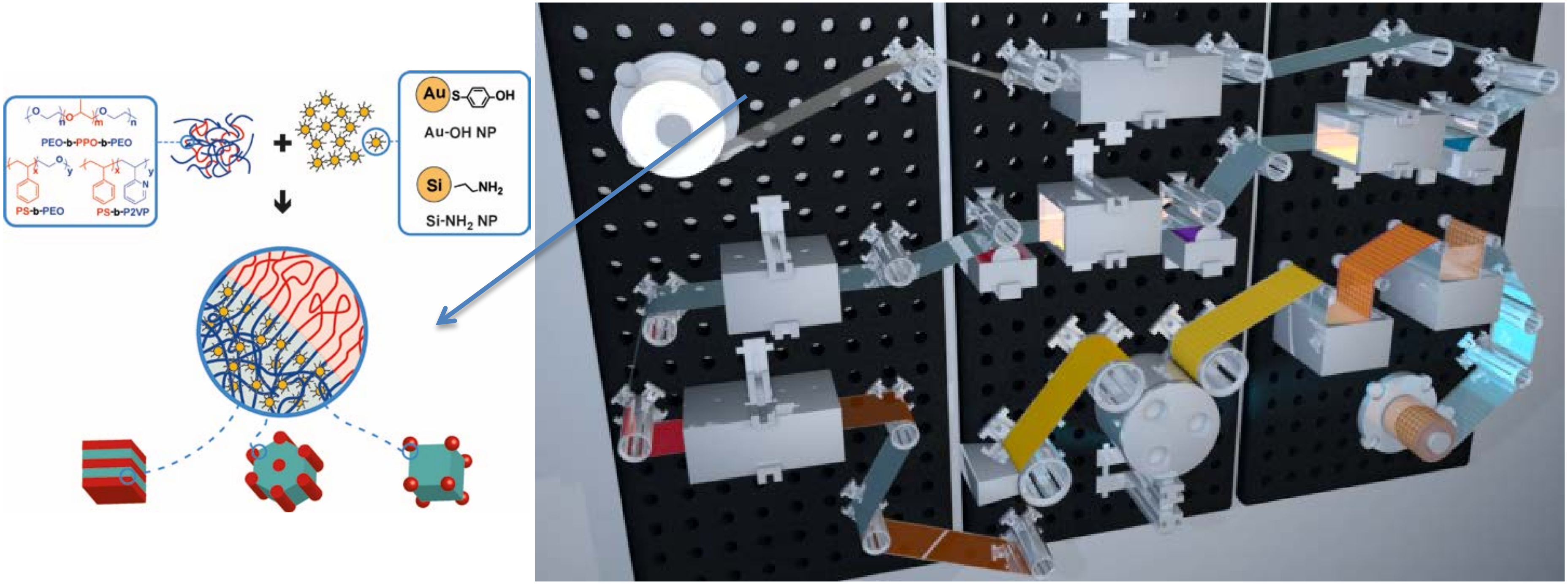
NANO - MATERIALS/SYSTEMS/DEVICES BY DESIGN

Courtesy P. Ajayan (Rice U.)

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

- Center for Hierarchical Manufacturing (CHM) *Video*
  - U. Mass Amherst/UPR/MHC/Binghamton
  Integrated roll-to-roll printed nanoelectronics
- Center for High-Rate Nanomanufacturing (CHN)
  - Northeastern/U. Mass Lowell/UNH
  Large-scale, directed assembling of nanostructures
- Center for Scalable and Integrated Nanomanufacturing (SINAM)
  - UC Berkeley/UCLA/UCSD/Stanford/UNC Charlotte
  Plasmonic processes for integrated systems
- Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS)
  - UIUC/CalTech/NC A&T
  Combined methods and materials for manufacturing

Open-access network
www.nanomanufacturing.org beta.internano.org



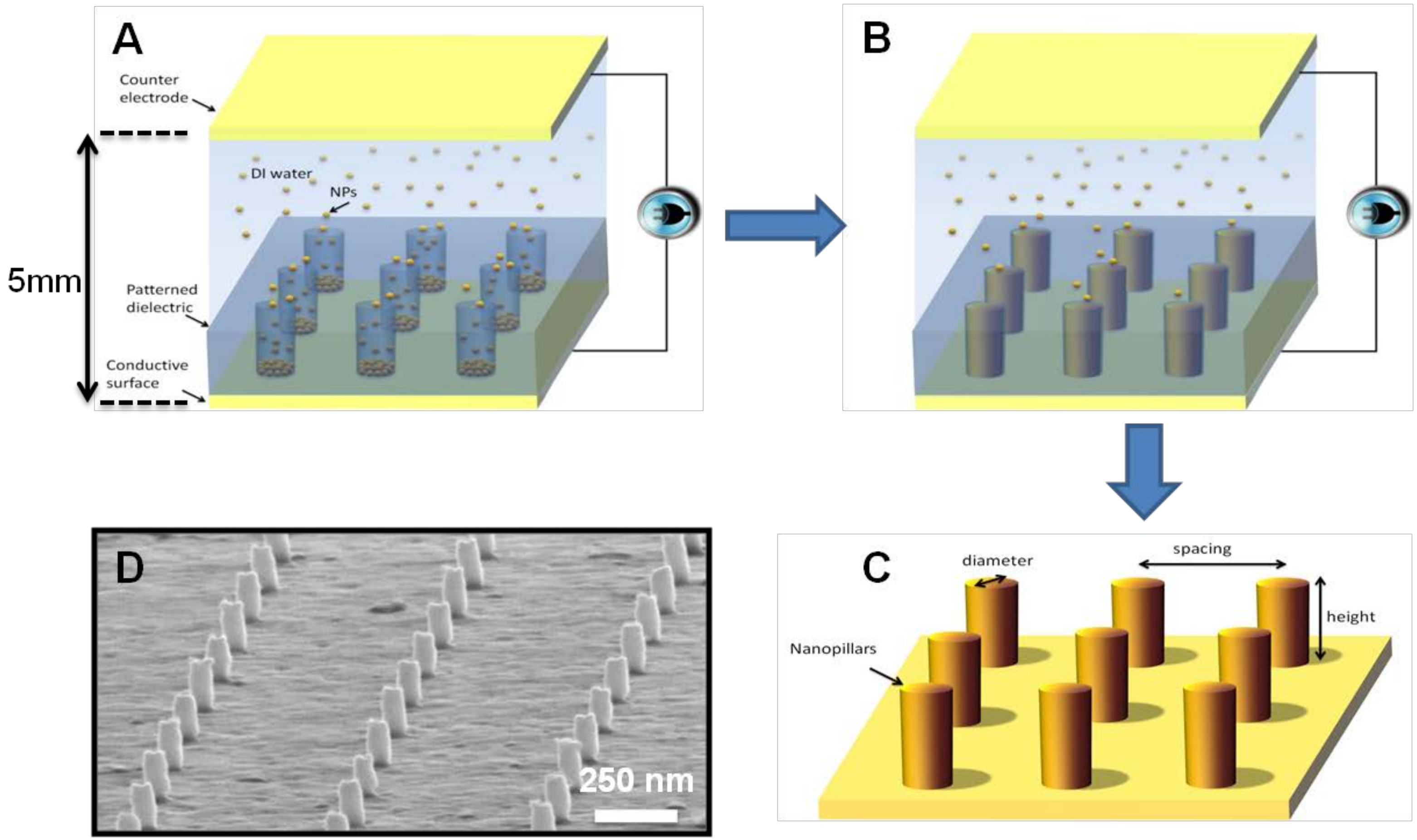
Additive selfassembling on roll-to-roll process

(U. Mass. – Amherst, J. Watkins)

Additive-driven self assembly yields well ordered periodic assemblies of nanoparticle polymer hybrids (left) while R2R nanoimprint lithography produces sub-100 nm device patterns 70 nm grating pattern shown (right).

3-D nanostructure manufacturing process using nano-colloids (Northeastern U.)

Center for High-rate Nanomanufacturing



Manufacturing of 3-D nanostructures using directed nanoparticle assembly process. (A and B) NPs suspended in aqueous solution are (A) assembled and (B) fused in the patterned via geometries under an applied AC electric field. (C) Removal of the patterned insulator film after the assembly process produces arrays of 3-D nanostructures on the surface. (D) Scanning electron microscopy (SEM) image of gold nanopillar arrays. Economic approach.

Center for High-rate Nanomanufacturing

Nanoscale Offset Printing System

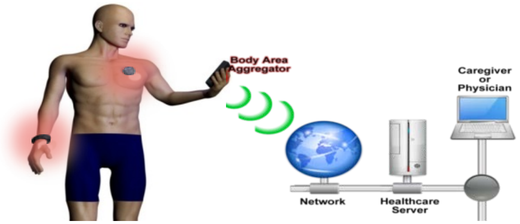
2014 spin-off of Northeastern University

NanoOPS will enable diverse manufacturing of nano-enabled products and devices. It eliminates some of the high-cost barriers to businesses seeking to fabricate devices and systems with of nanomaterials.

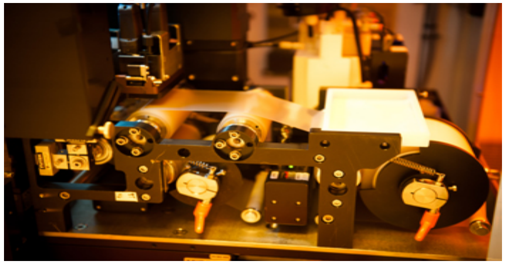
Nanosystems Engineering Research Centers

Three NSF awards of $55.5 million (2012-2017)

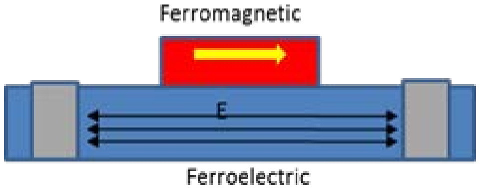
- **Advanced Self-Powered Systems of Integrated Sensors and Technology**, North Carolina State University: self-powered wearable systems that simultaneously monitor a person's environment and health



- **Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies**, UT-Austin: high-throughput, reliable, and versatile nanomanufacturing process systems with illustration to mobile nanodevices.



- **Transformational Applications of Nanoscale Multiferroic Systems**, UCLA: exploit nanoscale phenomena to reduce the size and increase the efficiency of components and systems whose functions rely on the manipulation of either magnetic or electromagnetic fields.



NRI Emerging Research Themes in Nanoelectronics

- plans for 10-20 years ahead -

The Field Effect Transistor (FET), sparked the information technology revolution decades ago. Oppor*tunities outside the "FET box" to reduce energy dissipation in logic are vast and suitable to be addressed by U-G-I partnerships:*

- *Abrupt Switching (i.e. improve Conventional Logic)*
- *Adiabatic Switching*
- *Reversible Logic*
- *Quantum Computing*, in which adiabatic switching and reversible logic circuits are implemented in quantum systems.

Programs on sustainable and safe nanomanufacturing

- Sustainable Nanomanufacturing a part of NNI and in support of Advanced Manufacturing (NSF, NASA, DOE, DOD, NIST, USDA ..)

- Nanotechnology Signature Initiative : www.nano.gov/NSINanomanufacturing

  - Scalable Nanomanufacturing (NSF 2011-2015)

  - NSF National Nanomanufacturing Network (NSF 2005-2016), http://www.internano.org/content/ newsletter-bounces@nanomanufacturing.org

Sustainable development: advances last ten years (1)

- Local initiatives are blossoming around the world;

  Non-profits specialize in helping communities achieve sustainability (e.g., ICLEI);

  Companies are increasingly implementing and promoting their sustainable practices
- Standards (e.g., ISO – 14000 series), certifications (e.g., LEED for buildings), and labeling (e.g., Energy Star) are proliferating
- Incipient programs to address long-term challenges

Sustainable development advances in the last ten years (2)

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

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

Convergence of Knowledge, Technology, and Society:

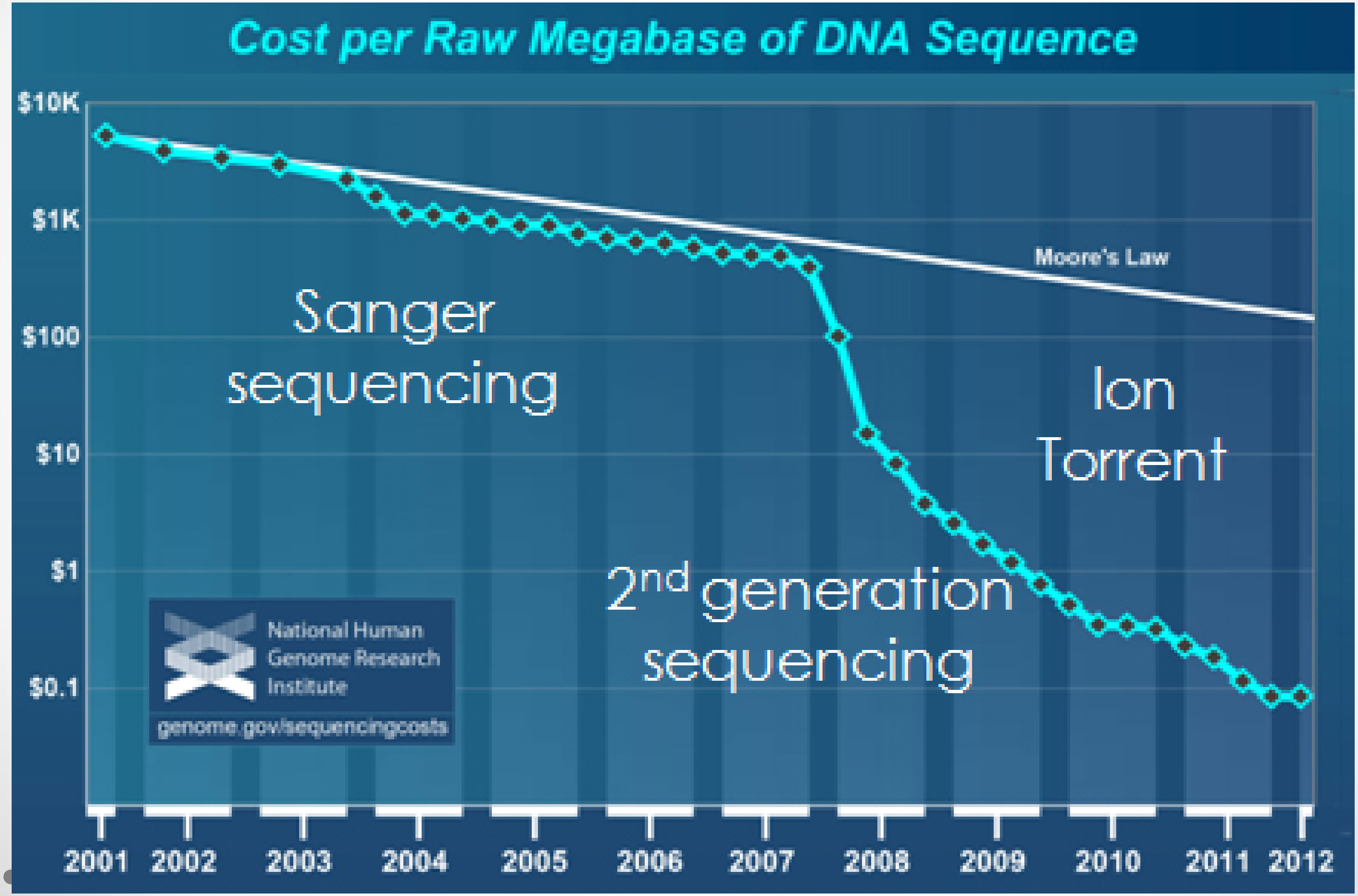
Beyond Convergence of Nano-Bio-Info-Cognitive Techologies

www.wtec.org/NBIC2-Report

Five convergence principles for progress applied in five human activity platforms.

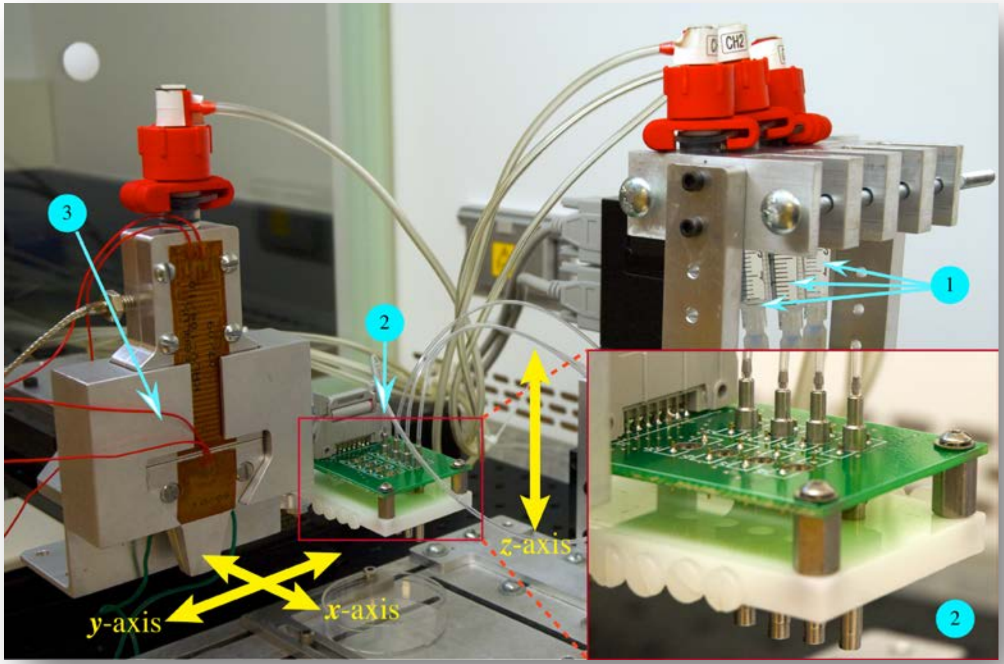
Gene sequencing cost after adoption of methods from nanoelectronics

(after NIH/NHGRI, K.A. Wetterstrand, 2013)



Tissue Engineering and NT meets 3-D Printing

- 3D printing technology
- Tissue engineering
- Nanotechnology
- Additive manufacturing enables printing of scaffolds with nanoscale precision for tissue engineering

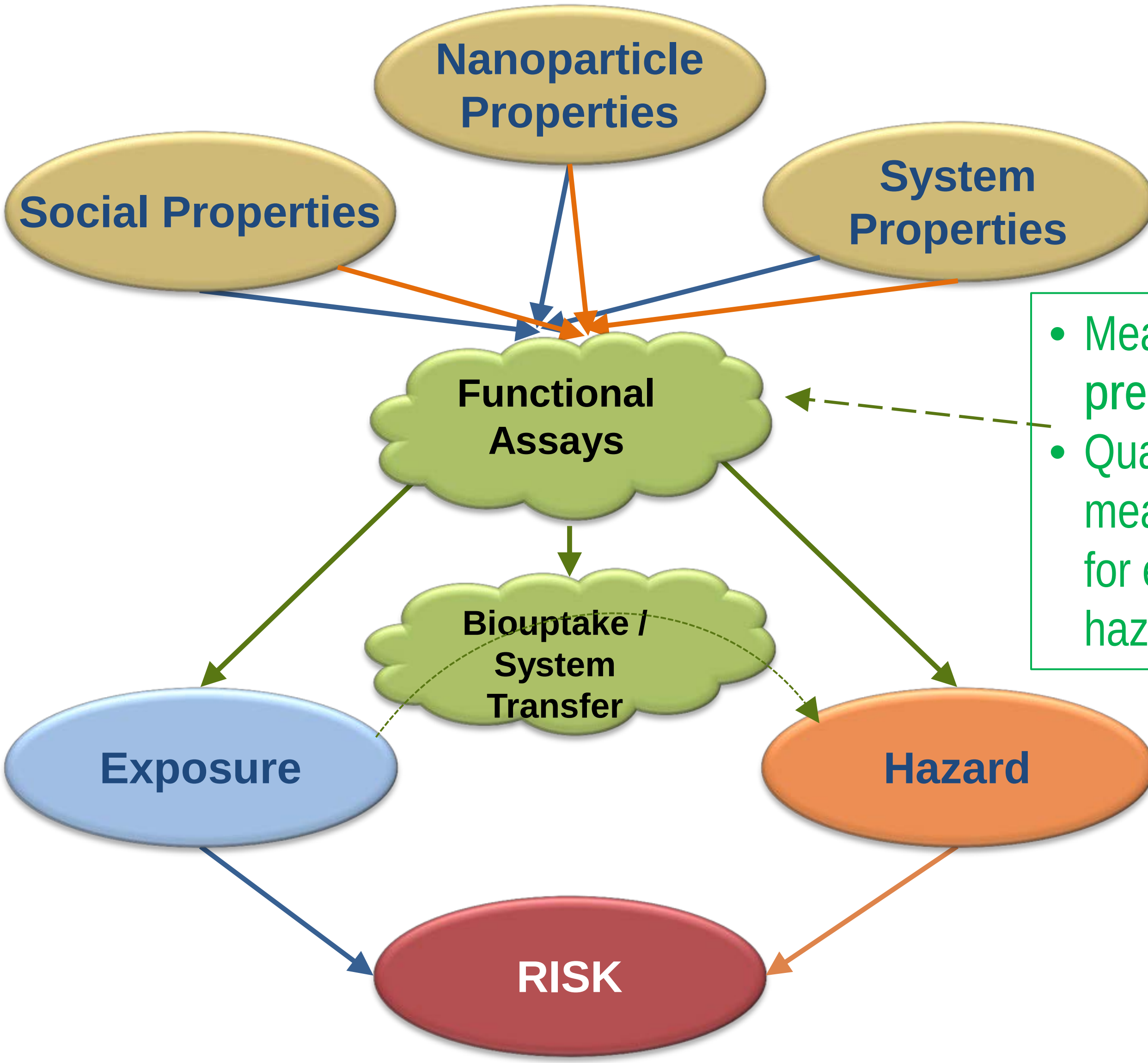


Doi, RPI

Convergence of four very different research directions

Example of convergent approach in nano-EHS

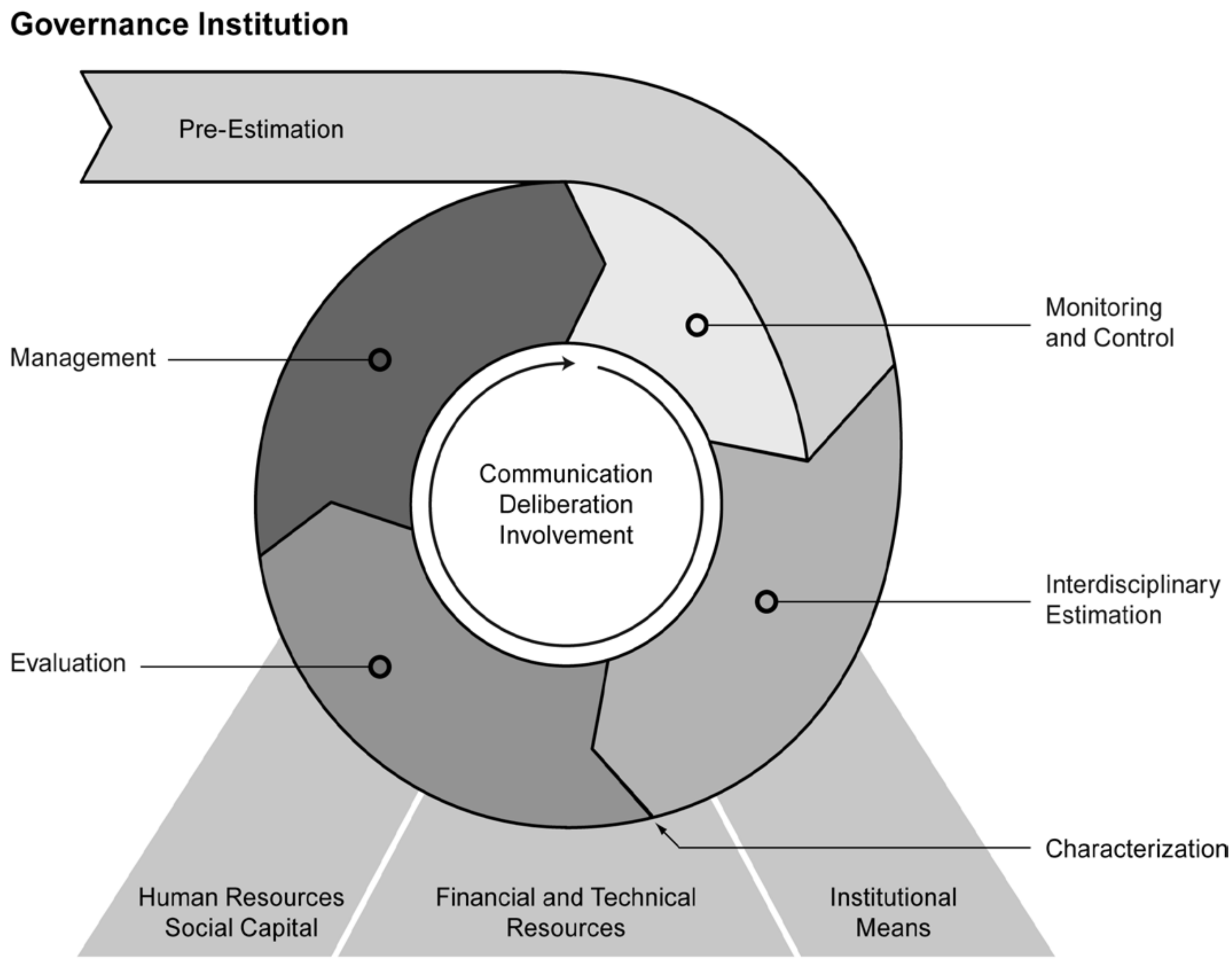
(risk estimation, CEINT, Duke University)



- Measurement in prescribed system
- Quantifies a meaningful process for exposure, hazard or both

Adaptive and integrative risk governance model

(Renn 2015, p. 280, in Convergence of S&T)

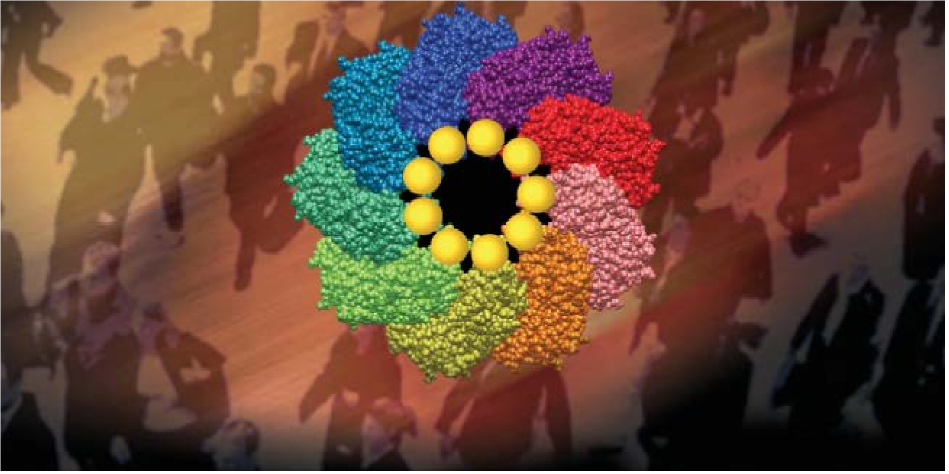


Relationship between stakeholder participation and risk categories in risk governance

(Renn 2015, p. 280 in Convergence of S&T)

Actors	Agency Staff	Agency Staff Scientists/ Researchers	Agency Staff Scientists/ Researchers Affected stakeholders	Agency Staff Scientists/ Researchers Affected stakeholders « Civil society »
Type of participation	Instrumental Find the most cost-effective way to make the risk acceptable or tolerable	Epistemological Use experts to find valid, reliable and relevant knowledge about the risk	Reflective Involve all affected stakeholders to collectively decide best way forward	Participative Include all actors so as to expose, accept, discuss and resolve differences
Dominant risk characteristic	Simple	Complexity	Uncertainty	Ambiguity

As the level of knowledge changes, so also will the type of participation need to change



World acceptance of nanotechnology

Recognized as
<u>an international scientific and technology revolution</u>
by industry, economists, politicians, and philosophers
(multidisciplinary community of 2M, publ. companies 12K, ~ all universities)

In all large research institutions

Small is not dangerous, it is at the foundation of life!

"We saw the future yesterday"

Several priorities

- Integration of knowledge at the nanoscale and of nanocomponents in nanosystems. Ex: Nanomodular systems; Nanoengineering; NBIC systems with emerging nano-bio behavior (hybrid, robot, synthetic)

- Nanotechnology for increased productivity and sustainability. Ex: Reducing energy dissipation in nanoelectronics by >100; Water resources; Wood, agriculture and food systems

- Institutionalize nanotechnology: Ex: Create standing organizations and programs for sustained support of future nanotechnology efforts

Related publications

(4 reports with R&D recommendations for 2020)

1. *"The new world of discovery, invention, and innovation: convergence of knowledge, technology and society"* (Roco & Bainbridge, JNR 2013a, 15)
2. *NANO1: "Nanotechnology research directions: Vision for the next decade"* (Roco, Williams & Alivisatos, Springer, 316p, 2000)
3. *NANO2: "Nanotechnology research directions for societal needs in 2020"* (Roco, Mirkin & Hersam, Springer, 690p, 2011a)
4. *NBIC1: "Converging technologies for improving human performance: nano-bio-info-cognition"* (Roco & Bainbridge, Springer, 468p, 2003)
5. *NBIC2: "Convergence of knowledge, technology and society: Beyond NBIC"* (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)
6. *"Nanotechnology: from discovery to innovation and socioeconomic projects: 2000-2020"* (Roco; CEP, 2011b)
7. *"Mapping nanotechnology innovation and knowledge: global and longitudinal patent and literature"* (Chen & Roco, Springer, 330p, 2009)
8. *"Global nanotechnology development from 1991 to 2012"* (JNR 2013c)
9. "Long View of Nanotechnology Development: the NNI at 10 Years"(JNR, 2011d)