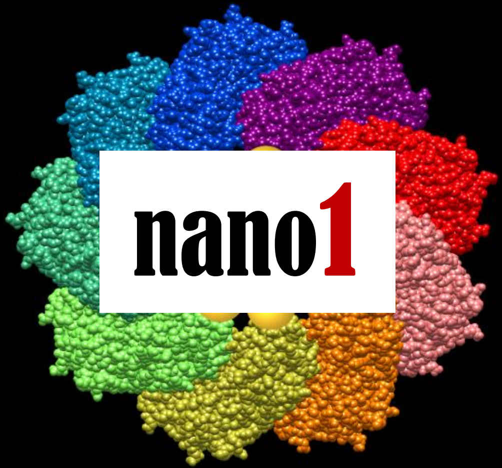
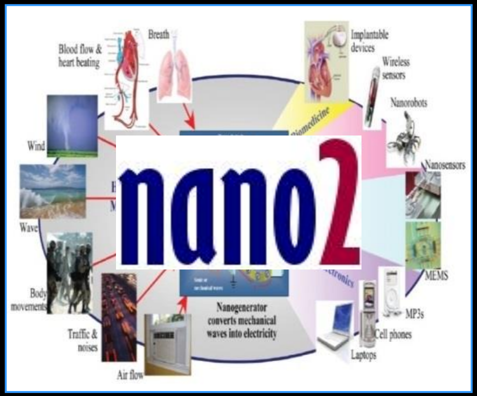
2000



2010



2020

2030

Nanotechnology Future and Sustainability Challenges

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

SNO Conference, Portland (OR), November 8, 2015

*Support for a foundational S&T field requires **a long/integrated view***

- **2000-2030 nanotechnology development in 3 stages**
  - **- Nanocomponent basics (about 2000-2010)**
  - **- System integration (2010-2020)**
  - **- Technology divergence (2020-2030)**
- **Sustainable nanotechnology challenges**
- **NSF/NNI and international context**

Sustainable and resilient society

Three overarching goals for nanotechnology development

- **Increase productivity**
  (in industry, agriculture, transportation, ..)
- **Quality of life**
  (health, culture, security, aging, ..)
- **Sustainable and resilient society**
  (physical surroundings, resources, biodiversity, economic, social, cultural, ..)

Sustainable and resilient society - many facets -

http://www.cnhlcms.org/uploads/hands_earth_many2_280x240.JPG

Social (population growth and needs, governance, enduring democracy)

economic (knowledge, technology, materials, water, energy, food, climate)

resilient (infrastructure, emergency response) and

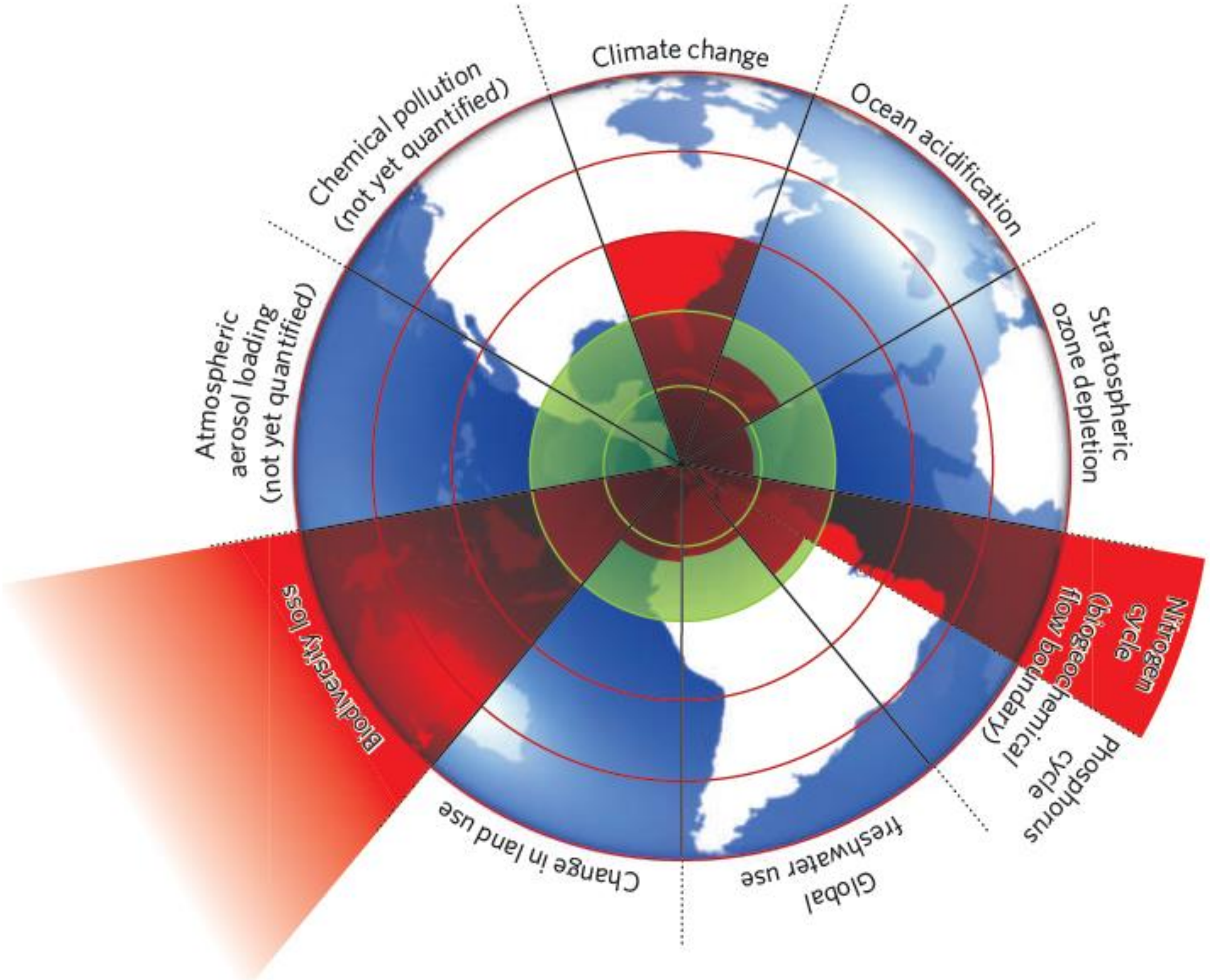
environmental (clean, renewable, biodiverse)

sustainability in planetary boundaries

Ref: Nano2 Report, 2011

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

- good criterion to evaluate the overall impact of nanotechnology -



Current most critical planetary boundaries are:

- **biodiversity**
- **nitrogen cycle**
- **climate change**

(Rockström et al. 2009)

Ref: Nano2 Report, 2011

Sustainability and resilient sustainability has emerged as key factor for human development

Need sustainable nanotechnology solutions for:

- **Energy, water, agriculture, food, mineral resources**
- **Green materials and manufacturing, habitat, transport**
- **Biodiversity, clean environment and climate change**
- **Human health and eell-being**
- **Urban and rural communities**
- **Societal engagement/acceptance, safety and public benefits for nanoproducts**

Ref: UN studies on human development

Nanotechnology and other convergent technologies solutions

Examples of possible targets

- **Nanosystems design and separations methods for desalinization**
- **Infinitely Recyclable, Re-usable, and Renewable Industrial Ecosystems (IR^3)**

  To reduce demand for virgin materials and carbon emissions
- **Community, buildings and household self-sufficiency**

  Focus on low-income communities and households

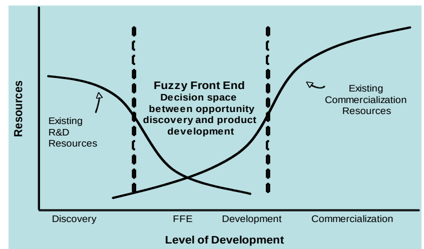
Nanotechnology Governance Principles

NANOTECHNOLOGY GOVERNANCE

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

<u>Four key functions:</u>

Visionary and anticipatory



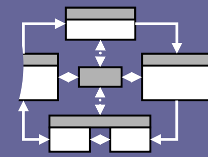
Transformative

Responsible

Benefit society

Sustain

Risk



→ Risk Governance

Inclusive

Ref: Roco and Bainbridge, Societal Implications of Nanoscience & Nanotech., 2001

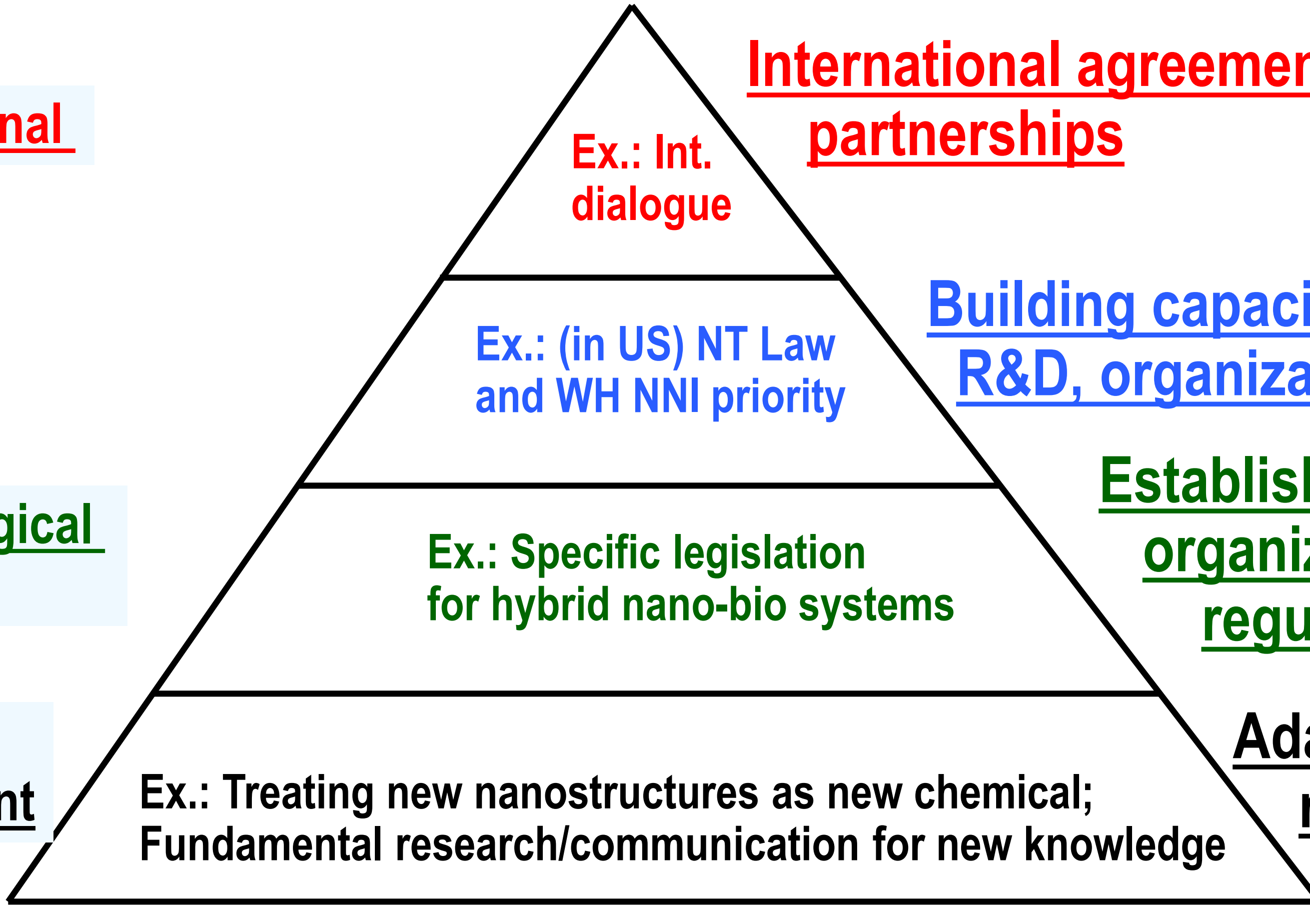
The functions of good governance are applied to
SEVERAL GOVERNANCE LEVELS

International — International agreements, partnerships

Societal — Building capacity in national R&D, organizations, policies

Technological system — Establish programs organizations and regulations

System component — Adapt existing regulations, organizations



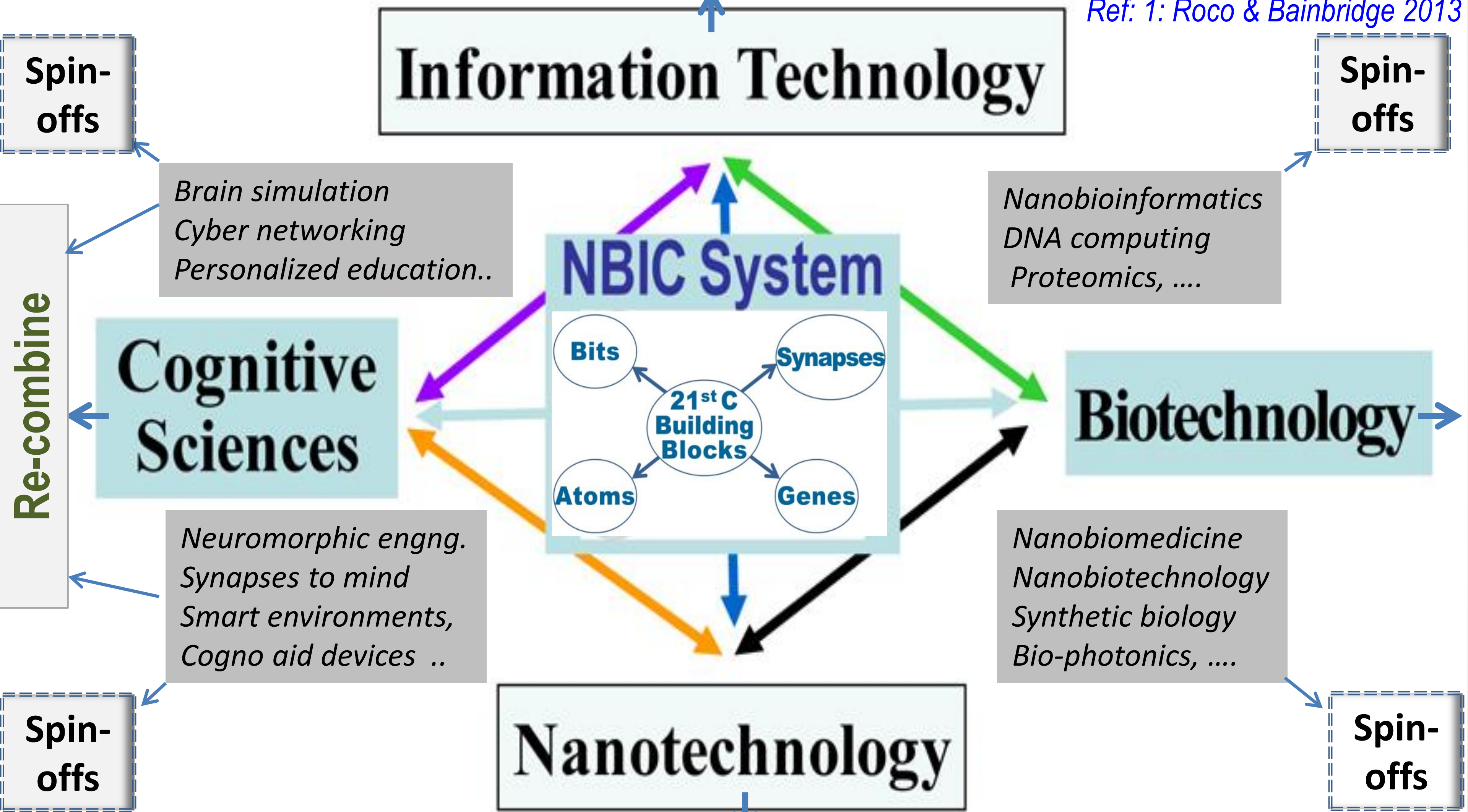
Ref: Roco, Possibilities for global governance of converging technologies, JNR, 2008 (10)

Long/integrated view of nanotechnology development

Emergence & convergence of foundational N B I C

Information Technology Spin-offs: Large databases, cyber-physical-social infrastructure, Internet of Things, connected sensorial systems, topical computer-aided design, cyber networks, ...

Ref: 1: Roco & Bainbridge 2013



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

Converging foundational technologies (NBIC) leads *to*
U.S. emerging S&T initiatives

Big Data | National Strategic Computing Initiative

National Information Technology R&D
(nitrd.gov)(with coordinating office)

Brain–like Computing

BRAIN Initiative
(whitehouse.gov/share/brain-initiative)

National Robotics Initiative

Info
Cogno
Bio
Nano

Biomedical / Health focus

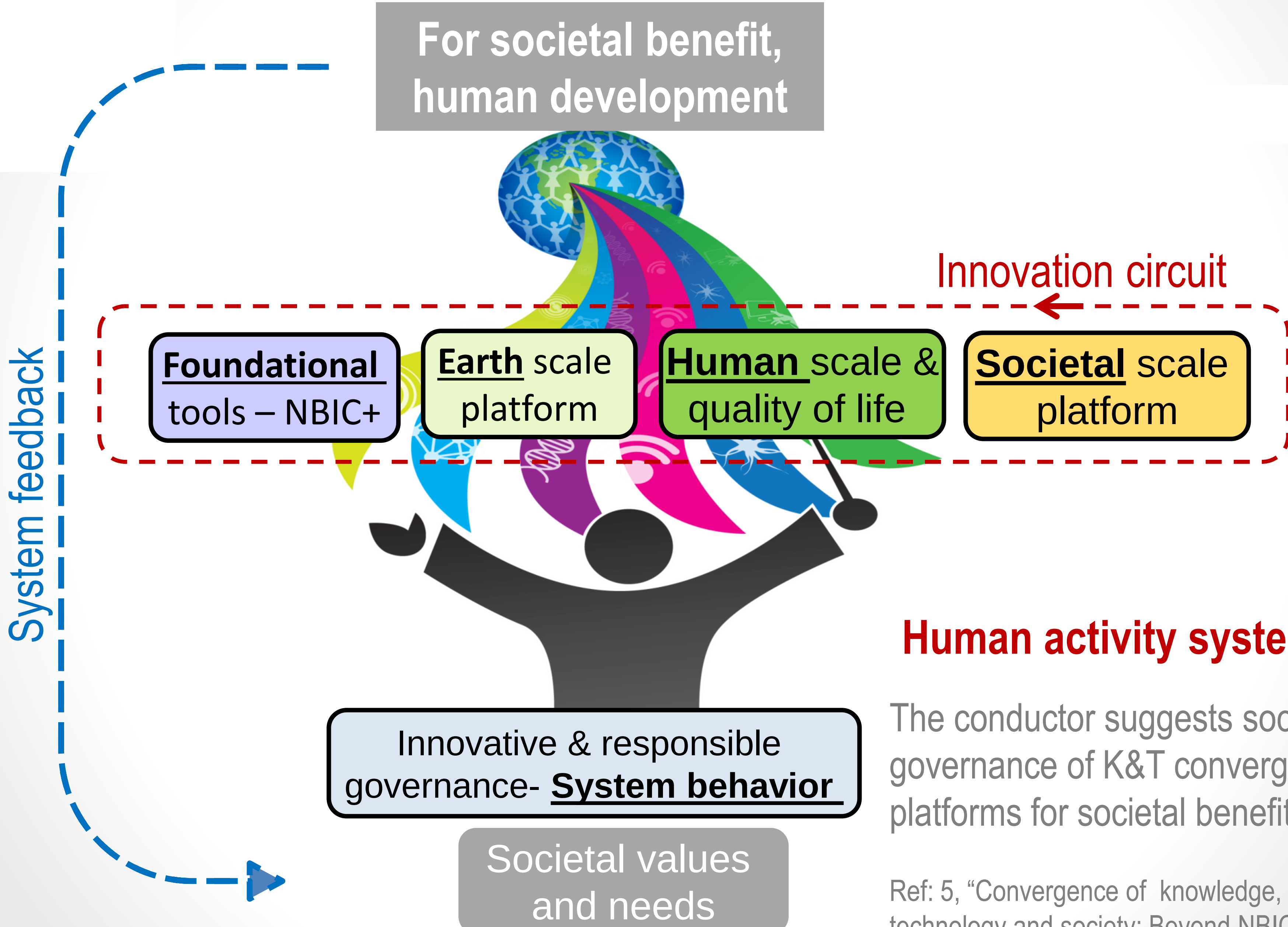
Precise medicine

National Nanotechnology Initiative
(nano.gov) (with coordinating office)

Materials Genome | Photonics | Grand challenges

Ref 9: Roco, "NBIC", in Handbook of S&T Convergence, 2015

Convergence of Knowledge, Technology and Society



Human activity system

The conductor suggests societal governance of K&T converging platforms for societal benefit.

Ref: 5, "Convergence of knowledge, technology and society: Beyond NBIC" 2013

Convergence of Knowledge and Technology (CKTS) leads to
U.S. society-oriented initiatives

Innovation

Smart Cities

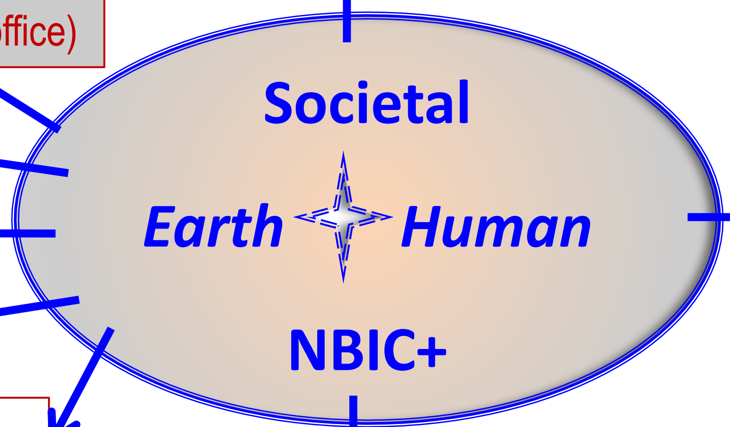
Global Change Research Program
(Global Change.gov) (with coordinating office)

Climate Action Plan

SunShot GC (DOE..)

Asteroid GC (NASA..)

Strategy for Arctic Region



STEAM Education Initiative (NSF, DoEd)

The National Network for Manufacturing Innovation (NNMI)
(http://www.manufacturing.gov/nnmi) (with program office)

(see Ref 8: "Principles and methods that facilitate convergence")

Context for Long View

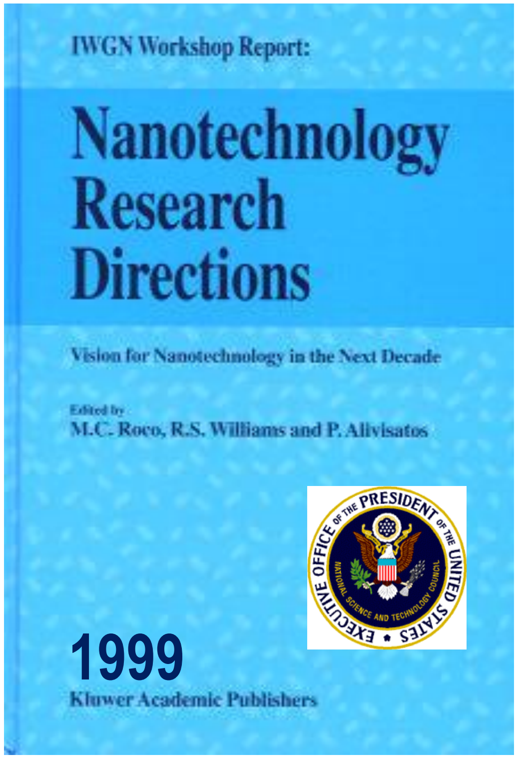
- **Since 2000, nanotechnology is an essential megatrend in S&E, the most exploratory field as a general foundation** as compared to IT and BIO

- **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

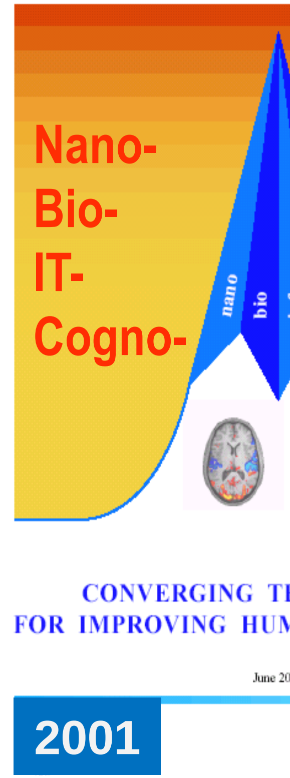
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects

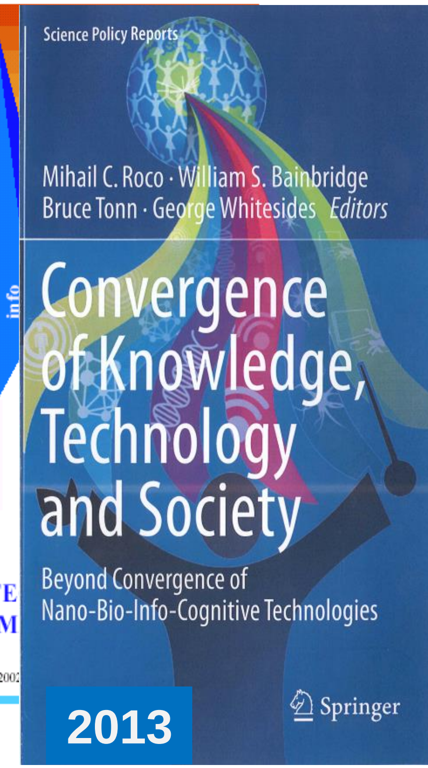
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1 & 2 (2011-2030)

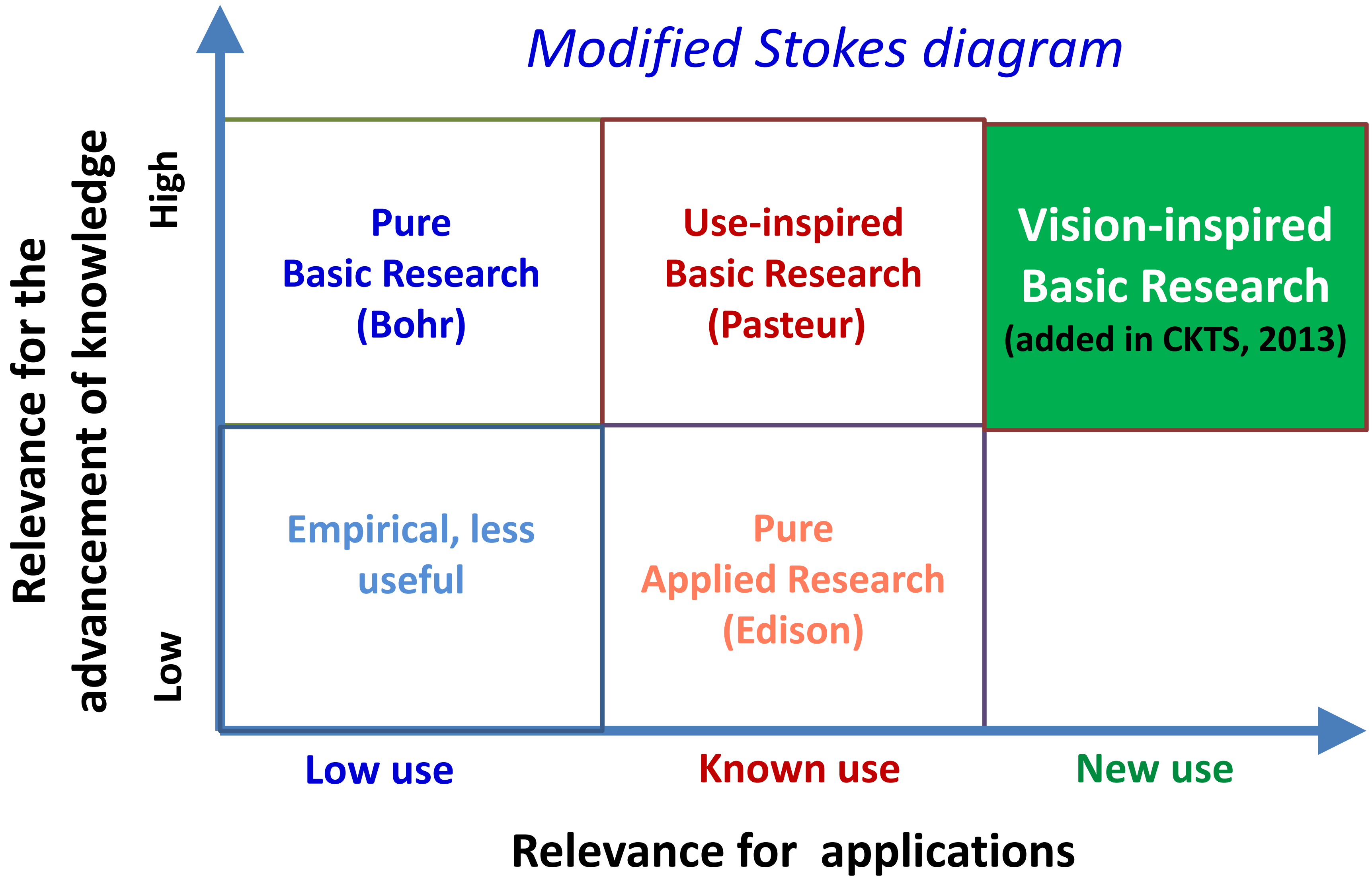




30 year vision to establish nanotechnology: changing focus and priorities (in over 80 countries)

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

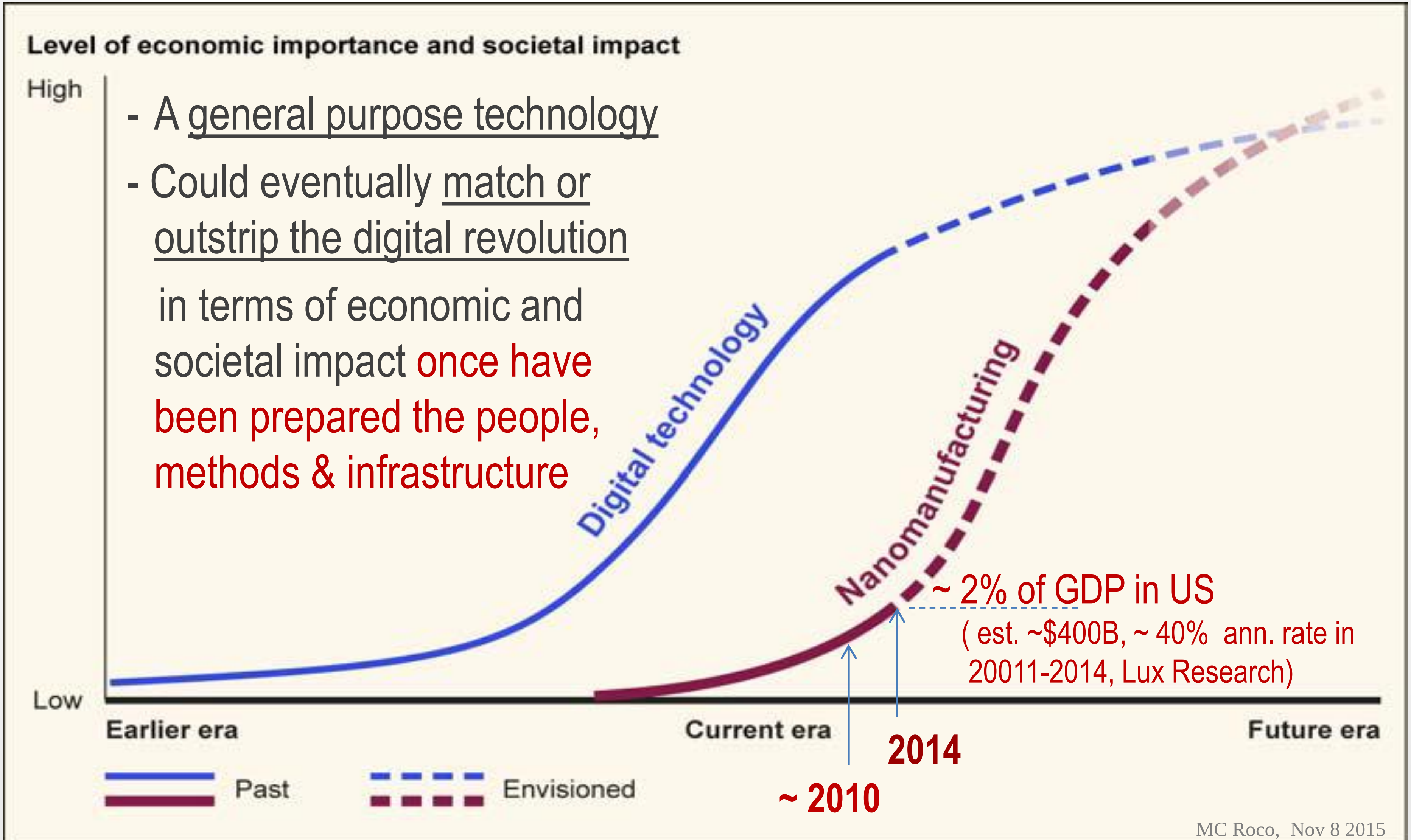
Vision inspired research is essential for the long-term view of nanotechnology



Ref 1: Roco and Bainbridge, 2013 , Fig 9

Conceptualization of "Nanomanufacturing" and "Digital Technology" megatrends (*S-curves*)

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



Global revenues from Nano-enabled products

(All budgets in $ billion)	2010 *(2001-2010)**	2011**	2012**	2013	2010-2013**
World revenues	***339*** ***(10 yr ~ 25%)***	*514*	*731*	***1,014***	*+ 676*
US	**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%**

(*) Data from Nano 2 Report, 2011; **(**) Data from Lux Research industry survey, Jan 2014**

MC Roco, Nov 8 2015

Total nanotechnology product revenues annual growth **> 40% in 2010-2013**

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

GENERATIONS OF NANOPRODUCTS

2030

DIVERGENCE

New socio-economic capabilities

nano3 Technology divergence

2020-2030

CONVERGENCE

To general purpose technology

nano2 System integration

2010-2020

Foundational research at the nanoscale

nano1 Nanocomponent basics

2000-2010

2000

Nanosystem Converg. Networks

NBIC Technology Platforms

Molecular Nanosystems

Systems of Nanosystems

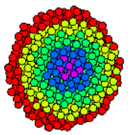
Active Nanostructures

Passive Nanostructures

MC Roco, Nov 8 2015

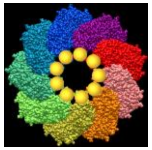
Introduction of New Generations of Products and Productive Processes (2000-2030)

Timeline for beginning of industrial prototyping and nanotechnology commercialization



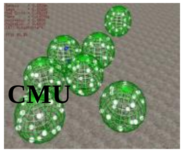
2000

1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics



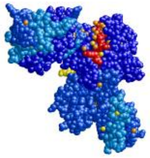
~ 2005

2nd: Active nanostructures Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures



~ 2010

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



~ 2015-2020

4th: Molecular nanosystems
Ex: molecular devices 'by design', atomic design, emerging functions

~ 2020-2030

5-6th: Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

Increased Complexity, Dynamics, Transdisciplinarity

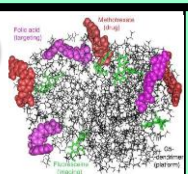
Ref: AIChE Journal, Vol. 50 (5), 2004

Perceived Higher Risks Areas (2000-2030)

as a function of the generation of products and productive processes

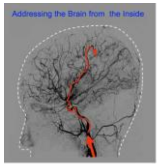
1st: Passive nanostructures ***Ex: Cosmetics (pre-market tests), Pharmaceuticals (incomplete tests for inflammatory effects, etc.), Food industry , Consumer products***

~ 2000



2nd: Active nanostructures ***Ex: Nano-biotechnology, Neuro-electronic interfaces, NEMS, Precision engineering, Hybrid nanomanufacturing***

~ 2005



3rd: Systems of nanosystems ***Ex: Nanorobotics, Regenerative medicine, Brain-machine interface, Eng. agriculture***

~ 2010

4th: Molecular nanosystems ***Ex: Neuromorphic eng., Complex systems, Human-machine interface***

~ 2015-2020

5-6th: Converging technologies ***Ex: Hybrid nano-bio-info-medical-cognitive application***

~ 2020-2030

Increase complexity, Higher risk

MC Roco, Nov 8 2015

Nanotechnology-enabled products in 2015

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)

Nanotechnology penetration in economy

(Nano 2020 study)

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%

Emerging Technology Parametrization

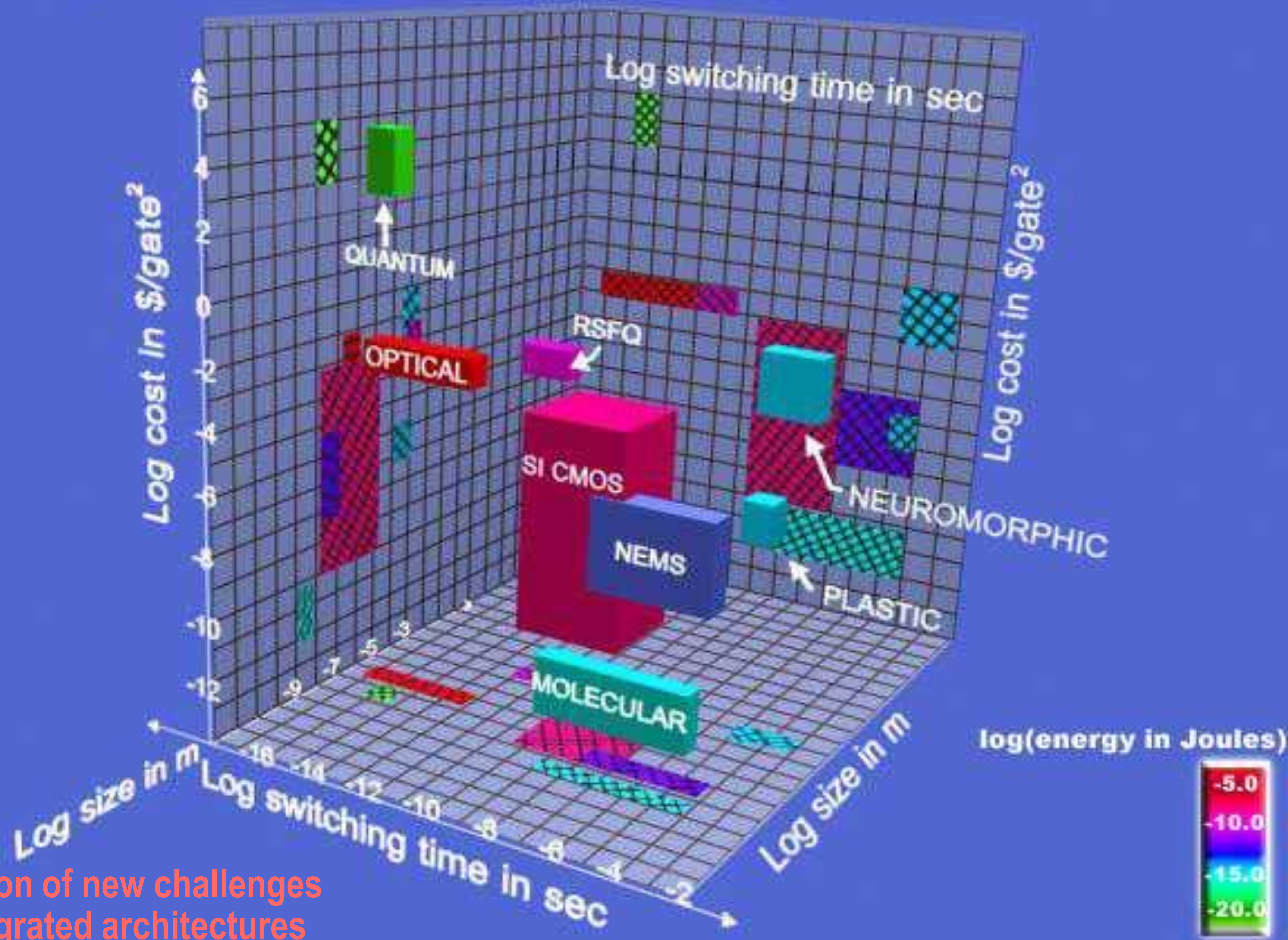
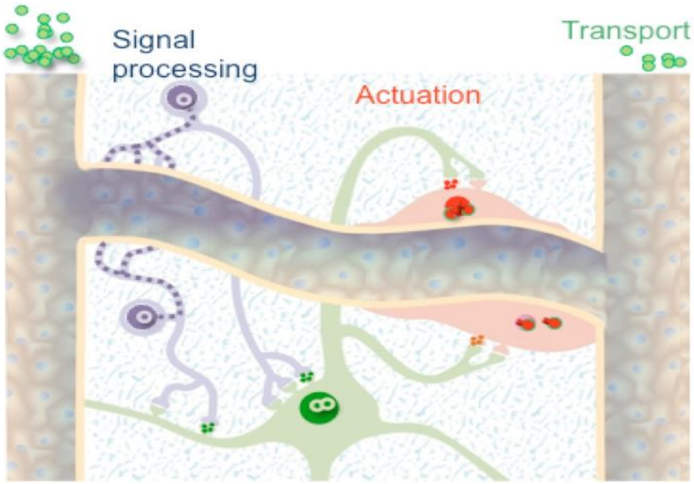


Illustration of new challenges for integrated architectures

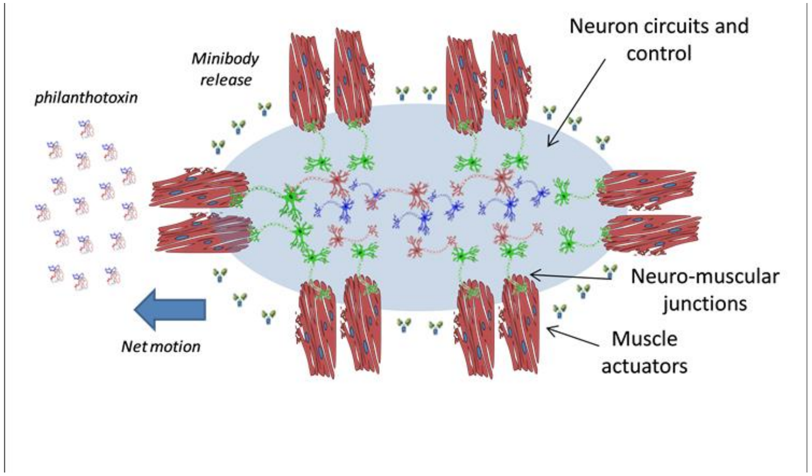
Courtesy Ralph Cavin/SRC

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



Controlling the complex functional behaviors of interacting cell clusters, and <u>their interaction with the surroundings</u>

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



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

NSF/NNI and the International Perspective

DOC/NIST DOE HHS/NIH OSTP OMB NSF DOD HHS/FDA

NASA

HHS/CDC/ NIOSH

USDA/NIFA
USDA/ARS

National Nanotechnology Initiative

USDA/FS

Vision: control of matter at nanoscale will bring a revolution in technology for societal benefit

DOS EPA

DOTr NRC

Impact of NNI in many areas / agencies

FY 2016 NNI Budget Request by WH

In preparation: New 2016 Strategic Plan

DOT DOC/ USPTO

IC/DNI DOI/ USGS

DOJ DOC/EDA DOC/BIS DHS CPSC ITC DOEd DOL

2001-
2014

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

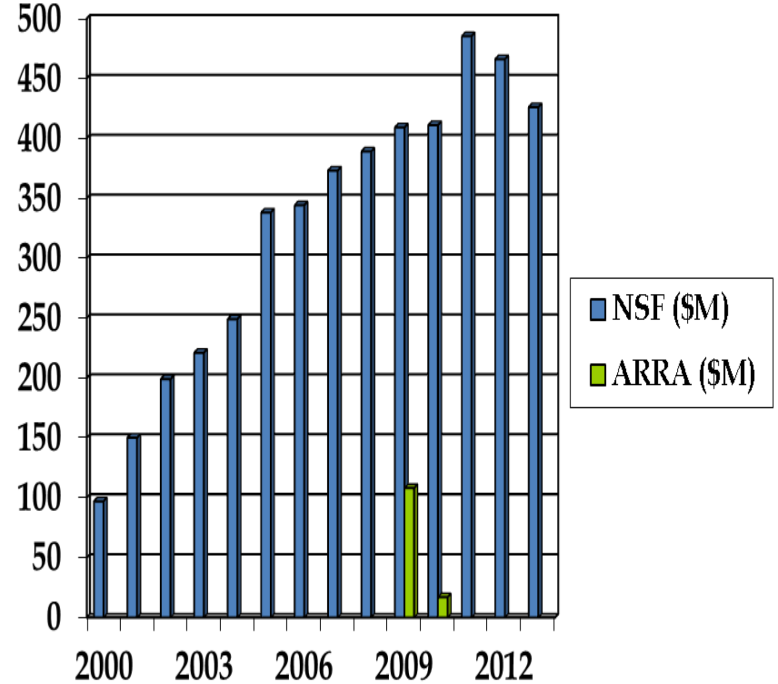
www.nsf.gov/nano , www.nano.gov

FY 2015 Budget: **$412 million + other core**

*FYs 2000-2015: NSF total investment is **$34.5 per capita** (US)*

– 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

Several NSF NSE awards in FY 2015

www.nsf.gov

- National Nanotechnology Coordinated Infrastructure, NNCI
- Scalable nanomanufacturing, SNM (also 2016)
- Two-Dimensional Atomic-layer Research and Engineering, 2-DARE / EFRI (2 competitions)
- NSE in Nexus of Food, Energy, and Water ("INFEWS")
- NSE in Understanding the Brain ("UtB")
- NSF Nanosystems Eng. Res: Center for Nanotechnology Enabled Water Treatment Systems (NEWT) at Rice University
- International nano-EHS collaboration: Communities of Research (http://us-eu.org/); Collaborative SIINN
- Nanotechnology Undergraduate Education, NUE
- Translational: GOALI; I/UCRP; PFI; Nano-ERC; I-Corps

Other activities at NSF

- **Core research in: BIO, CISE, E.H.R., ENG, GEO, MPS, SBE**
- **Science and Technology Centers (STC)**
  $5M/year per center for 5+5 yrs
- **Environmental, Health and Safety (**EHS**)** (5-6% of NSF NNI)
- **Part of Converging Knowledge and Technologies in Society (CKTS)**

FY 2016: Advancing Quantum Information Research in Engineering (EFRI/ AQUIRE)

Address key engineering research challenges to enable room temperature, chip-level transducers, repeaters, systems and architectures for a secure, scalable quantum communication network.

- Room temperature single photon sources, detectors, memories, repeaters and other low-energy photonic components
- Scalable on-chip integration of quantum photonics with silicon electronics
- Leveraging novel engineered materials, quantum structures, and devices
- Potential impact on ultra secure communication network and other capabilities

FY 2016: New Light & Acoustic Wave Propagation

Breaking Reciprocity &Time-Reversal Symmetry (EFRI: NewLAW)

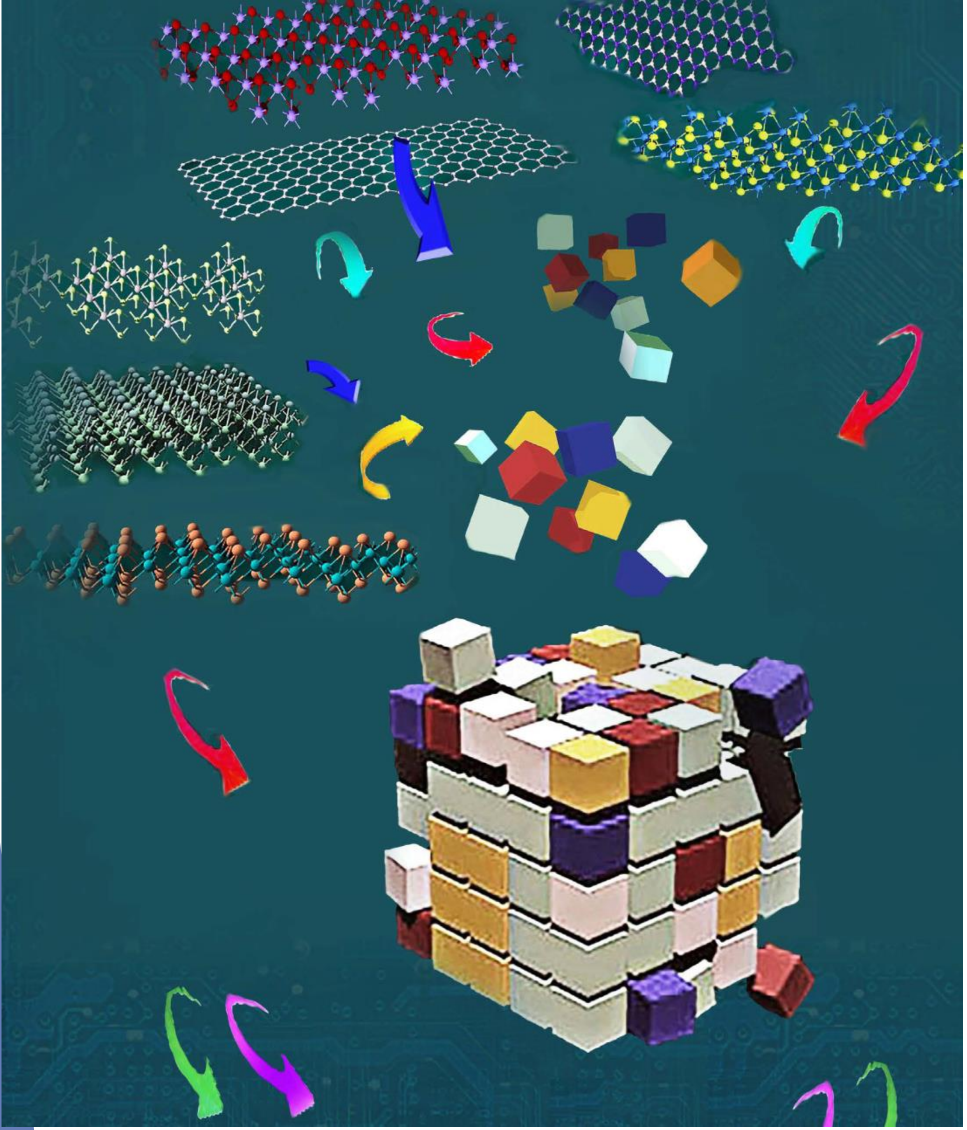
Breaking symmetries and challenging fundamental laws governing wave motion and field transport

- Disruptive approach to design of electronic, photonic and acoustic devices, and enabler of totally new functionalities.
- Acoustic technologies, such as soundproofing and sonar stealth systems, energy absorbing materials, and imaging
- Integrated nanophotonic elements based on topological insulators, full-duplex wireless communications

National Science Foundation

National Nanotechnology Coordinated Infrastructure (NNCI)

$81 Million
16 National Sites
5 Years of Funding

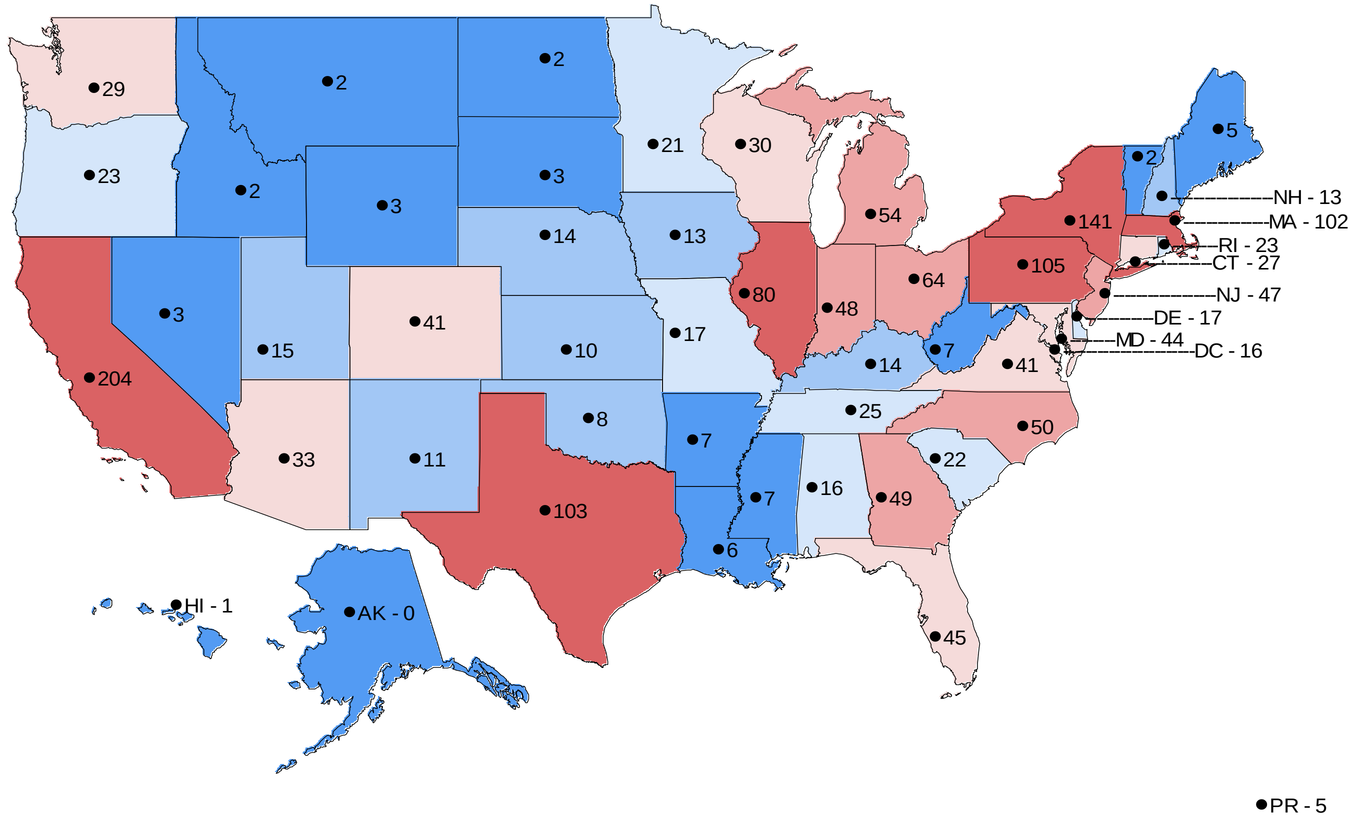


NanoModular Materials and Systems by Design, NSF/WTEC, Dec. 2015

NSF's NSE number of new awards per state

FY 2015: U.S. total new awards = 1,670

(total active awards = 7,843)



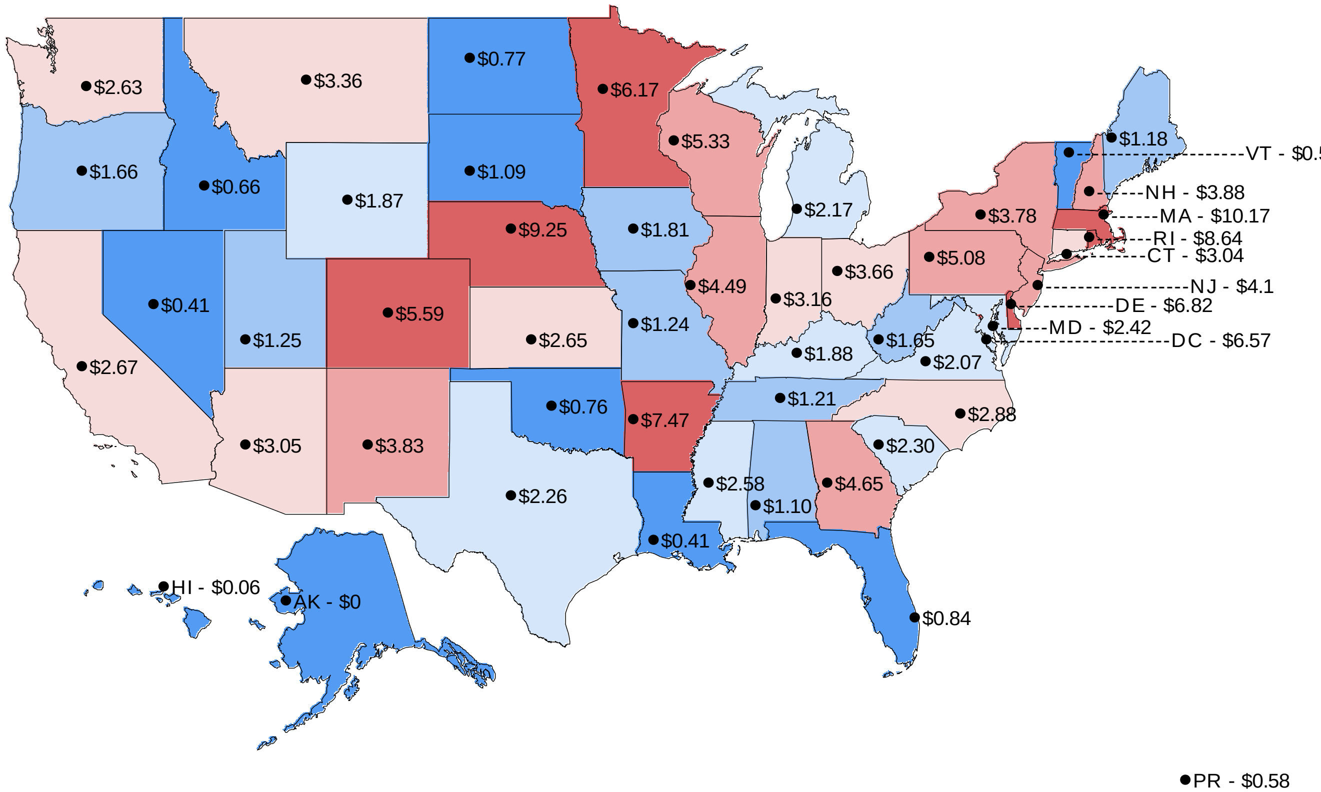
AK 0; AL 16; AR 7; AZ 33; CA 204; CO 41; CT 27; DC 16; DE 17; FL 45; GA 49; HI 1; IA 13; ID 2; IL 80; IN 48; KS 10; KY 14; LA 6; MA 102; MD 44; ME 5; MI 54; MN 21; MO 17; MS 7; MT 2; NC 50; ND 2; NE 14; NH 13; NJ 47; NM 11; NV 3; NY 141;

OH 64; OK 8; OR 23; PA 105; PR 5; RI 23; SC 22; SD 3; TN 25; TX 103; UT 15; VA 41; VT 2; WA 29; WI 30; WV 7; WY 3

MC Roco, Nov 8 2015

NSF's NSE amount new awards per capita, by state

FY 2015: U.S. average amount = $3.06 / capita

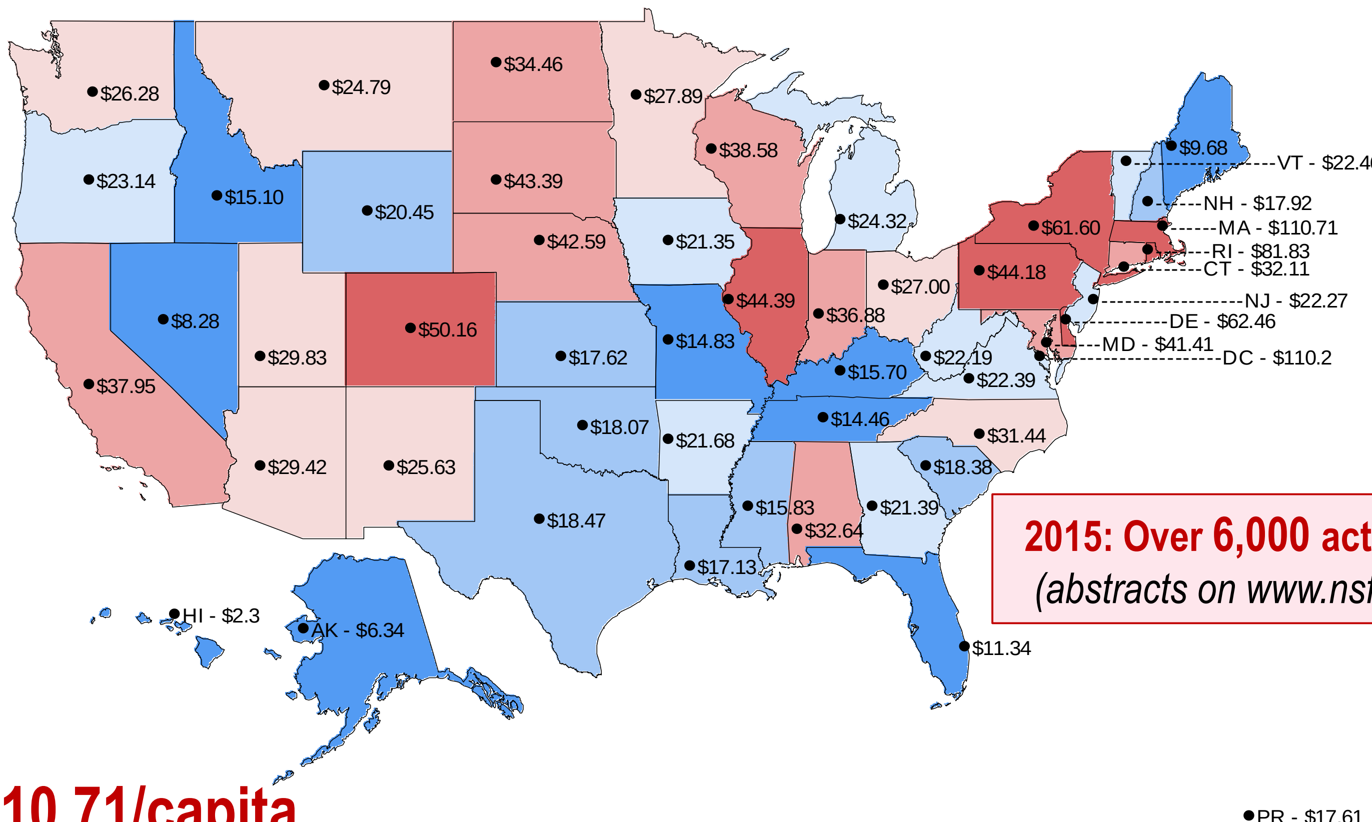


AK 0; AL 1.1; AR 7.47; AZ 3.05; CA 2.67; CO 5.59; CT 3.04; DC 6.57; DE 6.82; FL 0.84; GA 4.65; HI 0.06; IA 1.81; ID 0.66; IL 4.49; IN 3.16; KS 2.65; KY 1.88; LA 0.41; MA 10.17; MD 2.42; ME 1.18; MI 2.17; MN 6.17; MO 1.24; MS 2.58; MT 3.36; NC 2.88; ND 0.77; NE 9.25; NH 3.88; NJ 4.1; NM 3.83; NV 0.41; NY 3.78; OH 3.66; OK 0.76; OR 1.66; PA 5.08; PR 0.58; RI 8.64; SC 2.3; SD 1.09; TN 1.21; TX 2.26; UT 1.25; VA 2.07; VT 0.53; WA 2.63; WI 5.33; WV 1.65; WY 1.87

MC Roco, Nov 8 2015

NSF's NS&E amount new awards per capita

FYs 2000 - 2014: U.S. average amount = $31.5 / capita



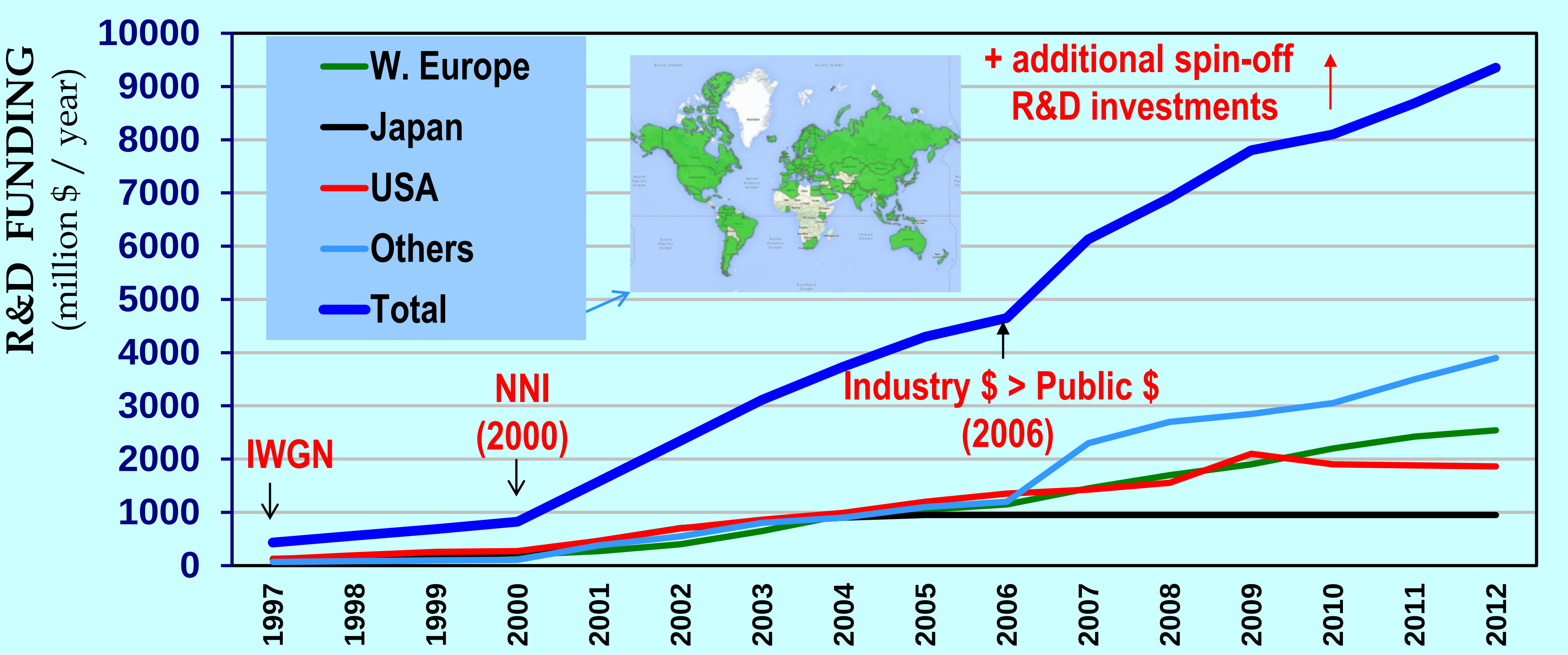
2015: Over 6,000 active awards
(abstracts on www.nsf.gov/nano)

#1 MA $110.71/capita

AK 6.34; AL 32.64; AR 21.68; AZ 29.42; CA 37.95; CO 50.16; CT 32.11; **DC 110.2; DE 62.46**; FL 11.34; GA 21.39; HI 2.3; IA 21.35; ID 15.1; IL 44.39; IN 36.88; KS 17.62; KY 15.7; LA 17.13; **MA 110.71**; MD 41.41; ME 9.68; MI 24.32; MN 27.89; MO 14.83; MS 15.83; MT 24.79; NC 31.44; ND 34.46; NE 42.59; NH 17.92; NJ 22.27; NM 25.63; NV 8.28; **NY 61.6**; OH 27; OK 18.07; OR 23.14; PA 44.18; PR 17.61; **RI 81.83**; SC 18.38; SD 43.39; TN 14.46; TX 18.47; UT 29.83; VA 22.39; VT 22.46; WA 26.28; WI 38.58; WV 22.19; WY 20.45

International government R&D funding

For interval 2000-2012, after 2013 - increase use of new terms & platforms
(using NNI definition, 81 countries, MCR direct contacts)



Seed funding 1991 - 1997

NNI Preparation vision/benchmark

1st Generation products passive nanostructures

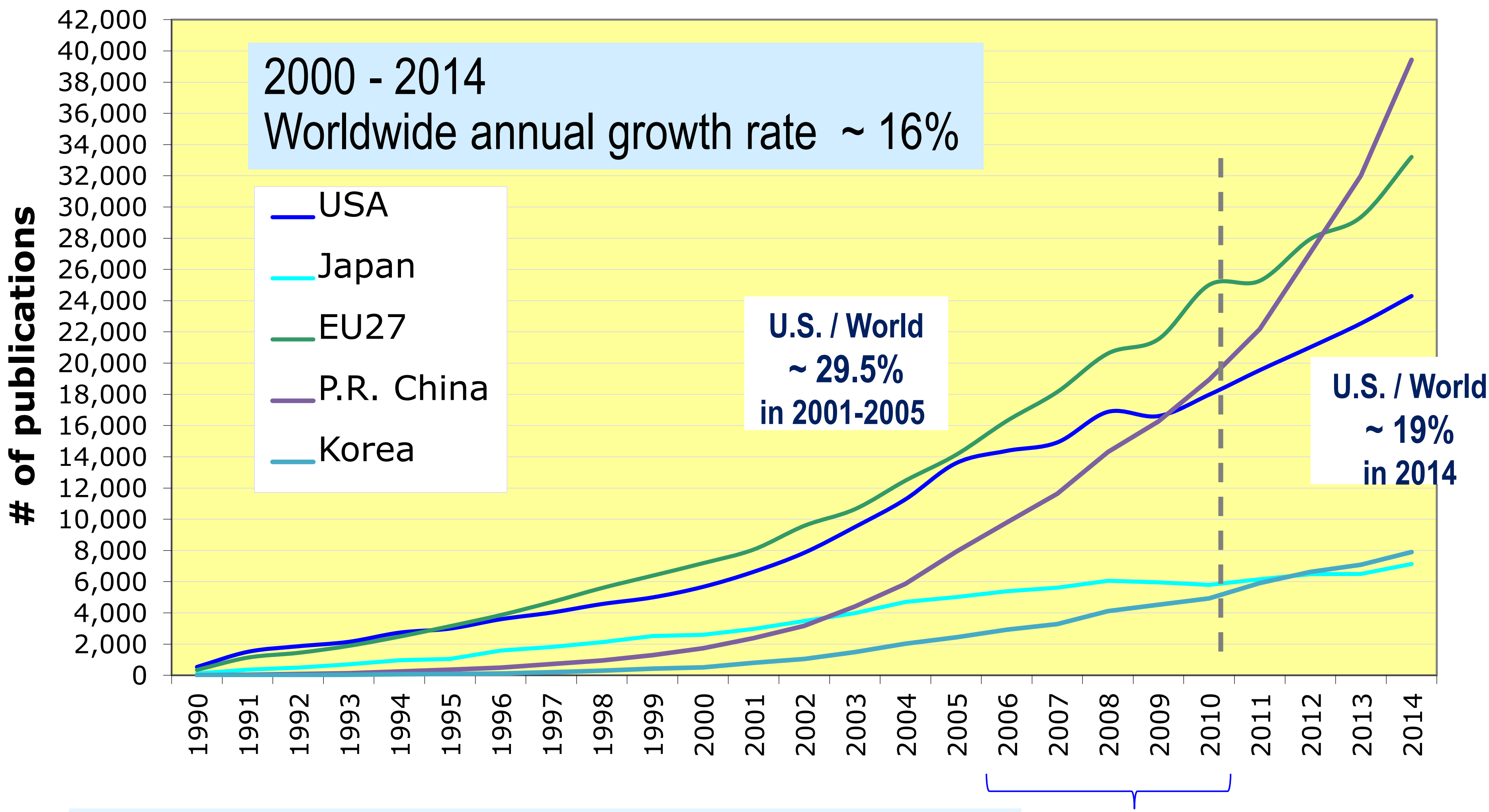
2nd Generation active nanostructures

3rd Generation nanosystems

Rapid, uneven growth per countries. Increase role of BRIC countries

Nanotechnology publications in the WoS: 1990 - 2014

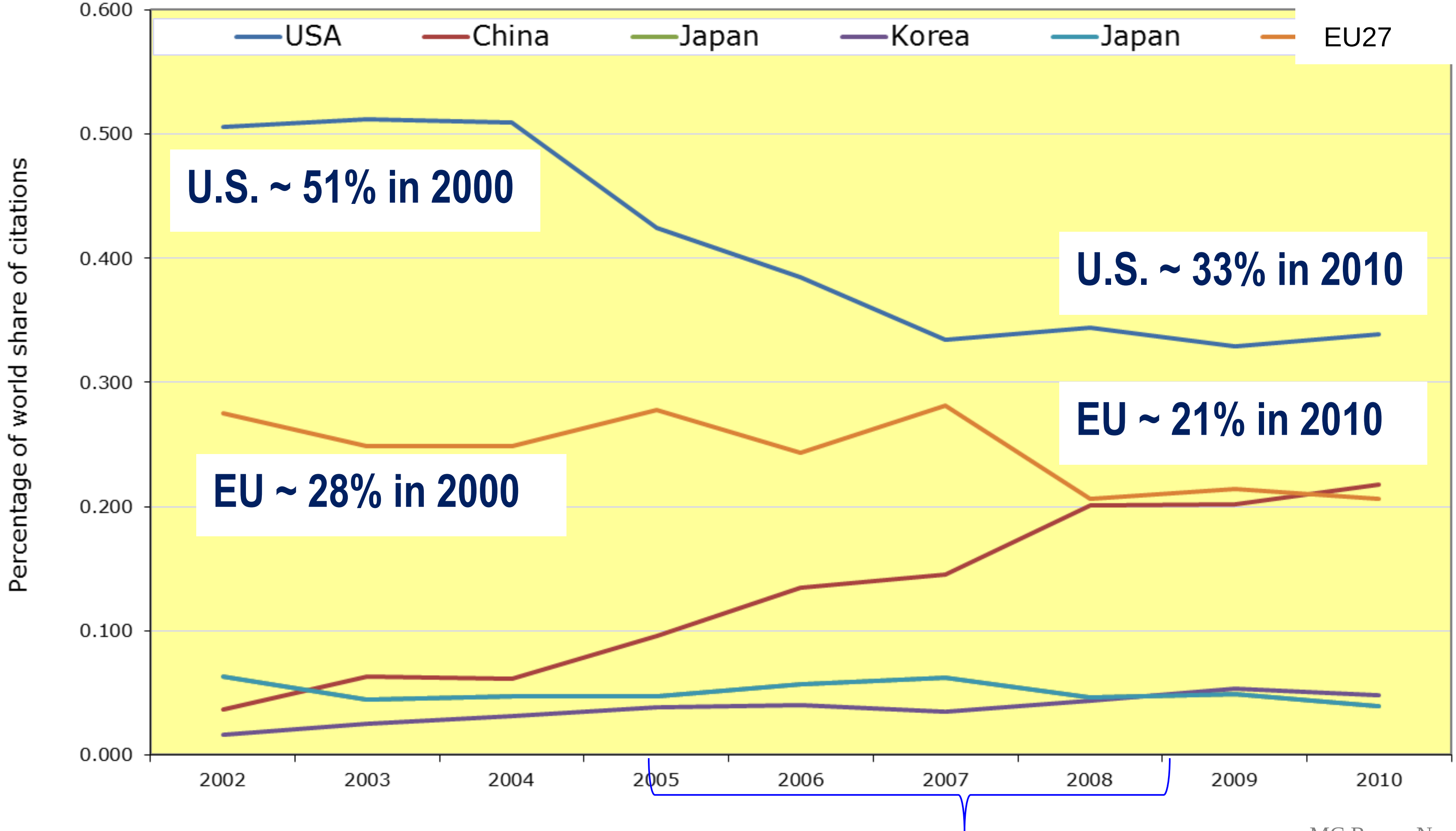
"Title-abstract" search for nanotechnology by keywords for six regions
(update of NANO2, Fig 1 (Ref. 3) using the method described in (Ref. 6))



Rapid, uneven growth per countries

Nanotechnology citations in 10 nano-specialized journals WoS in March 2013

"Title-abstract" search for nanotechnology by keywords (update Chen and Roco (Ref.6)



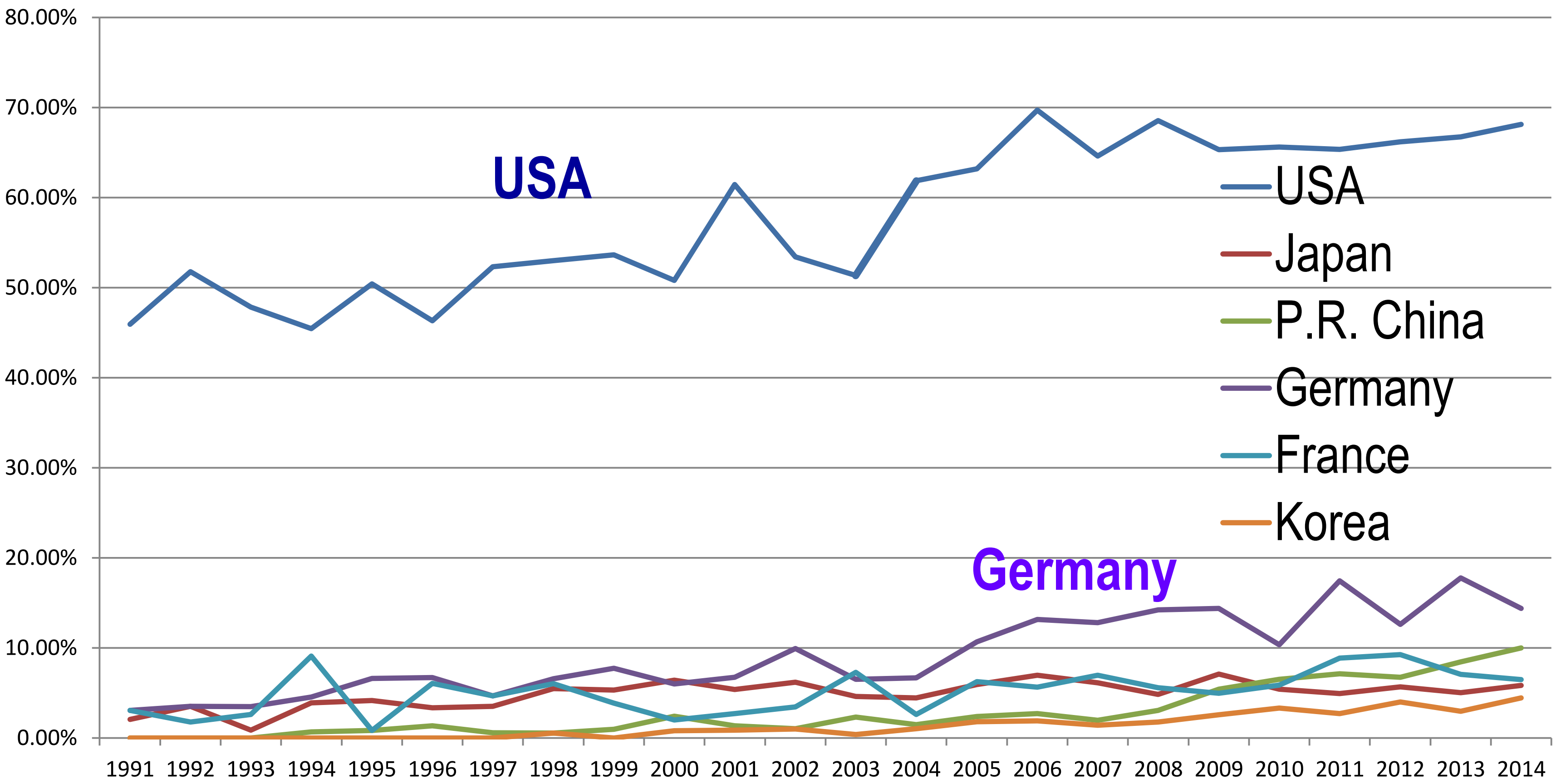
MC Roco, Nov 8 2015

U.S. citations in 10 journals from 51% in 2004 to 33% in 2010

Five countries' contributions to Top 3 Journals

(Nature, Science, PNAS) in 2014, by individual journals

"Title-abstract" search for nanotechnology by keywords (update Chen and Roco (Ref.6))

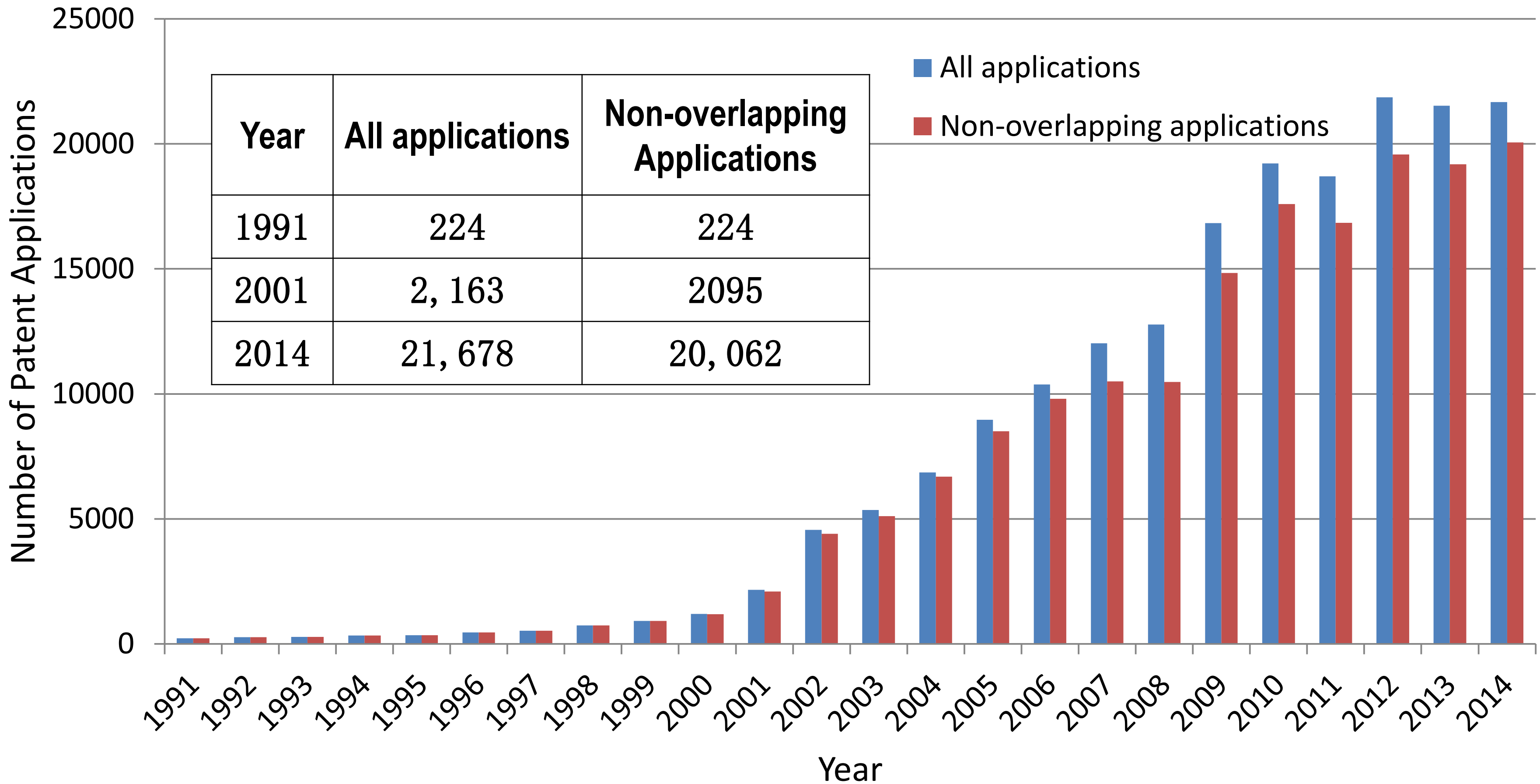


* Started to use Combined Keywords from 2014

MC Roco, Nov 8 2015

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

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

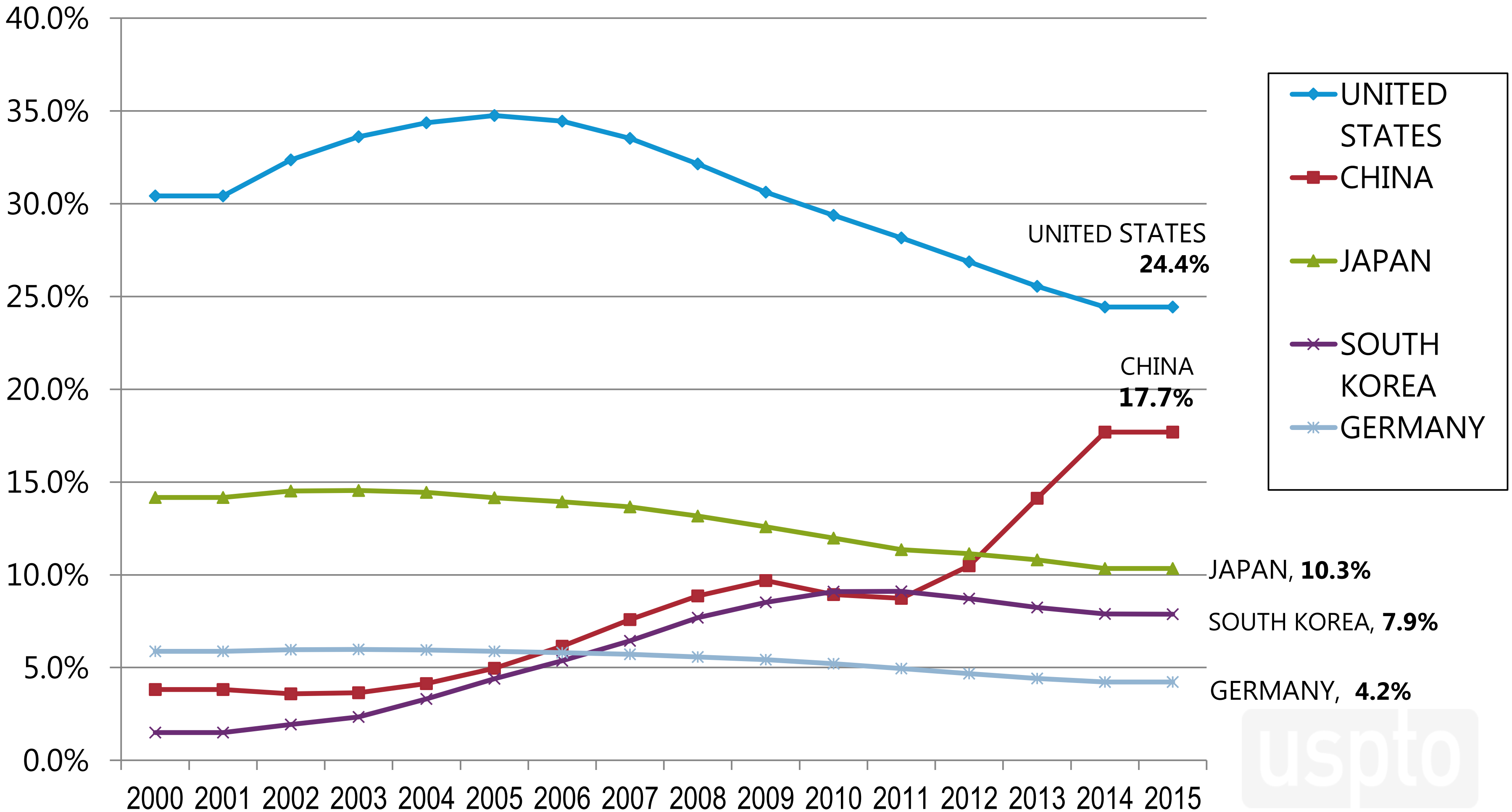


Year	All applications	Non-overlapping Applications
1991	224	224
2001	2, 163	2095
2014	21, 678	20, 062

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).

Nanotechnology Global Patent Statistics (First-Occurring Patent Publications): Top-5 Countries, Relative Percent of Total

Derwent World Patents Index with extension abstracts (WPIX): by First-named Inventor, patent publications 1986- June 2015)

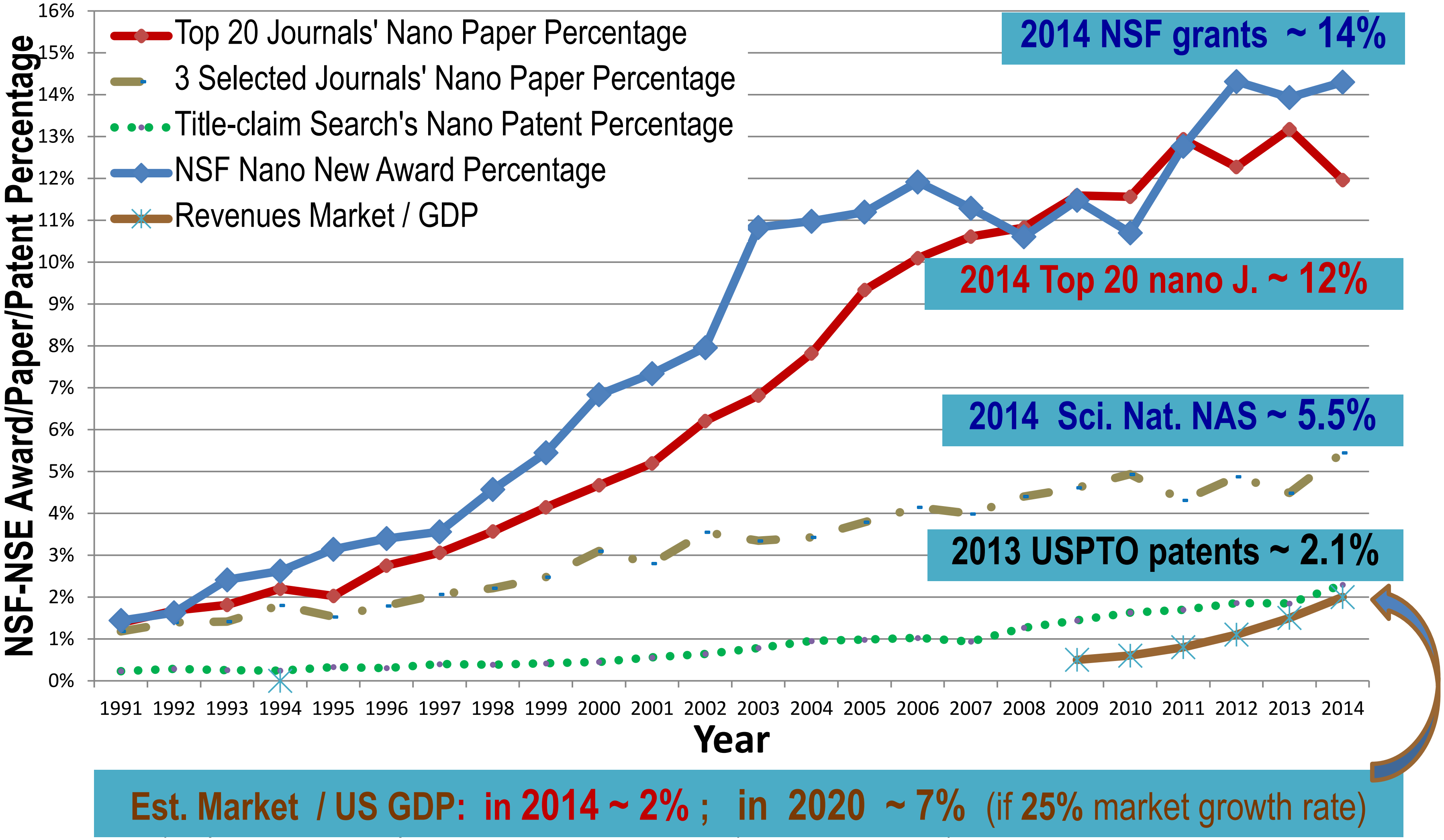


Nanotechnology Patents evaluated by USPTO

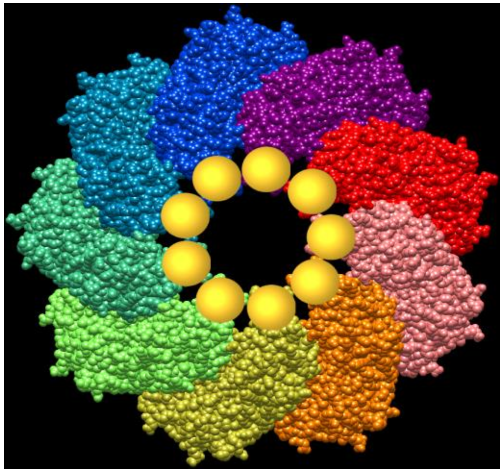
MC Roco, Nov 8 2015

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

Searched by keywords in the title/abstract/claims (update Encyclopedia Nanoscience, Roco, 2015)



MC Roco, Nov 8 2015



Nano 1 (2001-2010)

R&D focus:

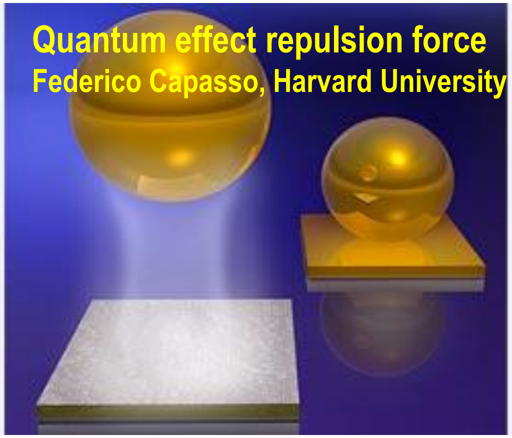
Foundational interdisciplinary research at nanoscale

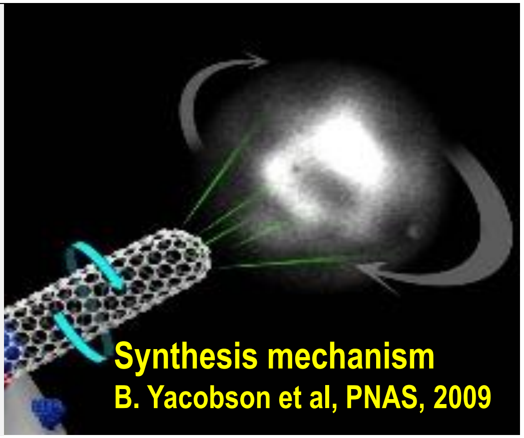
Major global changes in:

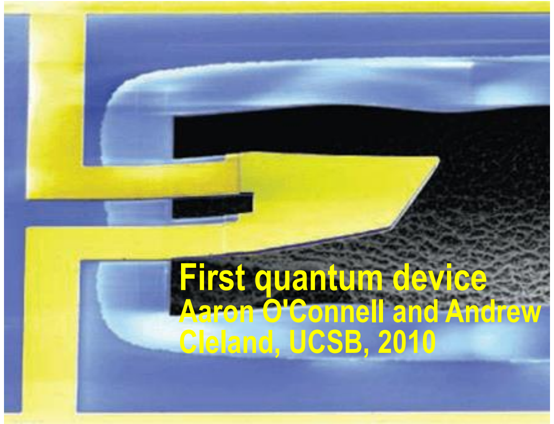
Infrastructure, Workforce, Partnerships

Examples for Nano 1 (2001-2010)

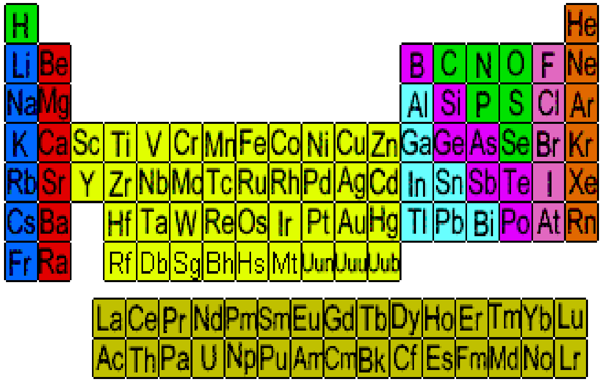
- **New individual phenomena, processes, structures**



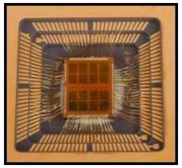




- **Semi-empirical synthesis of nanocomponents** (particle, quantum dots, tubes, coatings,..) **over all the periodic table**

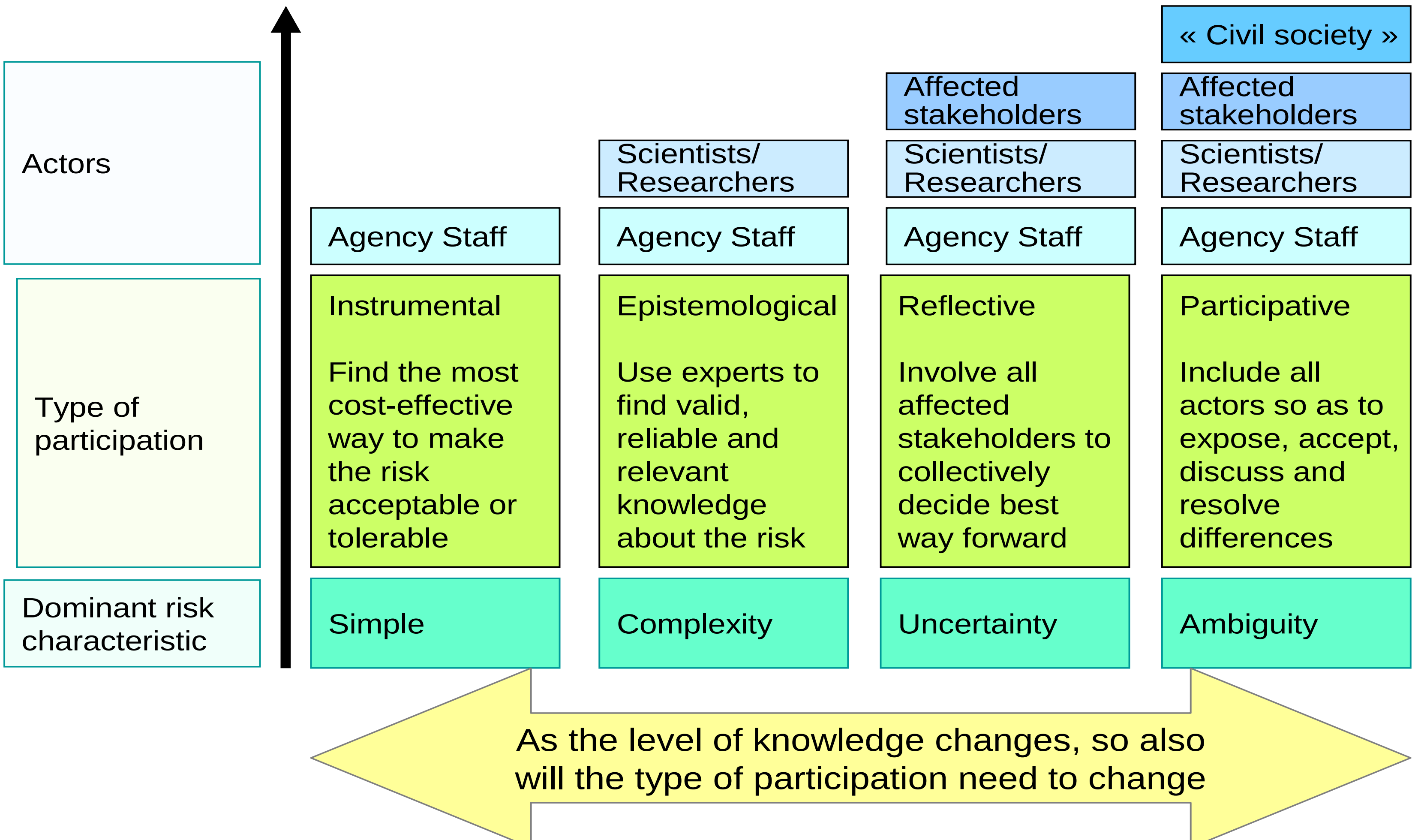


- **Nanocomponents have extended semiconductor's Moore's law** since 2000



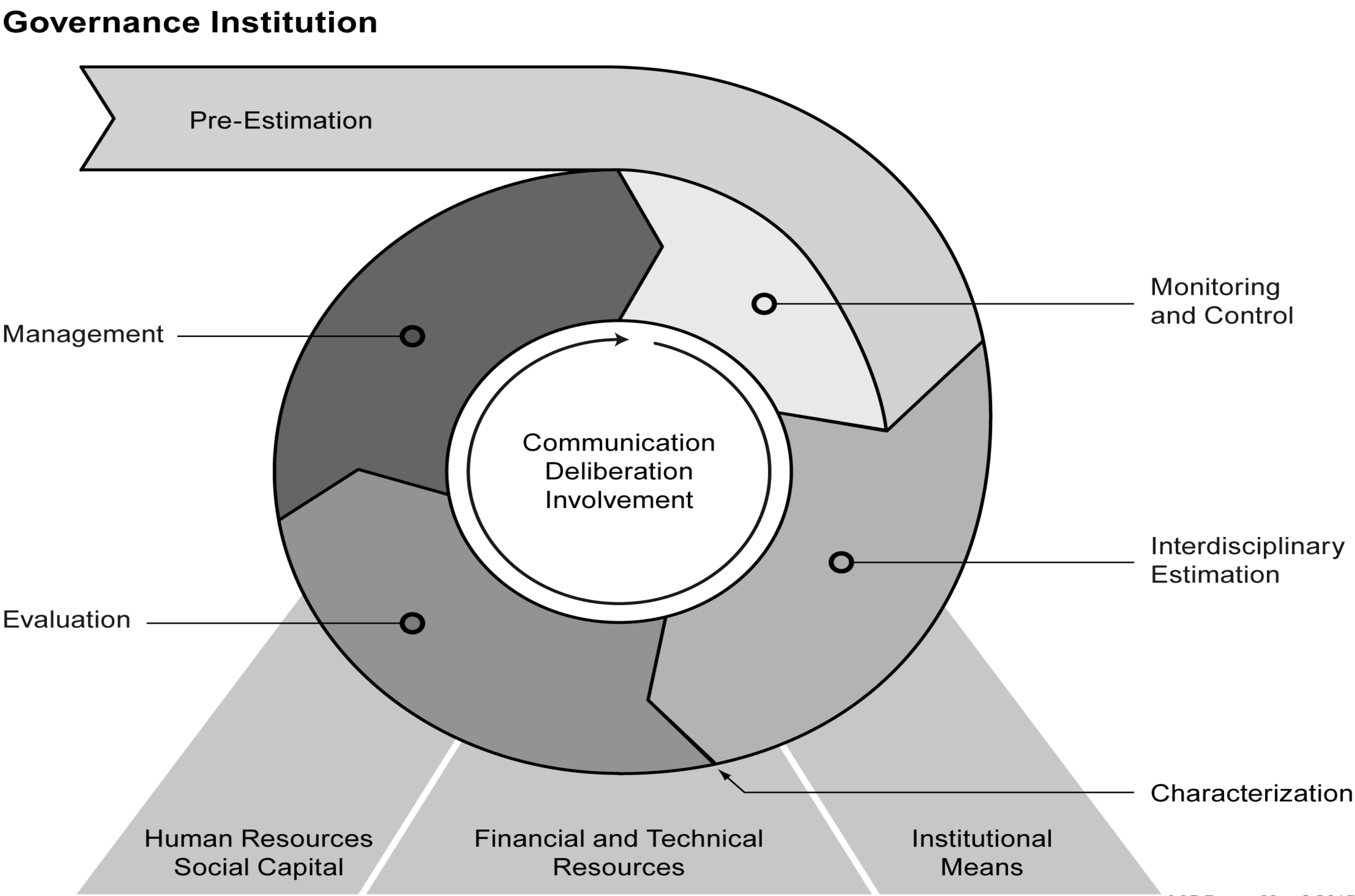
Relationship between stakeholder participation and risk categories in risk governance

(Renn 2015, p. 280 in Convergence of S&T, IRGC reports 2006)



Adaptive and integrative risk governance model

(Renn 2015, p. 280, in Convergence of S&T; IRGC reports 2006)



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

2000-2010: Sustainable Development

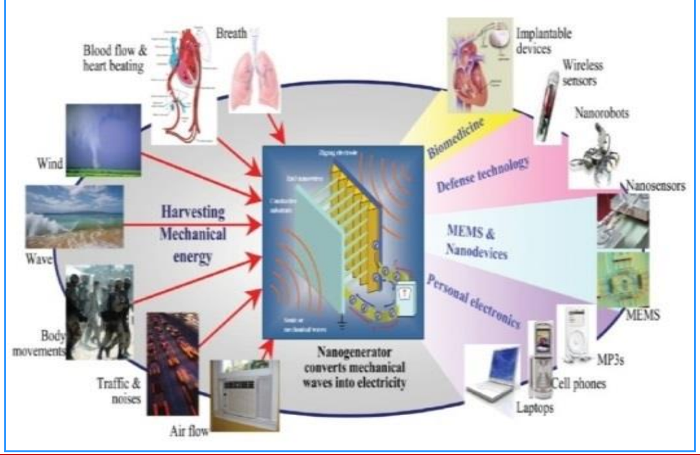
- **Nanotechnology has provided solutions for about half of the new projects** on energy conversion, energy storage, and carbon encapsulation in the last decade
- **Entirely new families have been discovered of nanostructured and porous materials** with very high surface areas, including metal organic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

Ref: NANO2 Report, 2011

Sustainable development: several programing advances in 2001-2010

- Adapt existing regulations to nanoparticles and other nanomaterials
- Local initiatives have grown 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

Others topics to be discussed in the following Panel



Nano 2 (2011-2020)

R&D focus:

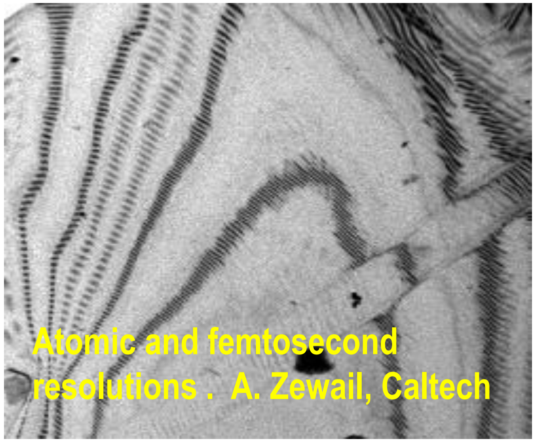
NS&E system integration for general purpose technology

Main global changes in:

New disciplines, New industries, Societal impact

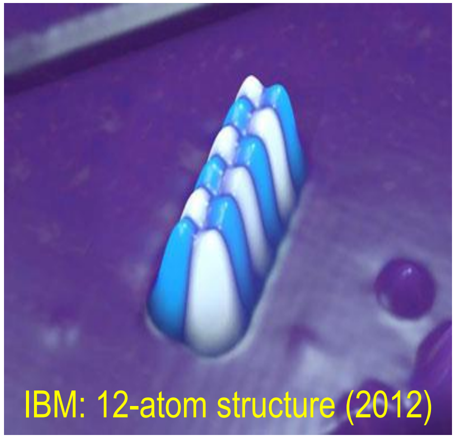
Examples for Nano 2 (2011-2020)

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

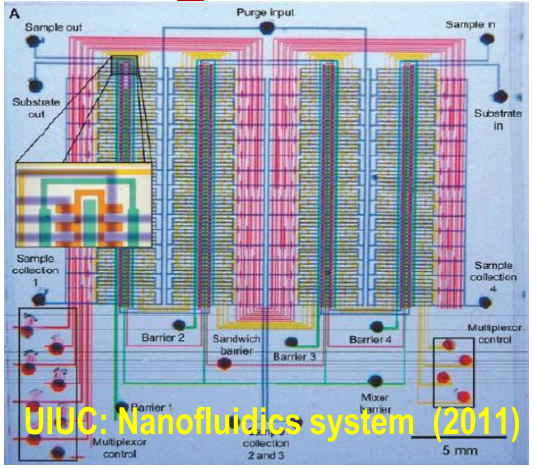


Atomic and femtosecond resolutions . A. Zewail, Caltech

- **Science based integrated nanosystems by design**



IBM: 12-atom structure (2012)



UIUC: Nanofluidics system (2011)

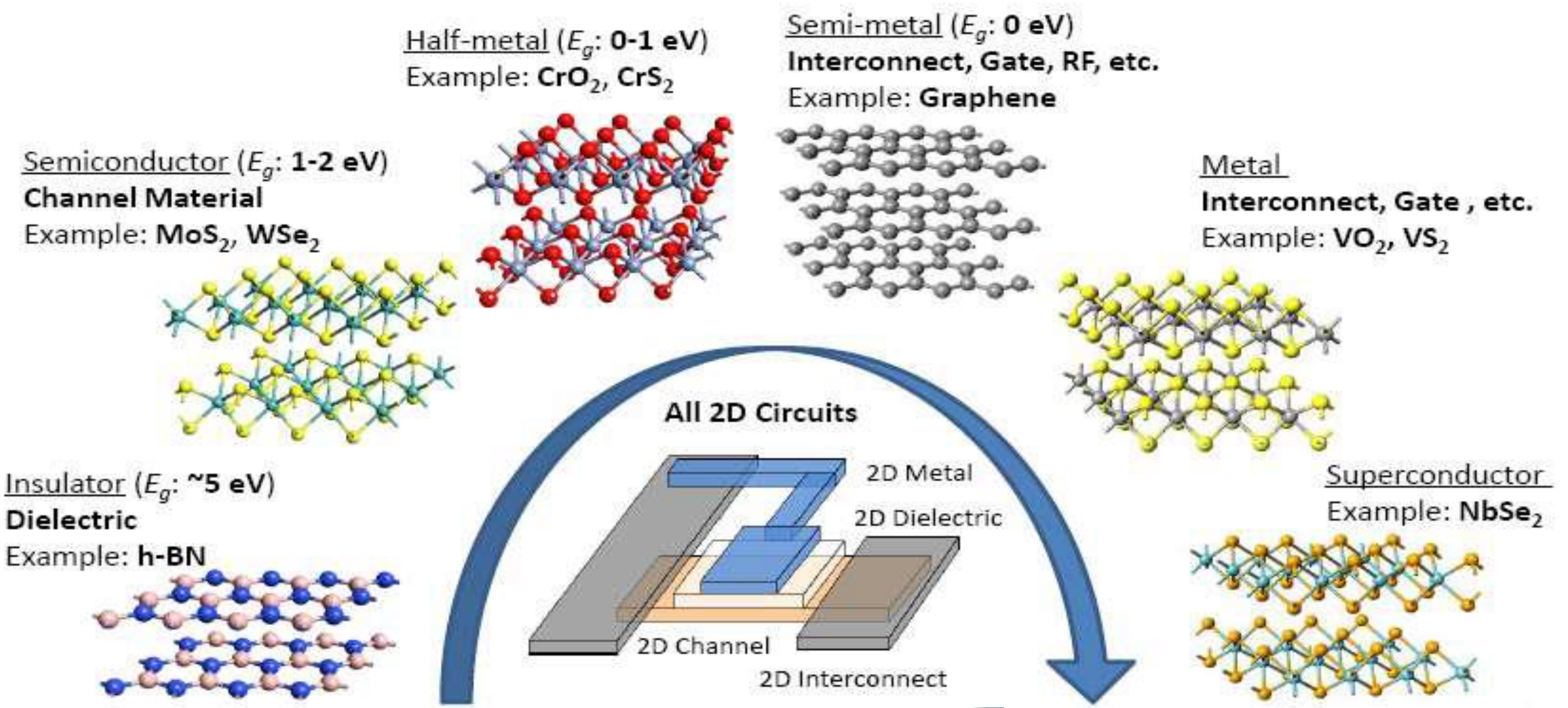
NCSU: Nanosystem for health and environmental monitoring (2014)

Modular Nanosystems

Example: using 2D electronic materials

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

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



Courtesy Kaustav Banerji (UCSB)

Some Components of the Nanotechnology Knowledge Infrastructure

- Supported by NIH, NIOSH, NIST, NSF, ONR, DOE

  http://nanoinformatics.org/2015/agenda/

Nanotechnology Signature Initiatives

National Nanotechnology Initiative (NNI), 2011-2015 (www.nano.gov)

Sustainable Nanomanufacturing

Nanoelectronics for 2020 and Beyond

Nanotechnology for Solar Energy (2011-2015)

Nanotechnology for Sensors and Sensors for Nanotechnology

Nanotechnology Knowledge Infrastructure

New topics under consideration after 2015:

water filtration, nanocellulose, nanomodular systems, nanophotonics, nano-city…

Example: Graphene Oxide Membranes for Ionic and Molecular Sieving

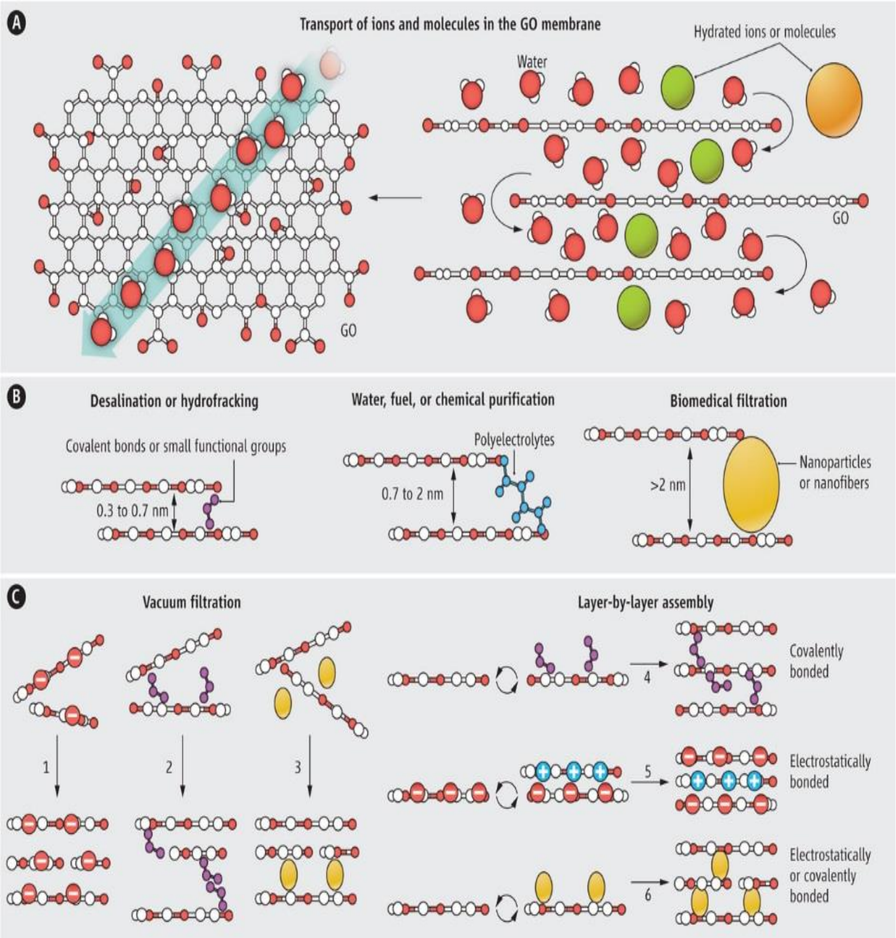


Image courtesy Baoxia Mi, University of California, Berkeley

- Sieving membranes that enable fast solute separations from aqueous solutions.
- The 2-D structure and tunable physicochemical properties of graphene oxide (GO) offer an opportunity to make a fundamentally new class of sieving membranes by stacking GO nanosheets.

The National Network for Manufacturing Innovation (NNMI) – 7 year plans

Experiment in *ecosystem establishment* in “valley of death”
All the institutes will deal with nanotechnology to some extent
Current list - **8 institutes** (http://manufacturing.gov/):

- **National Additive Manufacturing Innovation Institute** (DoD/DOE) FY12
- **Digital Manufacturing and Design Innovation** (DoD) FY14
- **Lightweight and Modern Metals Manufacturing** (DoD) FY14
- **Next Generation Power Electronics Manufacturing** (DOE) FY14
- **Clean Energy Manufacturing Innovation Institute for Composites Materials and Structures** (DOE) FY15
- **Photonics** (DoD) FY15
- **Hybrid Flexible Electronics** (DoD) FY15
- **Revolutionary Fibers and Textiles** (DoD) FY16

FY 2015 NS&E Priorities Research Areas (1)

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

A. Scientific challenges

- **New theories at nanoscale**
  Ex: transition from quantum to classical physics, collective behavior, for simultaneous phenomena
- **Non-equilibrium processes**
- **Designing new molecules with engineered functions**
- **New architectures for assemblies of nanocomponents**
- **The emergent behavior of nanosystems . . . .**

2015 Nano Grantees Conference (Dec 9-10): *nseresearch.org*

FY 2015 NS&E Priorities Research Areas (2)

B. Investigative and Transformative Methods

- Tools for measuring and restructuring
  with atomic precision
  and time resolution of chemical reactions

- Understanding and use of quantum phenomena

- Understanding and use of multi-scale selfassembling

- Nanobiotechnology – sub-cellular and systems approach

- Nanomanufacturing hybrid, on site

- Systems nanotechnology

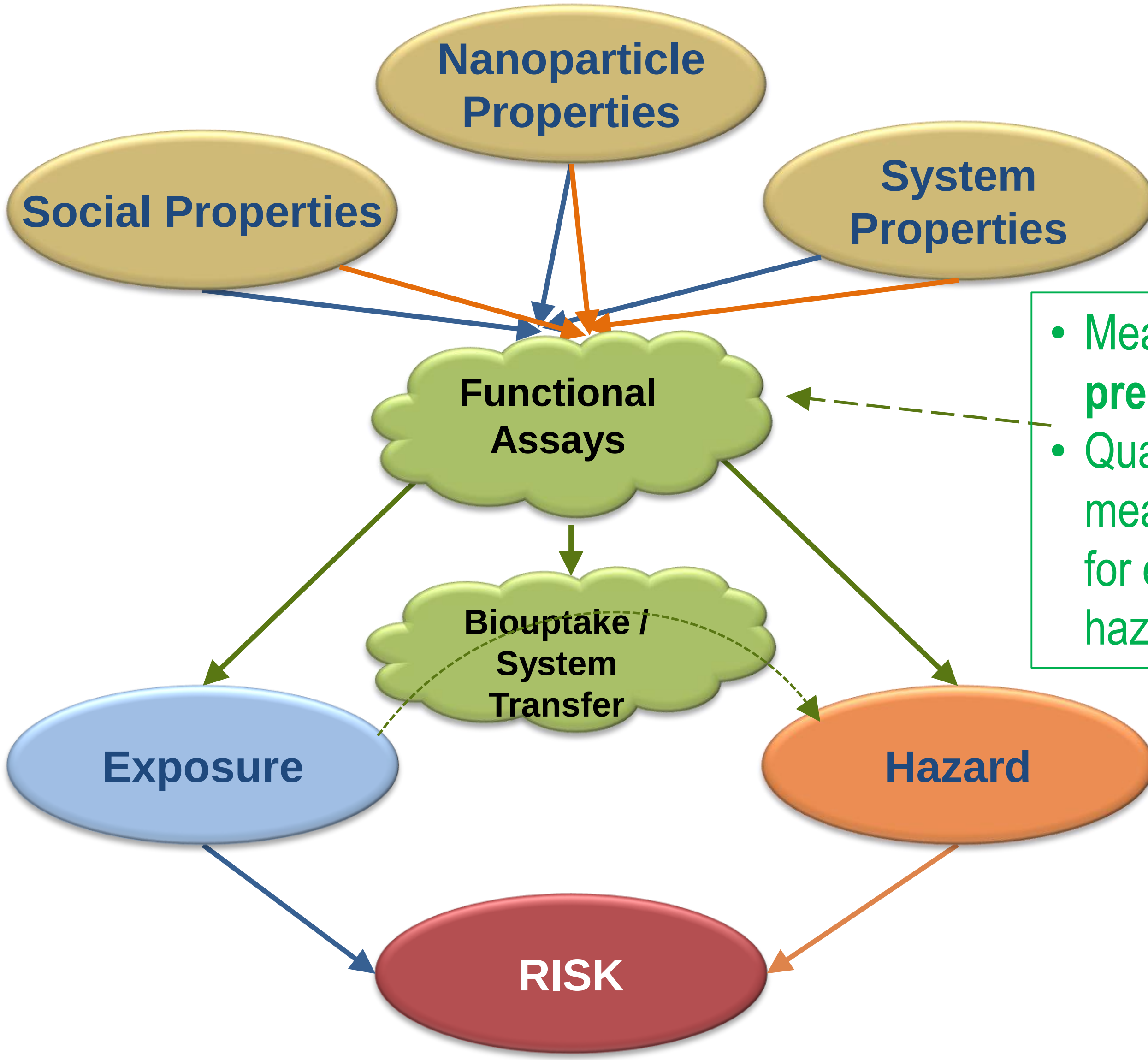
Twelve global trends to 2020

10 year perspective, 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, APM
- **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 **integrated** capabilities
- **Energy** photosynthesis, storage use – solar economic
- Enabling and **integrating with new areas** – bio, info, cognition
- **Earlier** preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - **institutionalization**

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

Sustainable development: examples of programing advances in 2010-2015

- Several voluntary and regulatory measures
- Science-based nano-toxicology & large data bases
- Societal values and economic development
- Sustainable urban communities
- Sustainable supply and utilization of critical materials
- US-EU Communities of nano-EHS Research
- EU states-US joint solicitation SIINN
- Labeling in Taiwan, Korea and Thailand

Others topics to be discussed in the following Panel

Nano 3 (2021-2030)

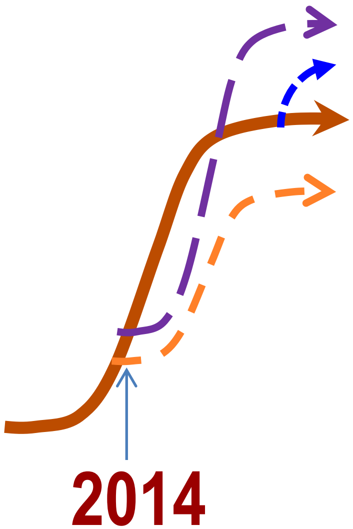
R&D Focus:

New convergence platforms & economy immersion

Main global changes in*:*

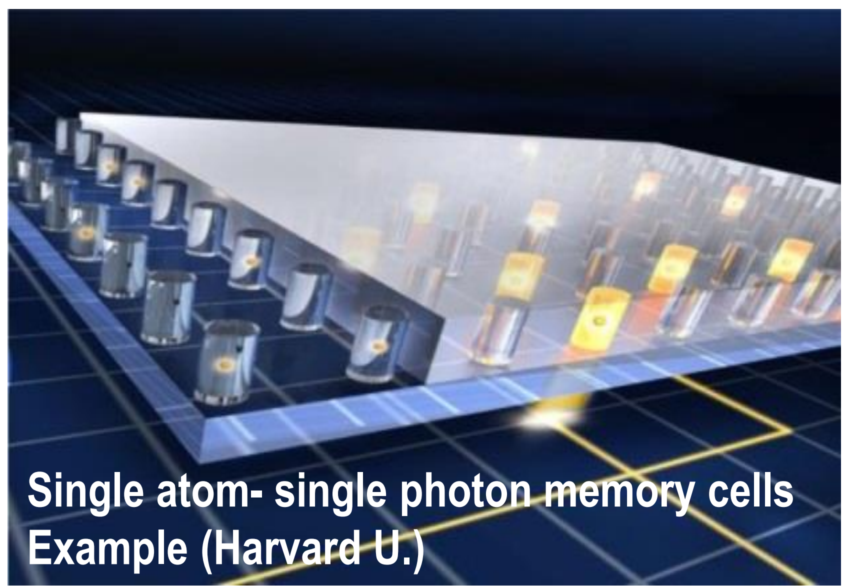
Socioeconomic NBIC platforms, capabilities & projects

To **Nano 3**



Overlapping S-curves:

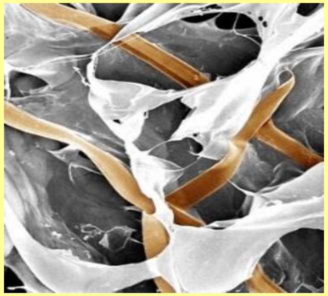
Successive breakthroughs in nanostructure system architectures and convergence



Single atom- single photon memory cells
Example (Harvard U.)

Ex. R&D drivers 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**

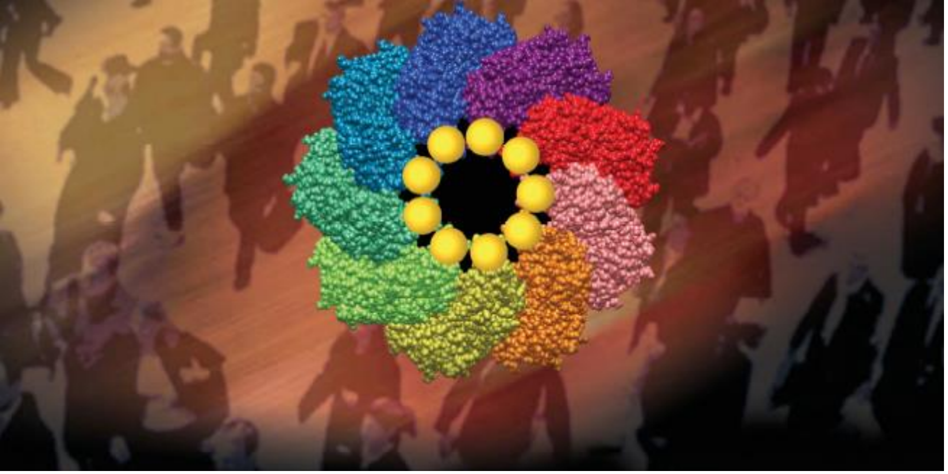


- **Service and molecular medicine** individualized
- Genetic – neurotechnologies – cognition - robotics - .. **to improve human potential**
- High productivity - high return **new industry sectors**

NANO 3 sustainability challenges

- Are renewable water/energy/food sources sufficient?
- Thermonuclear energy will be controlled and economically used?
- New convergence platforms will be sustainable?
- What will be the new minerals and materials crisis?
- DNA control and hybrid nanobiodevices will have safe regulations and organizations to implement them? Maintaining life security.

Others topics to be discussed in the following Panel



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"

Ten 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"*** (Springer, 316p, 2000)
3. ***NANO2**: **"Nanotechnology research directions for societal needs in 2020"*** (Springer, 690p, 2011a)
4. ***NBIC1**: **"Converging technologies for improving human performance: nano-bio-info-cognition"*** (Springer, 468p, 2003)
5. ***NBIC2**: **"Convergence of knowledge, technology and society: Beyond NBIC"*** (Springer, 604p, 2013b)
6. *"Mapping nanotechnology innovation and knowledge: global and longitudinal patent and literature"* (Chen & Roco, Springer, 330p, 2009)
7. *"Global nanotechnology development from 1991 to 2012"* (Chen .., JNR 2013c)
8. "Principles and methods that facilitate convergence" (Roco, Springer, Handbook of S&T Convergence, 2015)
9. "NBIC" (Roco, Springer, Handbook of S&T Convergence, 2015)
10. Two nano websites: www.nano.gov/publications-resources; www.nsf.gov/nano