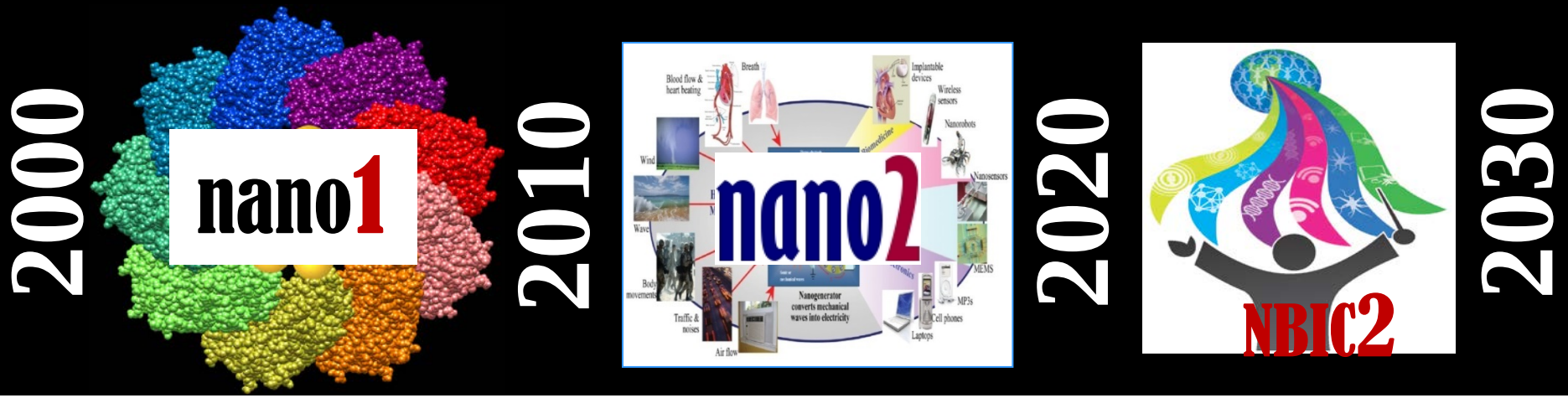


Nanotechnology at NSF in the International Context

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

12th US-Korea Nano Forum, Arlington, Virginia, October 5, 2015

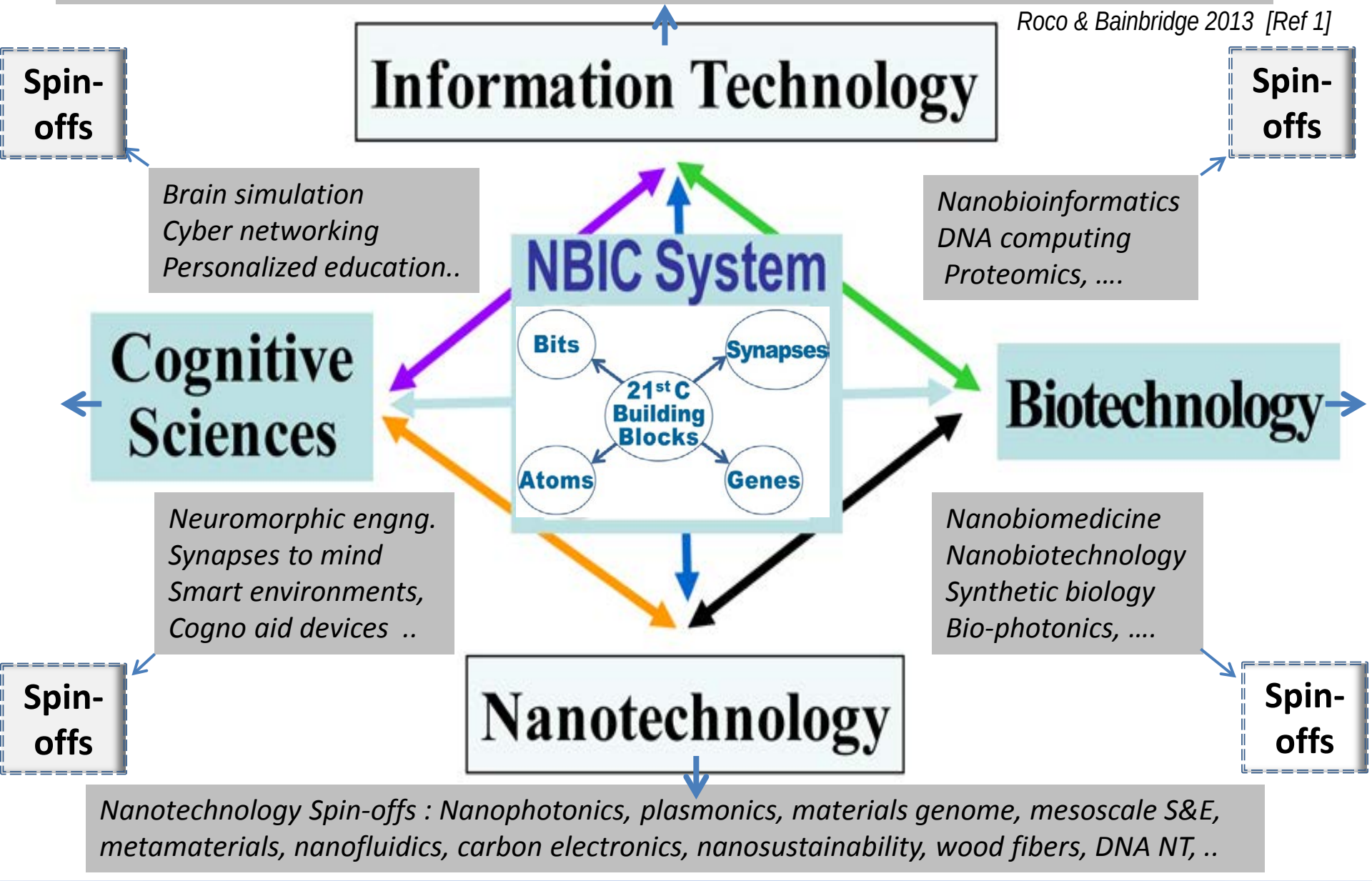
Support for a foundational S&T field requires a long-view approach

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

Emergence 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, ...

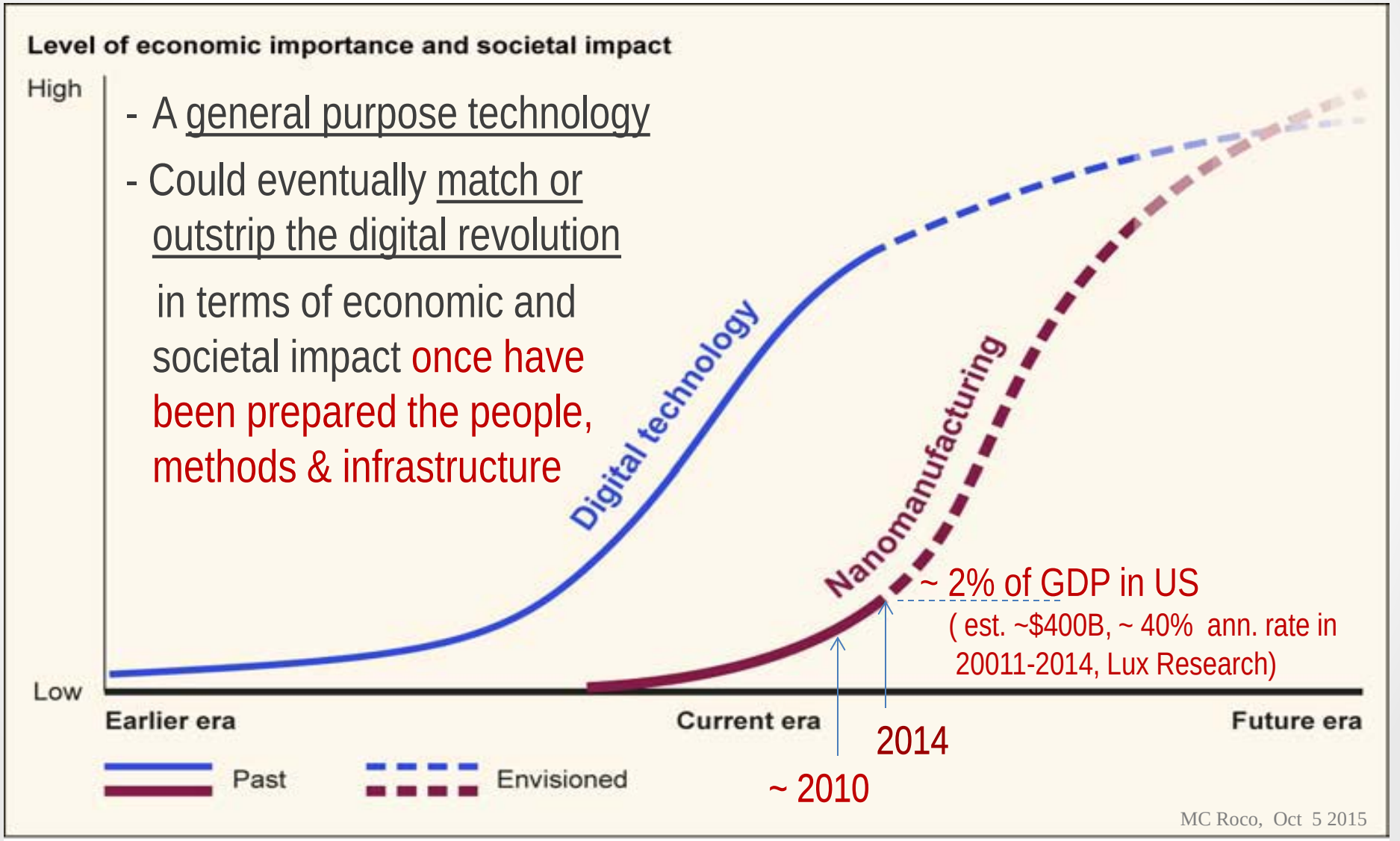
Roco & Bainbridge 2013 [Ref 1]



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

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

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



MC Roco, Oct 5 2015

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%

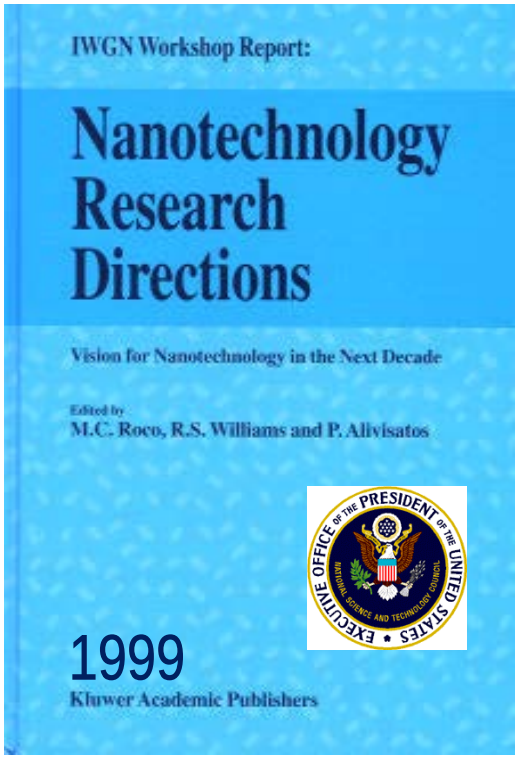
(*) Data from Nano 2 Report, 2011; (**) Data from Lux Research industry survey, Jan 2014

MC Roco, Oct 5 2015

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

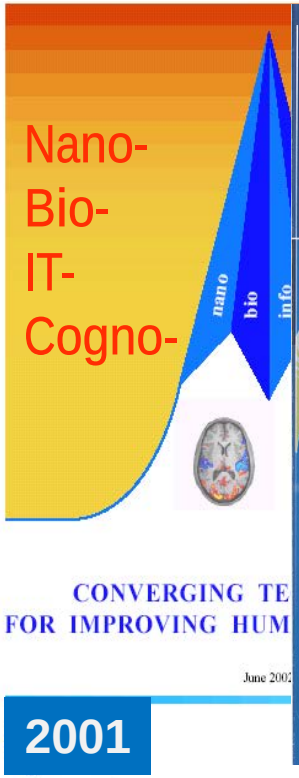
Nanotechnology: from scientific curiosity to immersion in socioeconomic projects

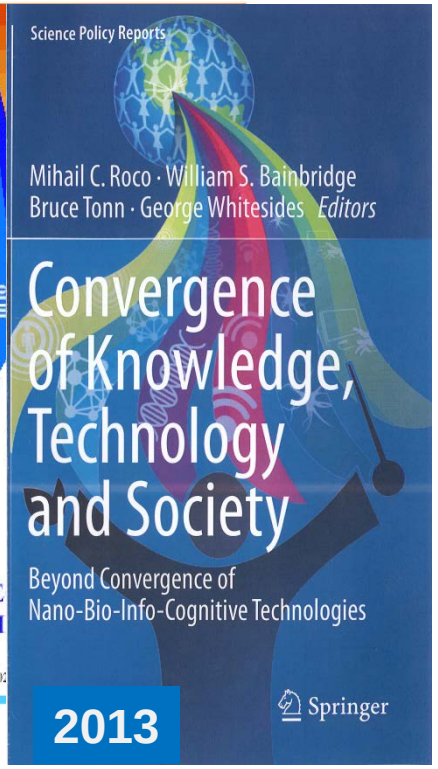
nano1 (2001-2010)



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)

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

GENERATIONS OF NANOPRODUCTS

2030

DIVERGENCE

CONVERGENCE

2000

New socio-economic capabilities

nano3 Technology divergence

2020-2030

To general purpose technology

nano2 System integration

2010-2020

Foundational research at the nanoscale

nano1 Nanocomponent basics

2000-2010

Nanosystem Converg. Networks

NBIC Technology Platforms

Molecular Nanosystems

Systems of Nanosystems

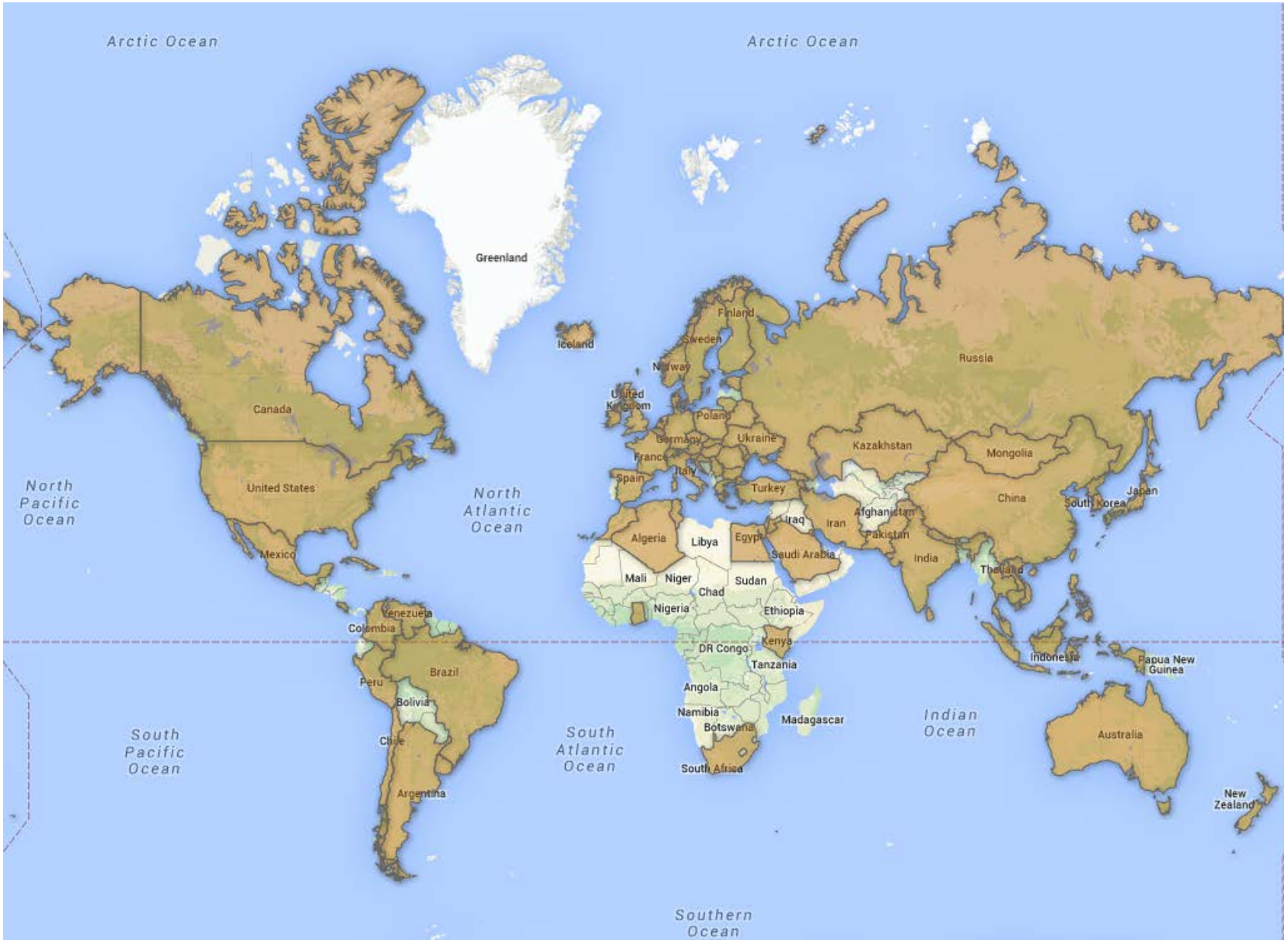
Active Nanostructures

Passive Nanostructures

NSF/NNI and the International Perspective


DOE
HHS/NIH
OSTP
OMB
NSF
DOD
DOC/NIST
HHS/FDA
NASA
USDA/NIFA
USDA/ARS
HHS/CDC/
NIOSH
USDA/FS
National Nanotechnology Initiative
DOS
EPA
Vision: control of matter at nanoscale will bring a revolution in technology for societal benefit
DOTr
NRC
DOT
DOC/
USPTO
Impact of NNI in many areas / agencies
IC/DNI
DOI/
USGS
DOJ
DOL
DOC/EDA
DOC/BIS
DHS
CPSC
ITC
DOEd

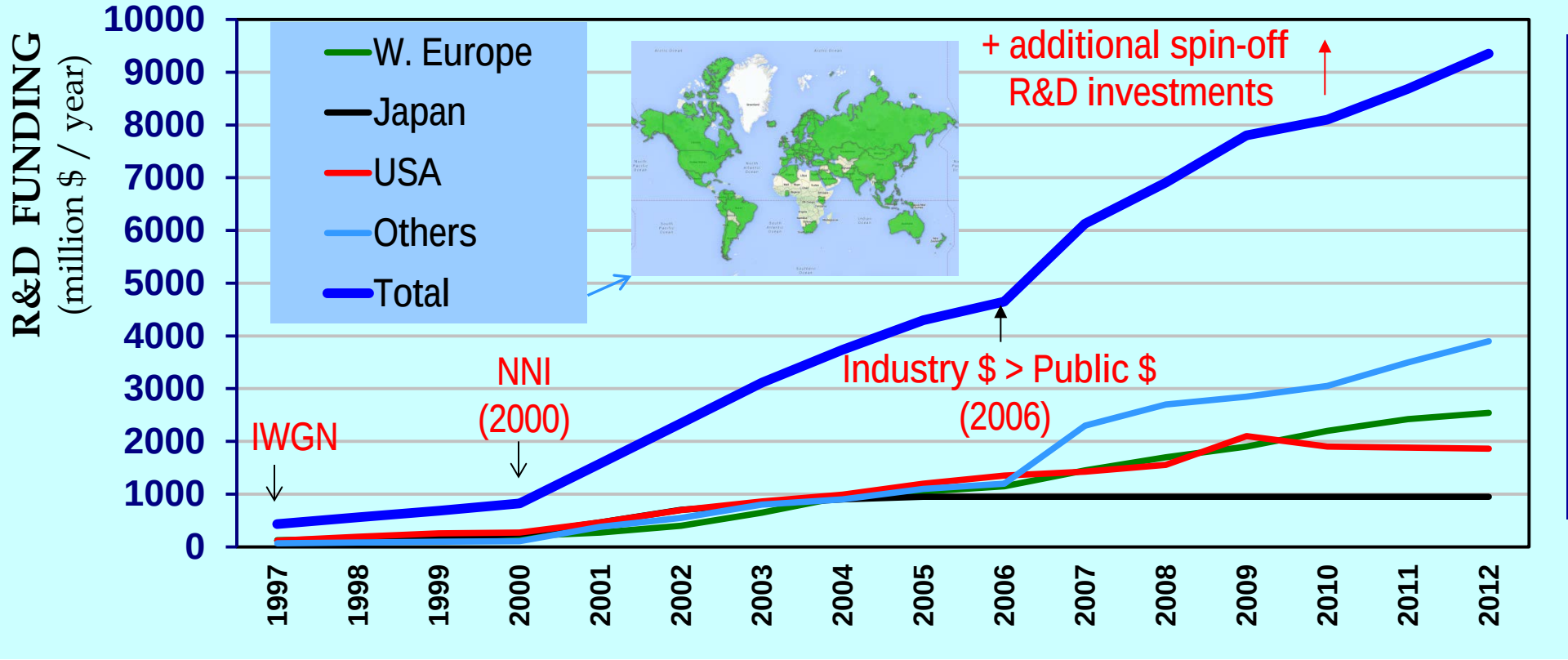
A truly global science endeavor; S-curve 2000-2030



Over 80 countries with nanotechnology programs

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

2001-2014

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

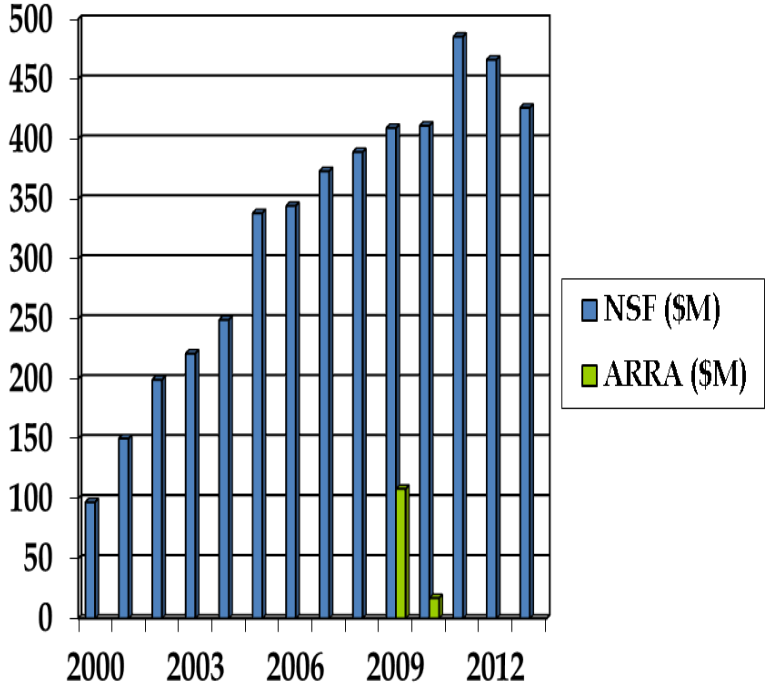
www.nsf.gov/nano , www.nano.gov

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

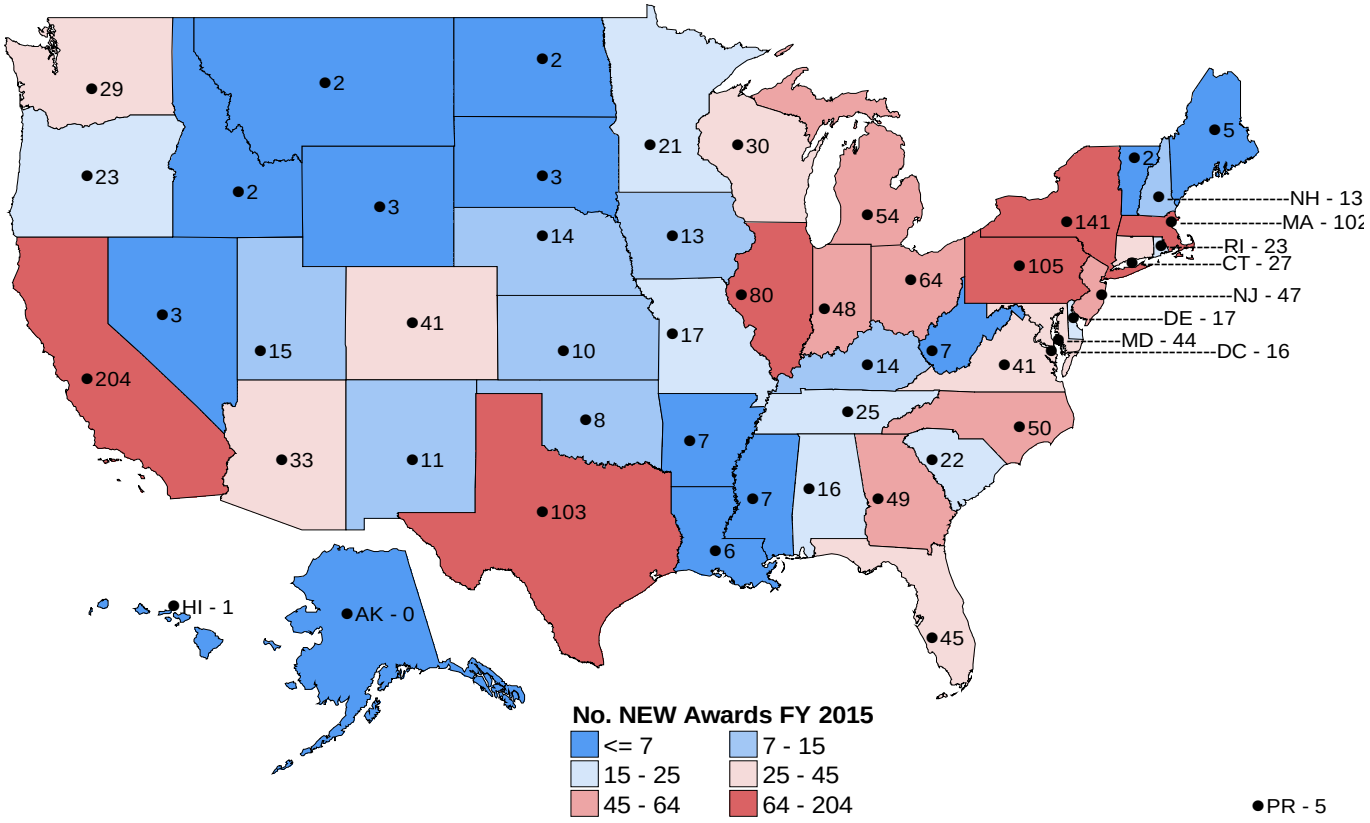
www.nsf.gov

- National Nanotechnology Coordinated Infrastructure, NNCI
- Scalable nanomanufacturing, SNM
- Two-Dimensional Atomic-layer Research and Engineering, 2-DARE/EFRI (2 competitions)
- NSE activities for Innovations at Nexus of Food, Energy, and Water ("INFEWS") and 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

NSF's NSE number of new awards per state

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

(total active awards = 7,843)

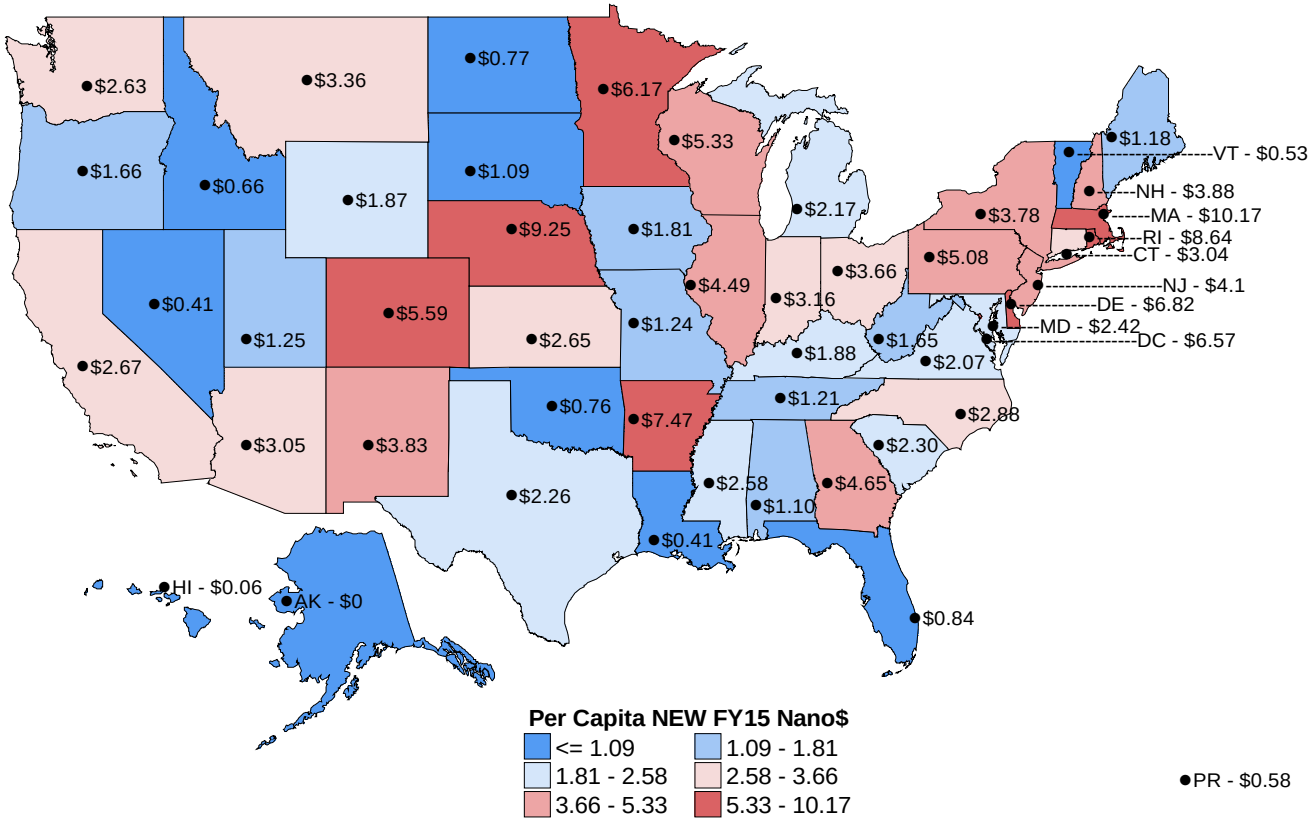


AK 0; AL 16; AR 7; AZ 33; CA 204; CO 41; CT 27; DC 16; DE 17; FL 45; GA 49; HI 1; IA 13; ID 2; IL 80; IN 48; KS 10; KY 14; LA 6; MA 102; MD 44; ME 5; MI 54; MN 21; MO 17; MS 7; MT 2; NC 50; ND 2; NE 14; NH 13; NJ 47; NM 11; NV 3; NY 141;

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

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

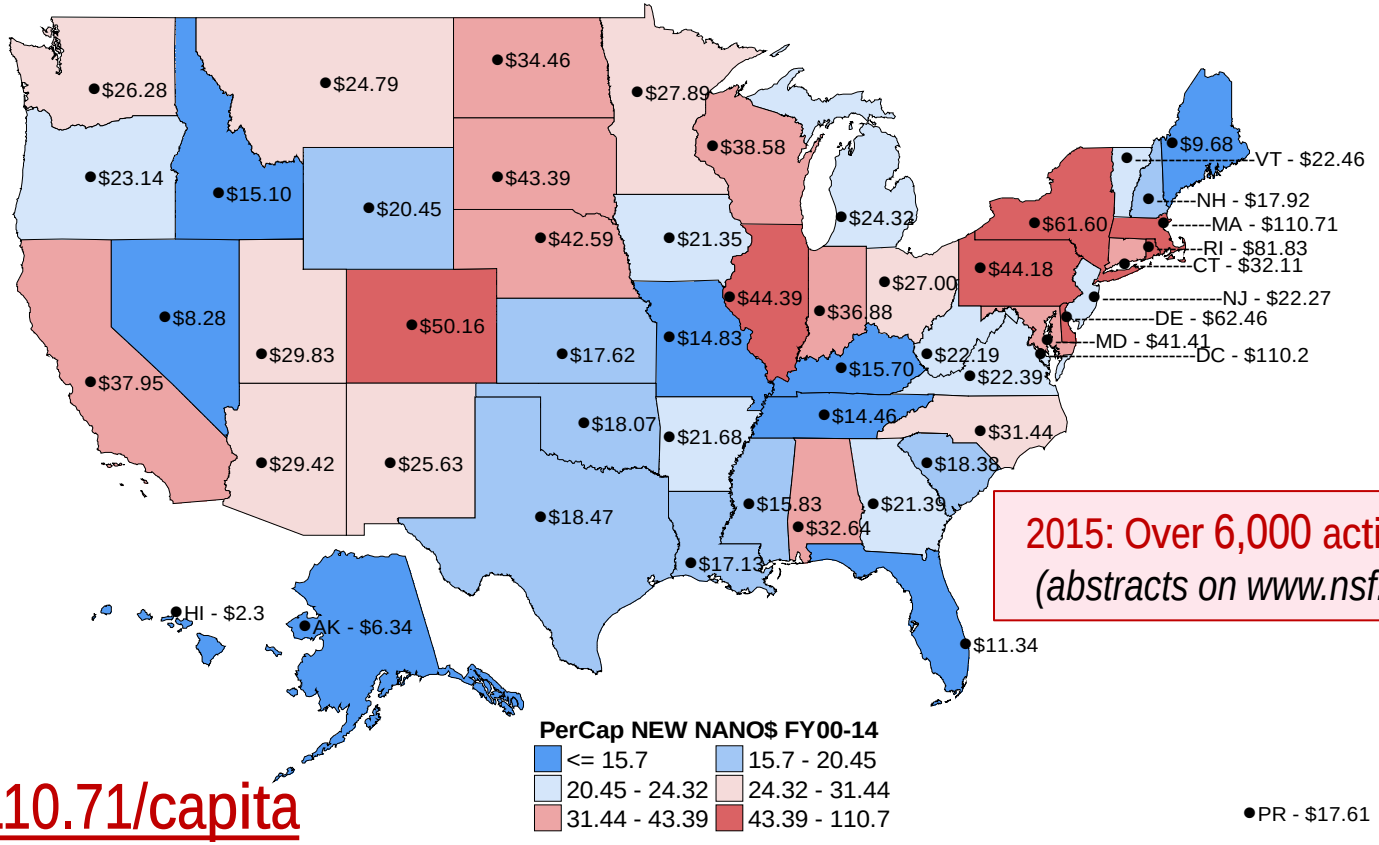
FY 2015: U.S. average amount = $3.06 / capita



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

NSF's NS&E amount new awards per capita

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



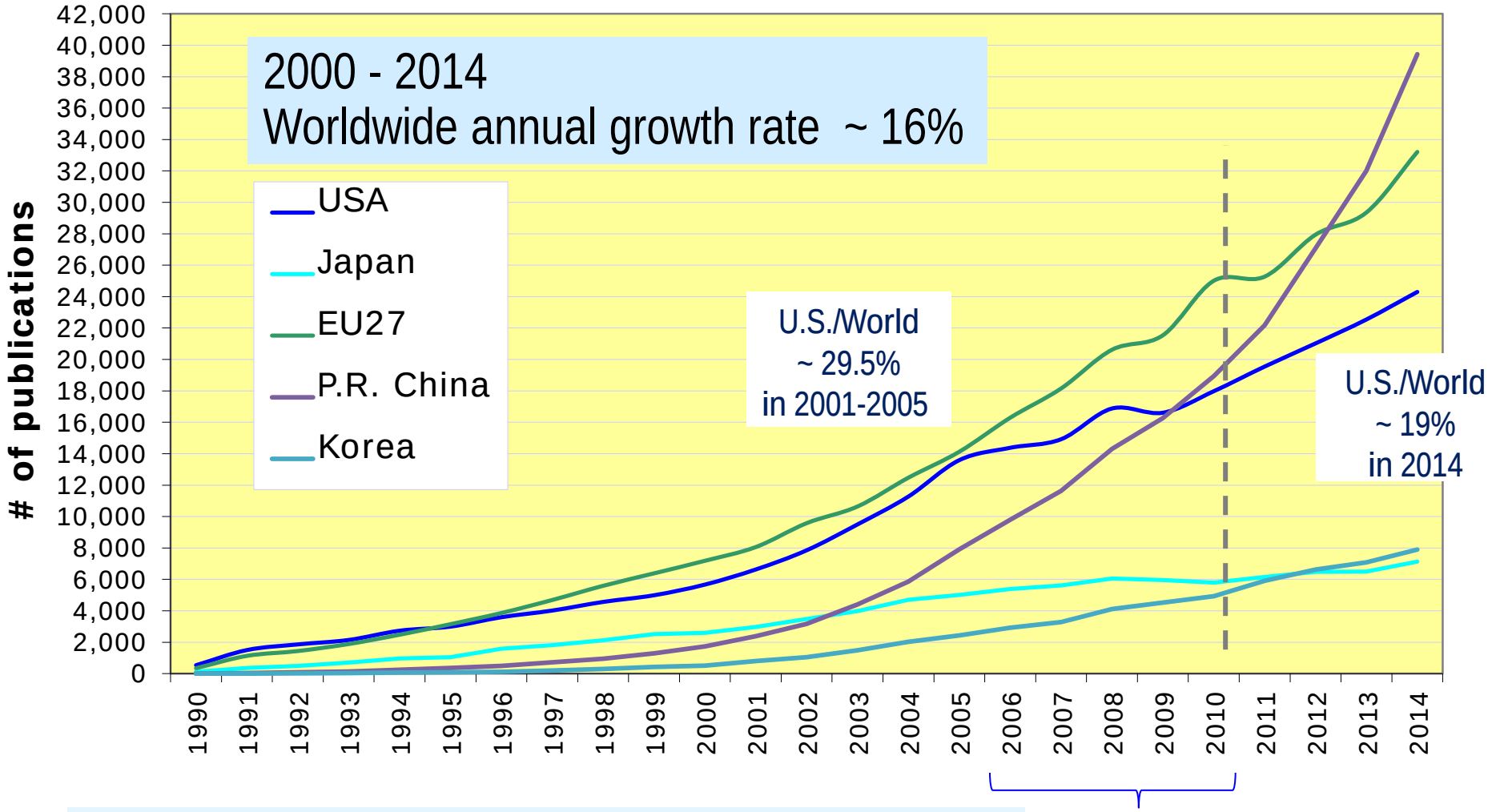
2015: Over 6,000 active awards
(abstracts on www.nsf.gov/nano)

#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

Nanotechnology publications in the WoS: 1990 - 2014

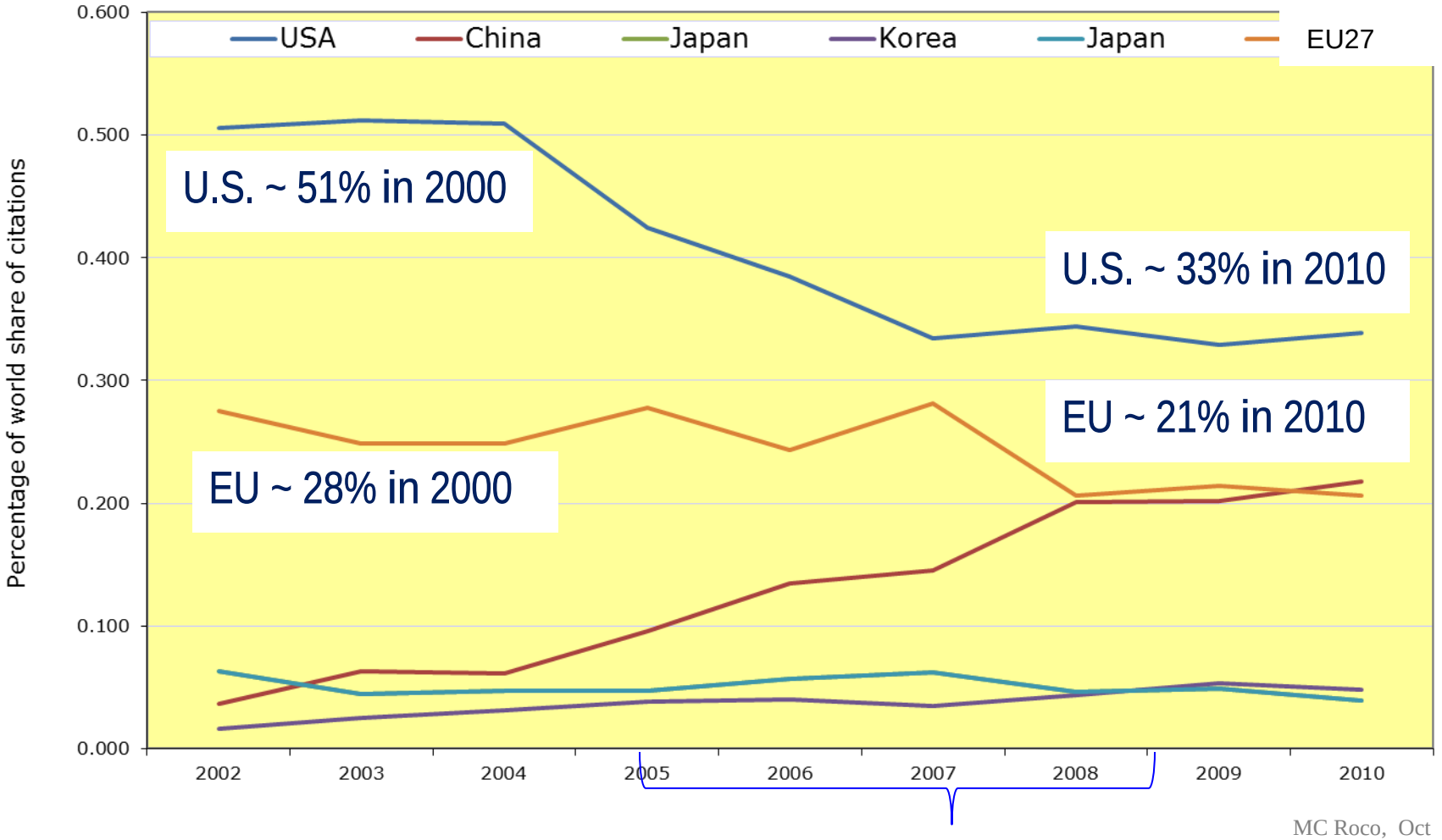
"Title-abstract" search for nanotechnology by keywords for six regions
(update of NANO2, Fig 1 (Ref. 3) using the method described in (Ref. 6))



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)



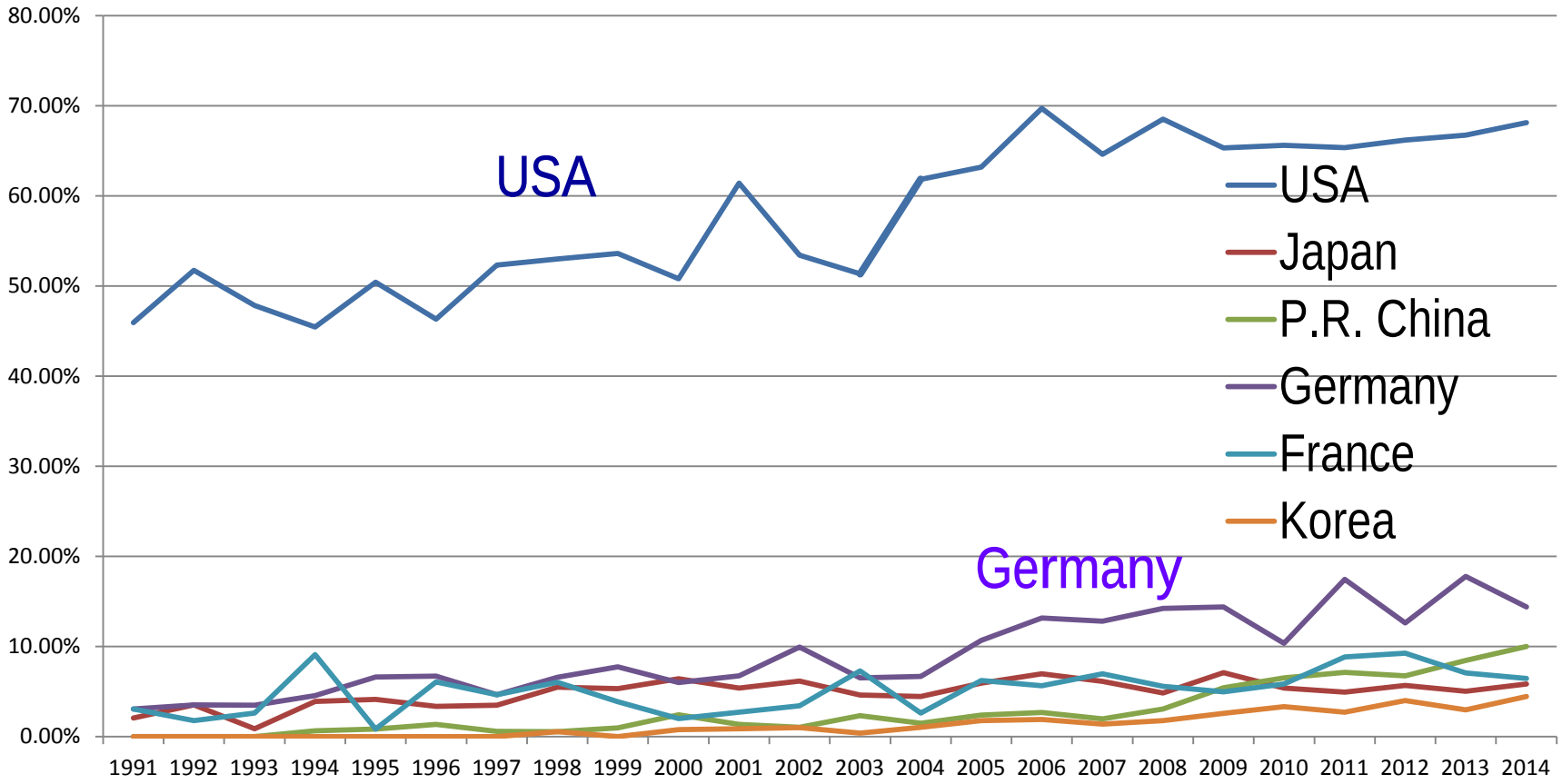
MC Roco, Oct 5 2015

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))



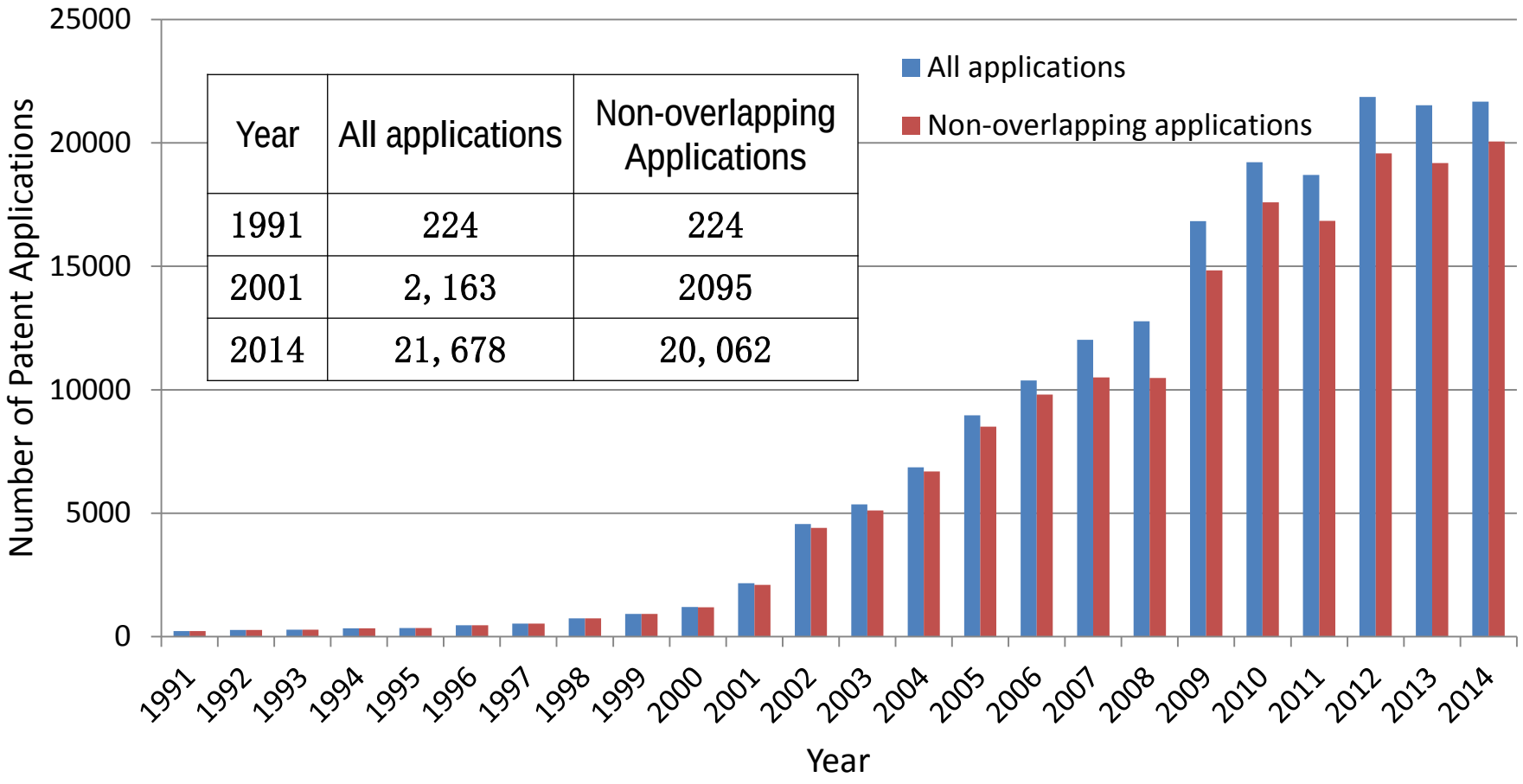
* Started to use Combined Keywords from 2014

MC Roco, Oct 5 2015

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

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

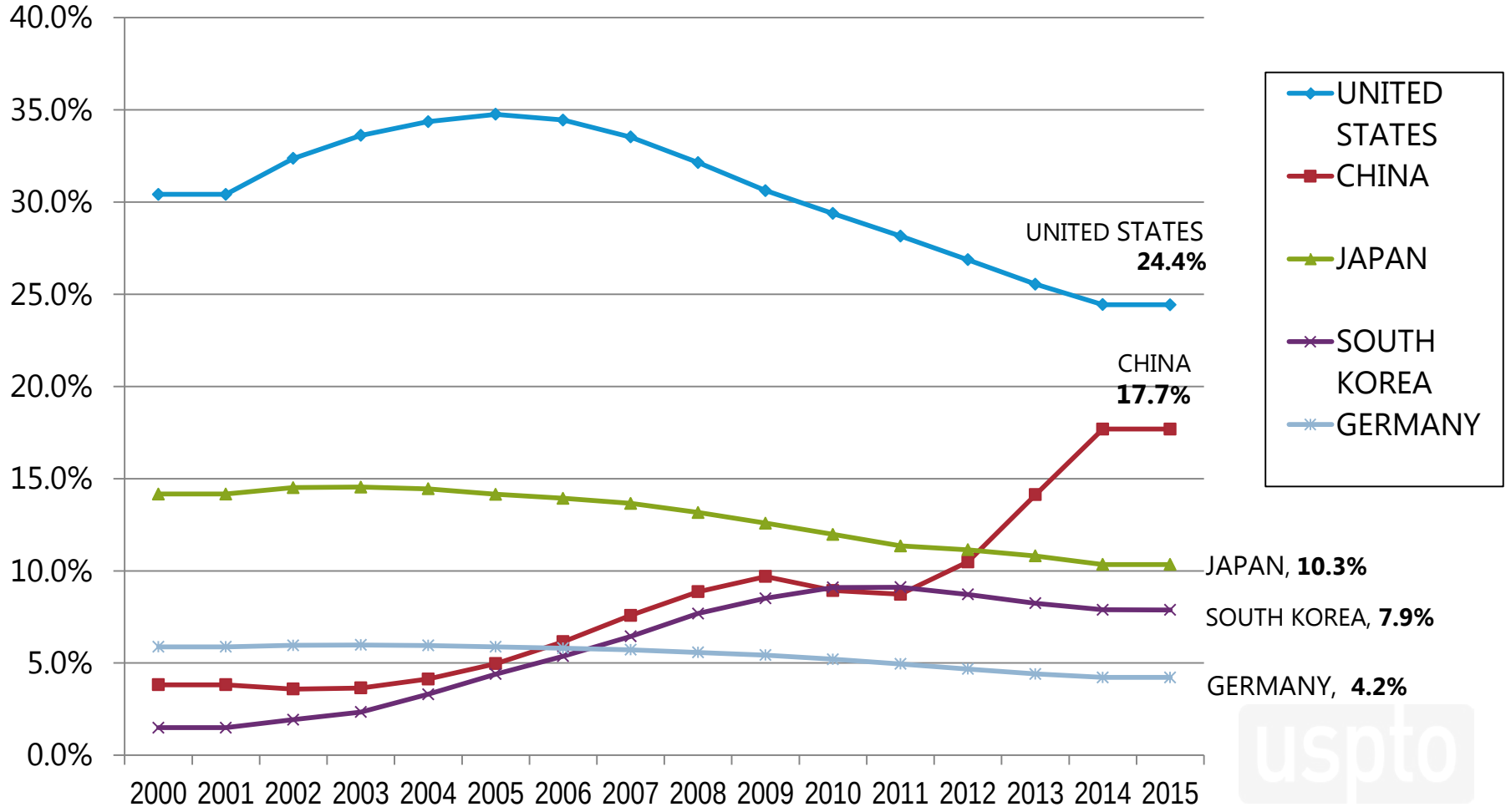
Year	All applications	Non-overlapping Applications
1991	224	224
2001	2, 163	2095
2014	21, 678	20, 062



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

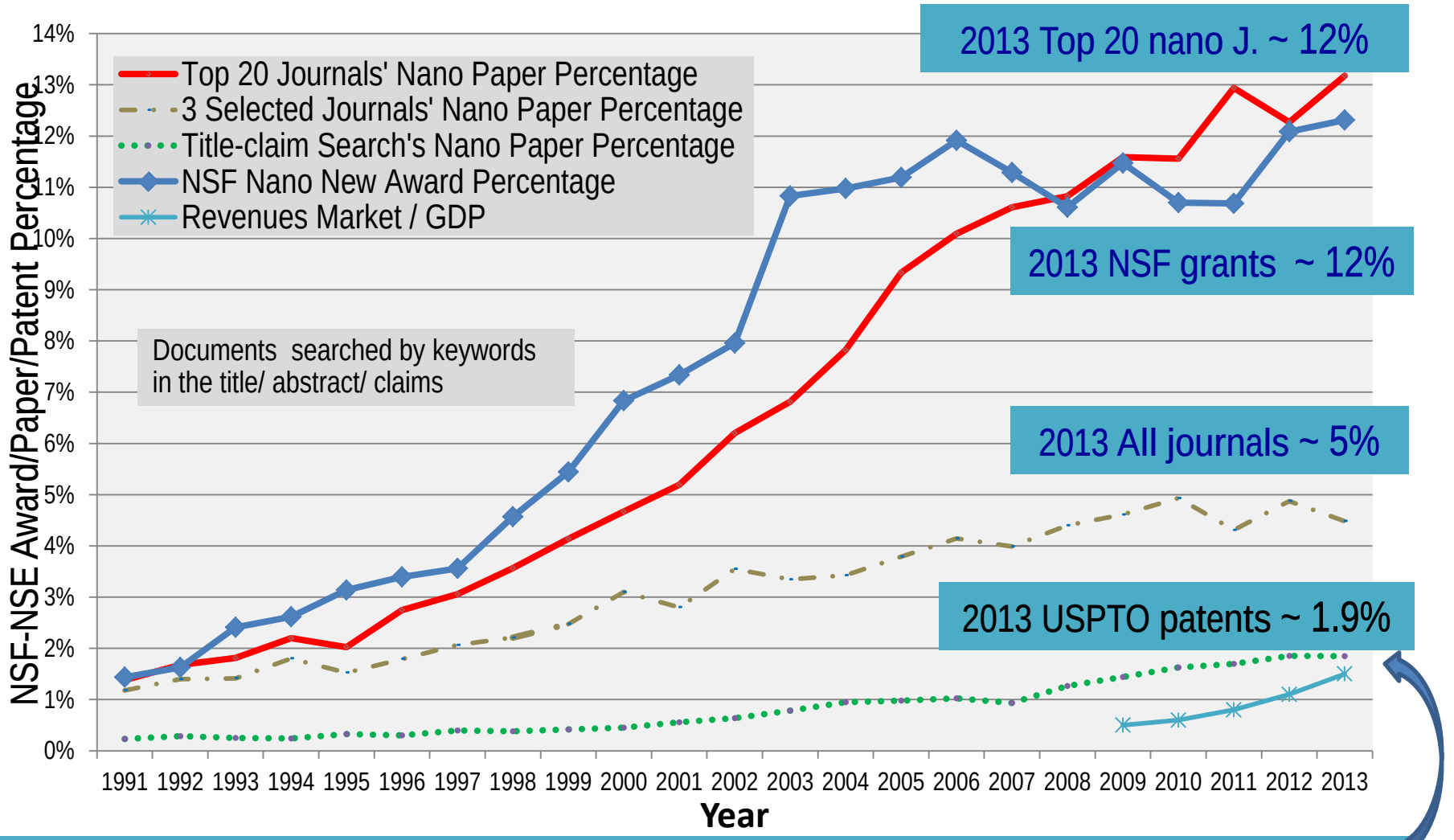
Derwent World Patents Index with extension abstracts (WPIX):
by First-named Inventor, patent publications 1986- June 2015)



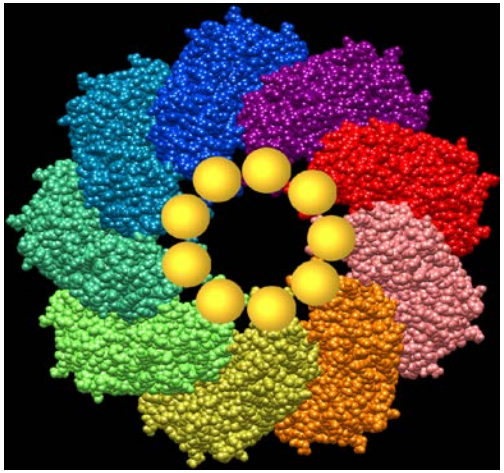
Nanotechnology Patents evaluated by USPTO

Percentage rate of penetration of nanotechnology in NSF awards, WoS papers and USPTO patents (1991-2013)

(update Encyclopedia Nanoscience, Roco, 2014)



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



Nano 1 (2001-2010)

R&D focus:

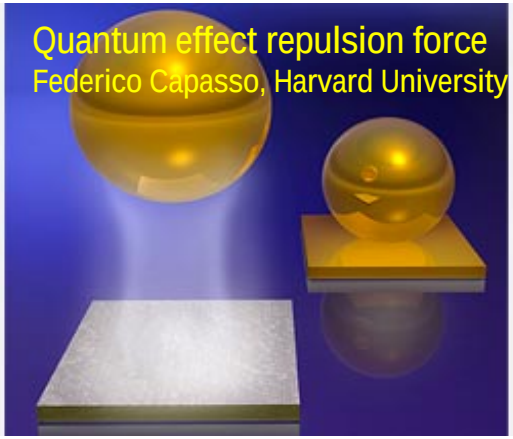
Foundational interdisciplinary research at nanoscale

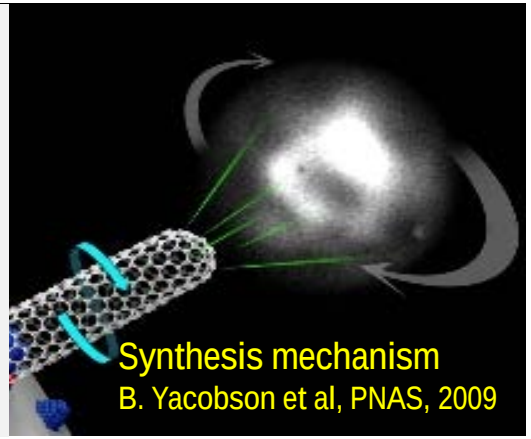
Major global changes in:

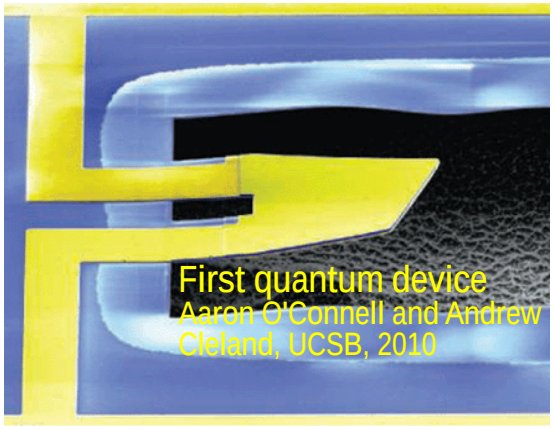
Infrastructure, Workforce, Partnerships

Examples for Nano 1 (2001-2010)

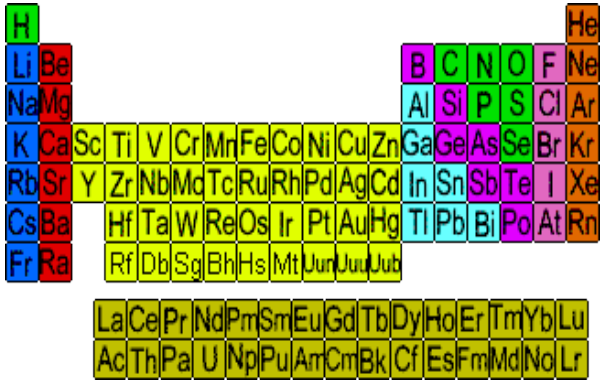
- New individual phenomena, processes, structures



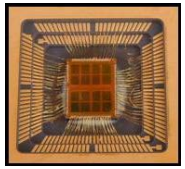


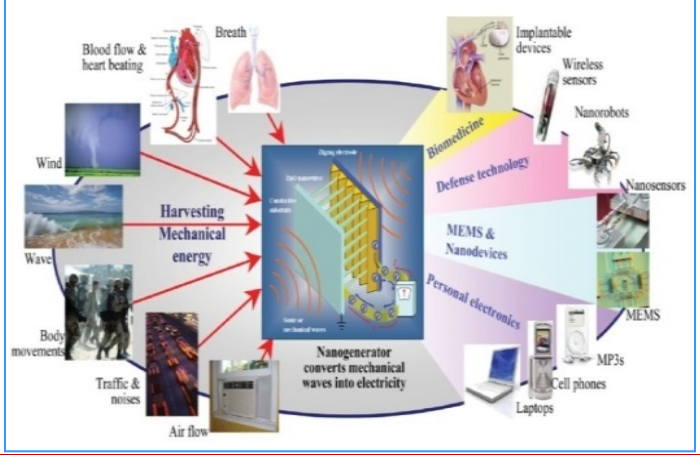


- Semi-empirical synthesis of nanocomponents (particle, quantum dots, tubes, coatings,..) over all the periodic table



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





Nano 2 (2011-2020)

R&D focus:

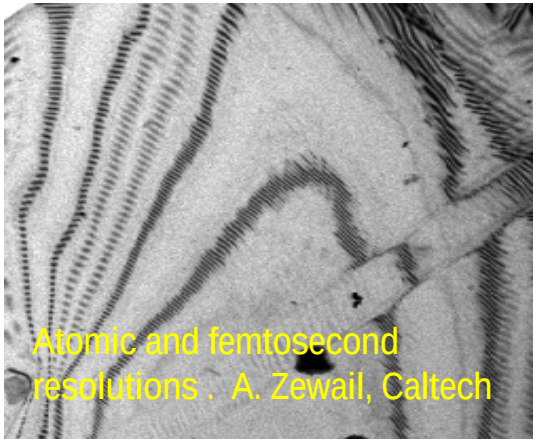
NS&E system integration for general purpose technology

Main global changes in:

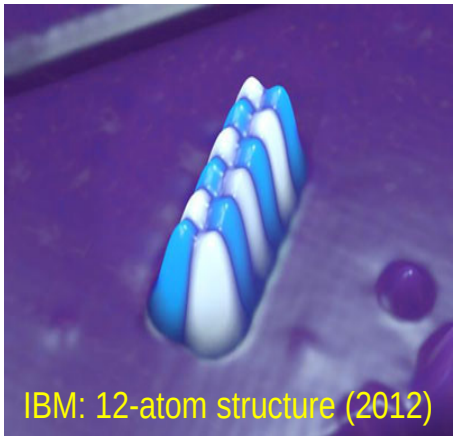
New disciplines, New industries, Societal impact

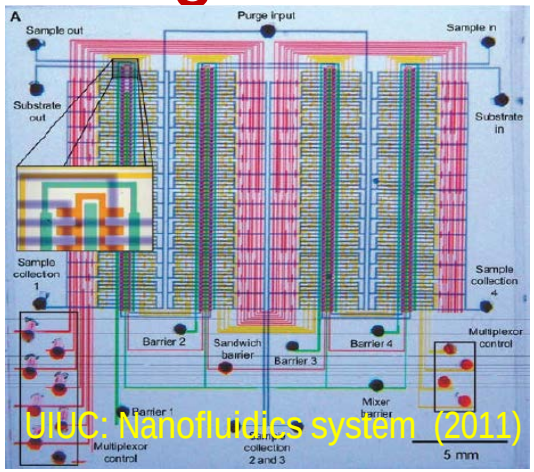
Examples for Nano 2 (2011-2020)

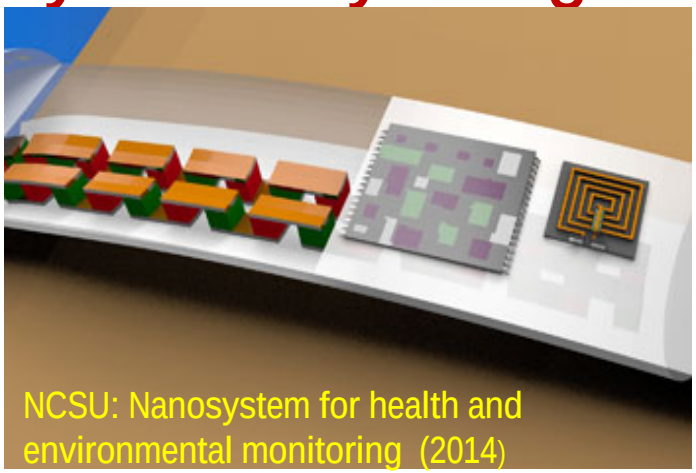
- Simultaneous nanoscale phenomena
- Direct measurements & simulations (at femtosecond, N interacting atoms) for domains of biological and engineering relevance



- Science based integrated nanosystems by design







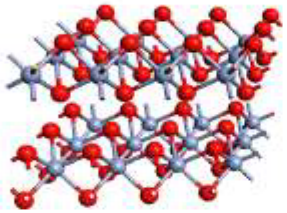
Modular Nanosystems

Example: using 2D electronic materials

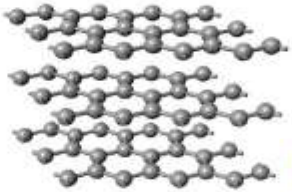
- A Broad Range of Choices:
  - From Insulator to Superconductor
  - Provide Possibility for 2D Circuits

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

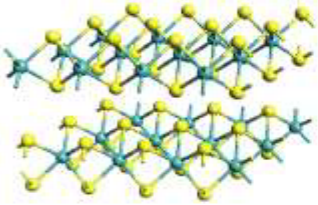
Half-metal (E_g: **0-1 eV**)
Example: **CrO_2, CrS_2**



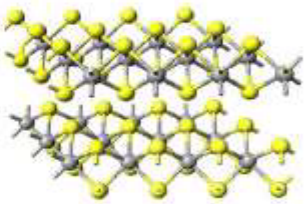
Semi-metal (E_g: **0 eV**)
Interconnect, Gate, RF, etc.
Example: **Graphene**

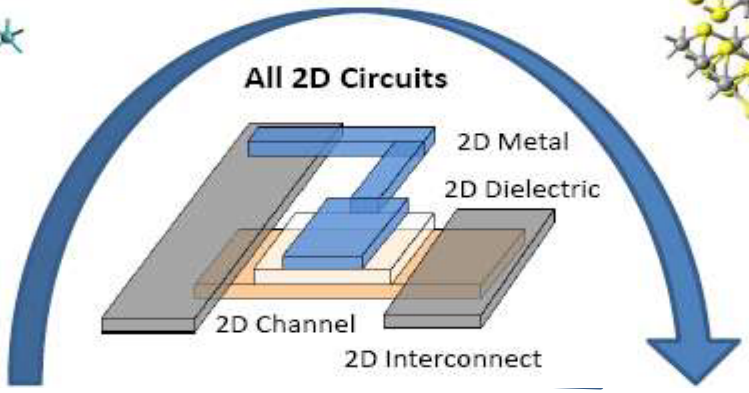


Semiconductor (E_g: **1-2 eV**)
Channel Material
Example: **MoS_2, WSe_2**

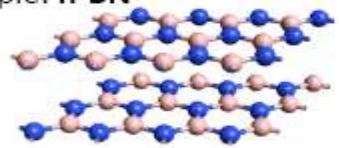


Metal
Interconnect, Gate , etc.
Example: **VO_2, VS_2**

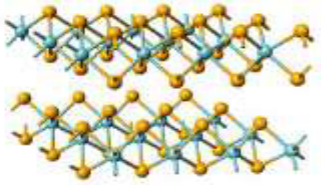




Insulator (E_g: **~5 eV**)
Dielectric
Example: **h-BN**

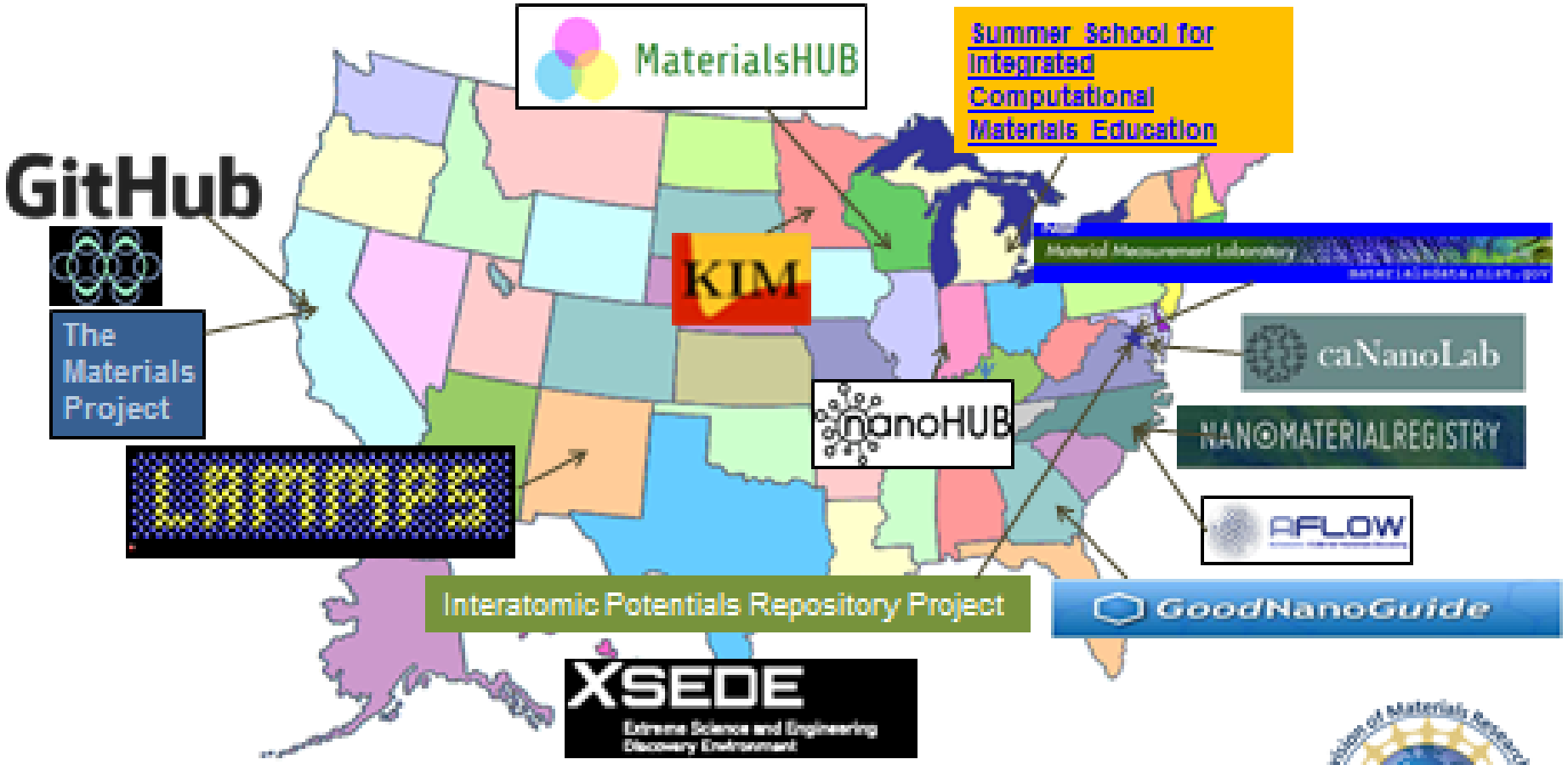


Superconductor
Example: **$NbSe_2$**



Courtesy Kaustav Banerji (UCSB)

Some Components of the Nanotechnology Knowledge Infrastructure



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

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

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

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

Nanotechnology Signature Initiatives

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

Sustainable Nanomanufacturing

Nanoelectronics for 2020 and Beyond

Nanotechnology for Solar Energy

Nanotechnology for Sensors and Sensors for Nanotechnology

Nanotechnology Knowledge Infrastructure

New topics under consideration after 2015:

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

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

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**

Nano 3 (2021-2030)

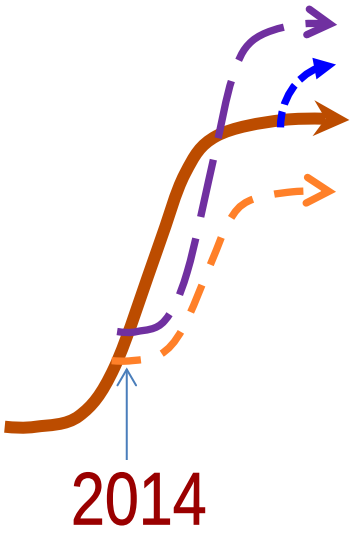
R&D Focus:

New convergence platforms & economy immersion

Main global changes in*:*

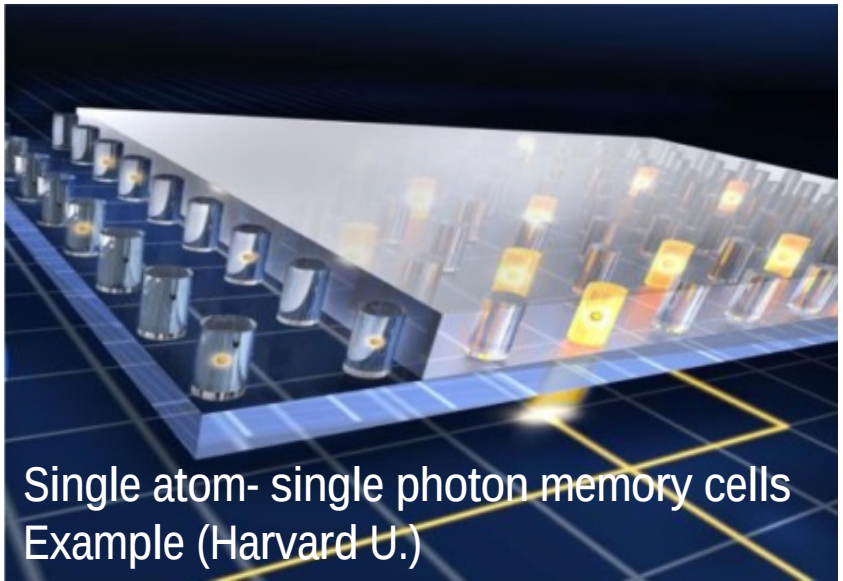
Socioeconomic NBIC platforms, capabilities & projects

To Nano 3



Overlapping S-curves:

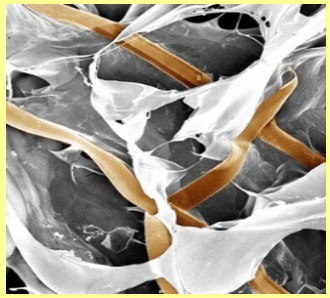
Successive breakthroughs in nanostructure system architectures and convergence



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**

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