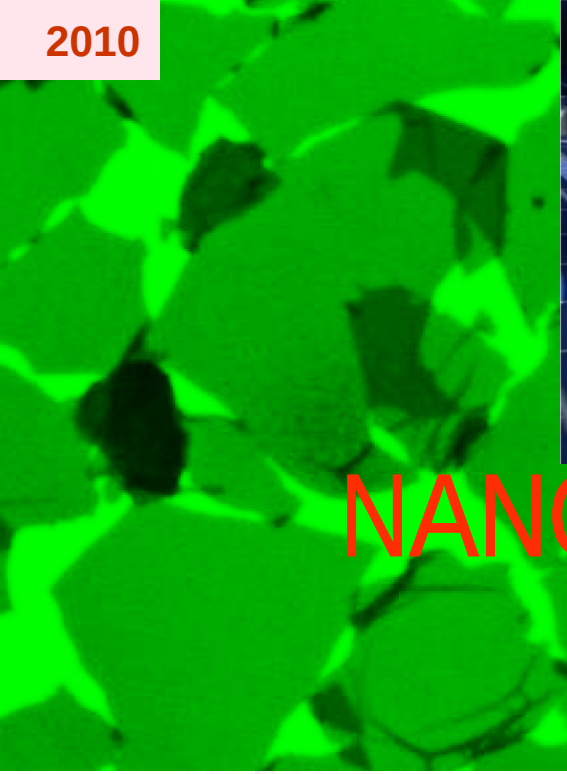
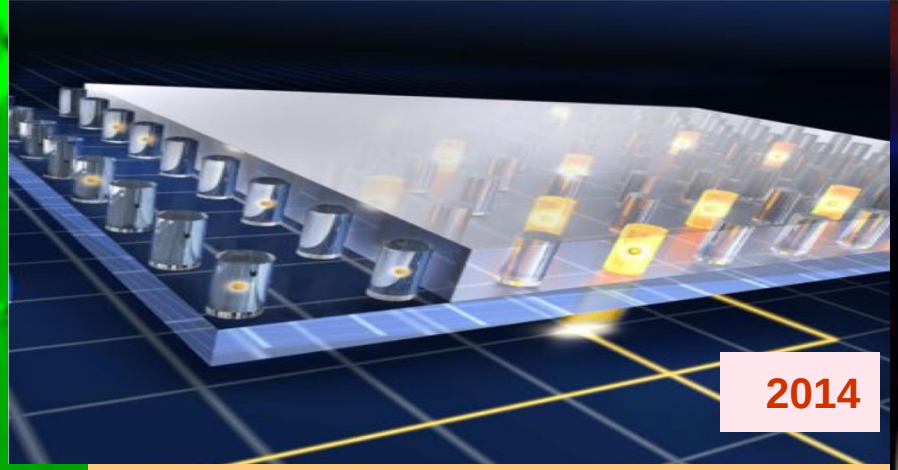
Nanoscale Science and Engineering at NSF

Mike Roco

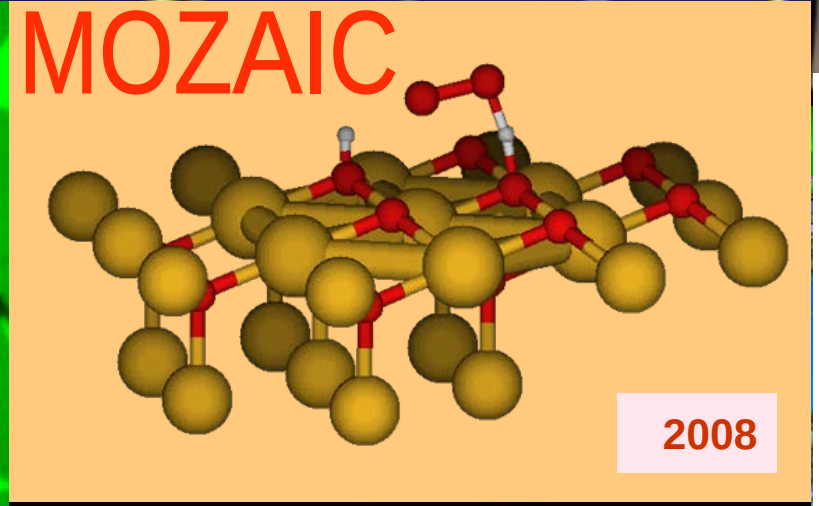
NSF and NNI

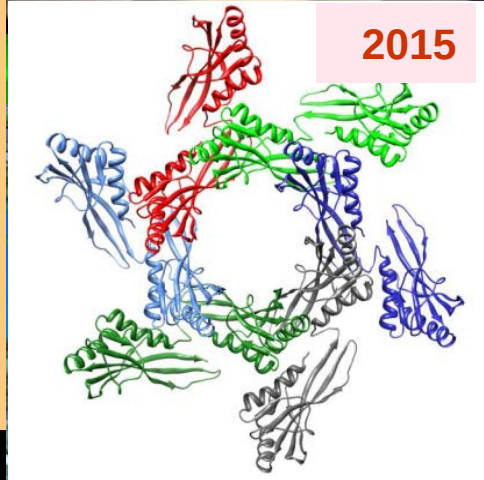
2015 NSF Nanoscale Science and Engineering Grantees Conference
Arlington, December 9-10

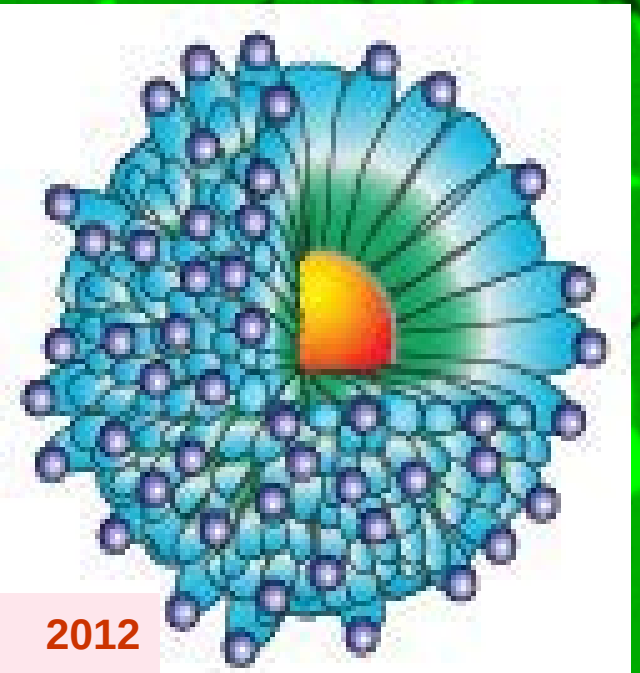


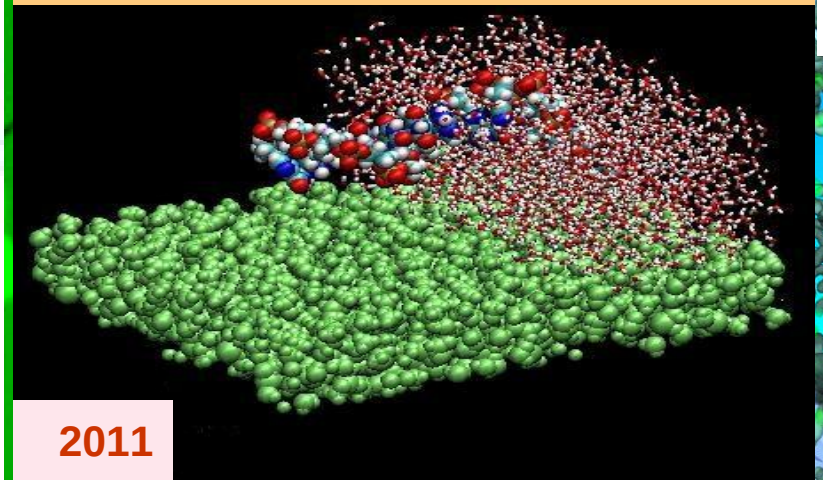


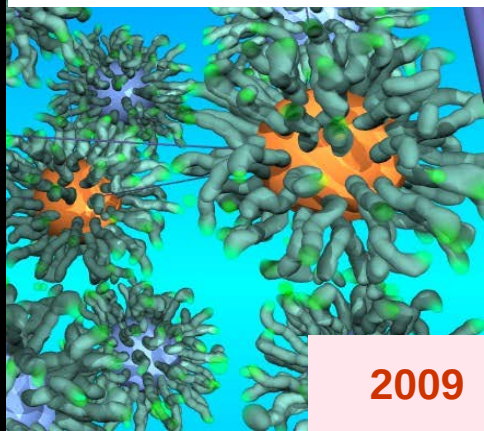
NANO MOZAIC







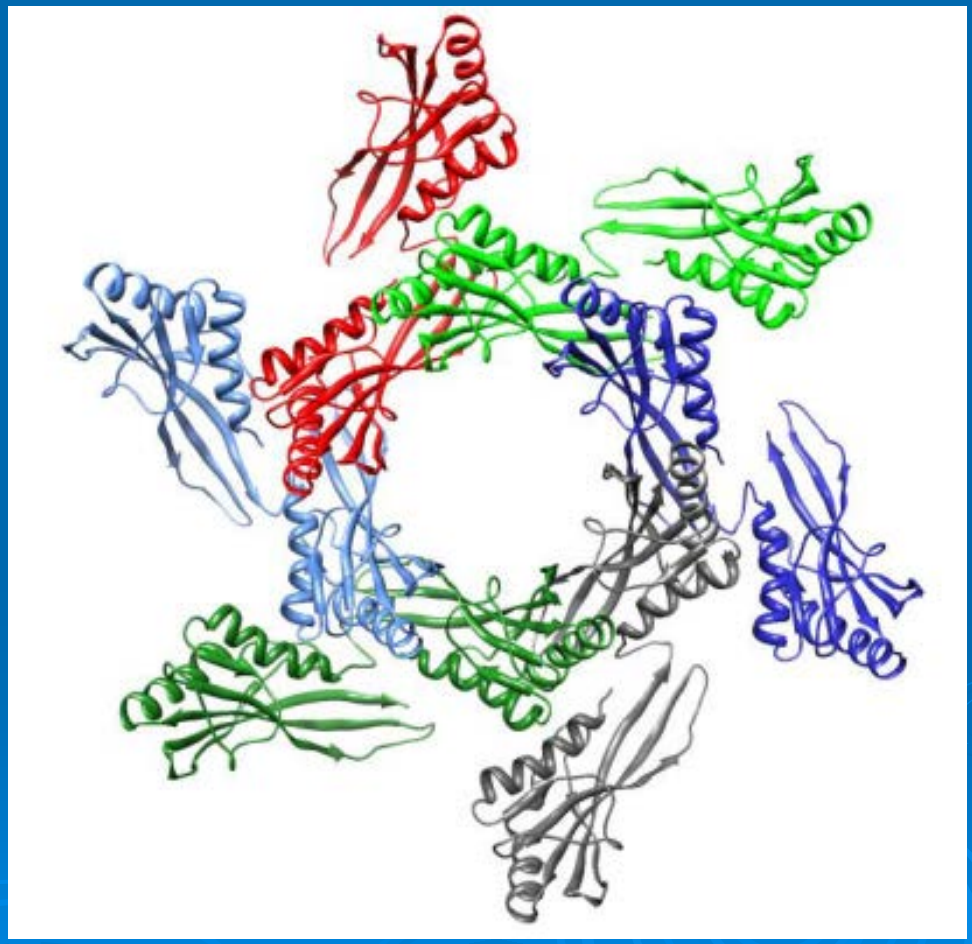




2015 NSF Nanoscale Science and Engineering Grantees Conference

December 9-10, 2015

www.nseresearch.org/2015/



Building block in two-dimensional protein arrays:
A TTM homo-hexamer with six nucleation sites
Courtesy: François Baneyx et al., University of Washington, Seattle, 2015

Topics

- 2000-2030 – S&T convergence in 3 stages
  - nanotechnology
  - nano-bio-info-cognition (NBIC)
  - knowledge and technology
- Nanoscale science and engineering activities at NSF
- On priorities, outcomes and challenges

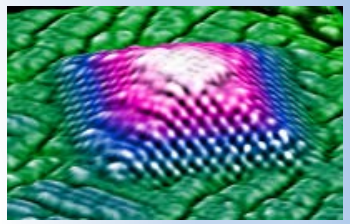
Three stages of S&T Convergence

Three stages of convergence

(Ref 6: CKTS, Springer, 2013)

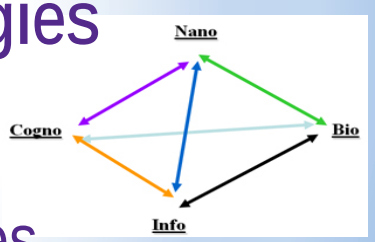
I. Nanoscale Science, Engineering and Technology "Nanotechnology"

Integrates disciplines and knowledge of matter from the nanoscale



II. Nano-Bio-Info-Cognitive Converging Technologies "NBIC"

Integrates foundational and emerging technologies from basic elements using similar system architectures

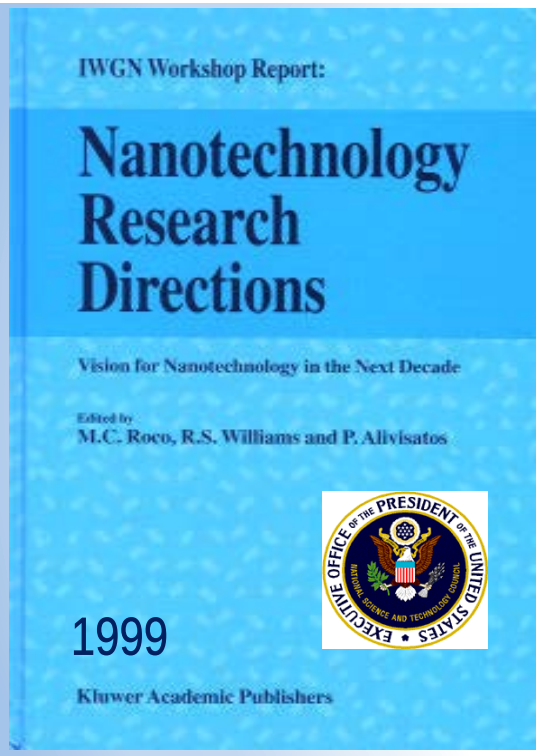


III. Convergence of Knowledge, Technology and Society "CKTS"

Integrates the essential platforms of human activity using five convergence principles

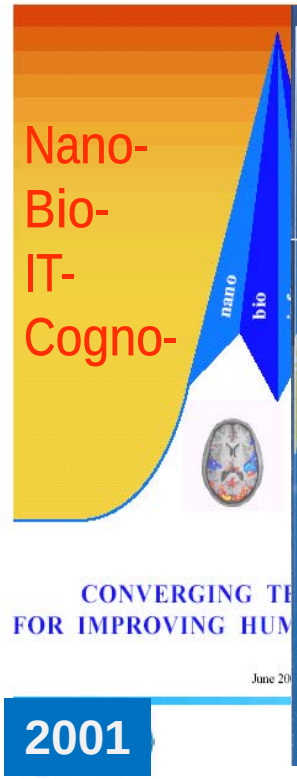
Nanotechnology: from scientific curiosity to immersion in NBIC&CKTS socioeconomic projects

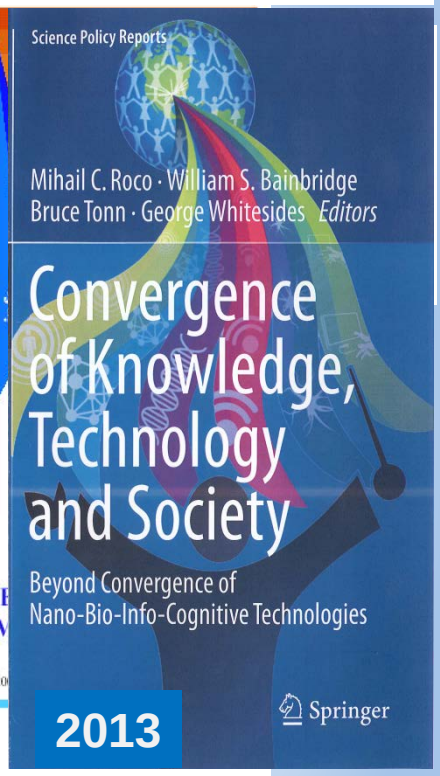
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1 & 2 (2011-2030)



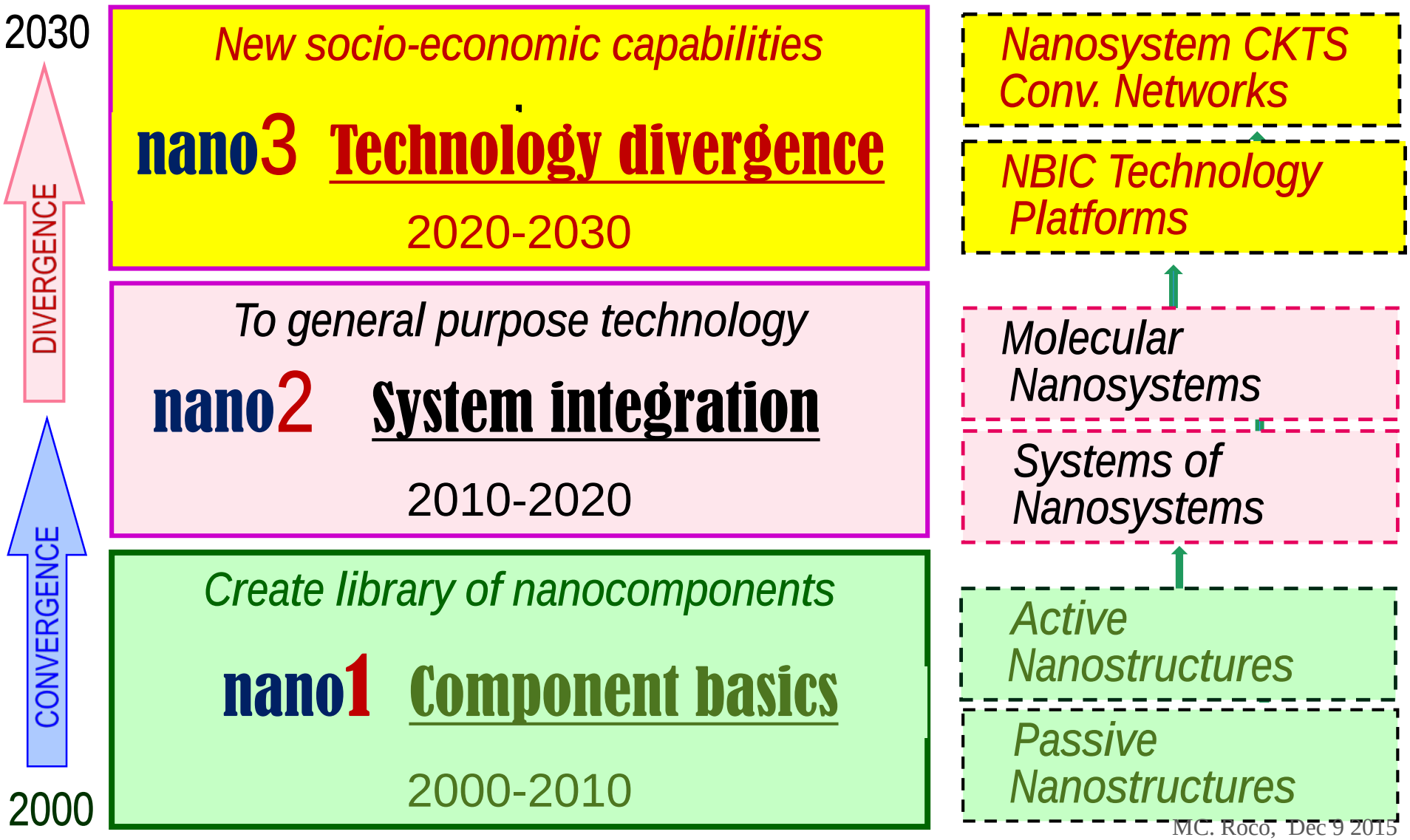


30 year vision to establish nanotechnology and convergence:
In 3 stages changing focus and priorities

Reports available on: www.wtec.org/nano2/ and www.wtec.org/NBIC2-report/ (Refs. 3-6)

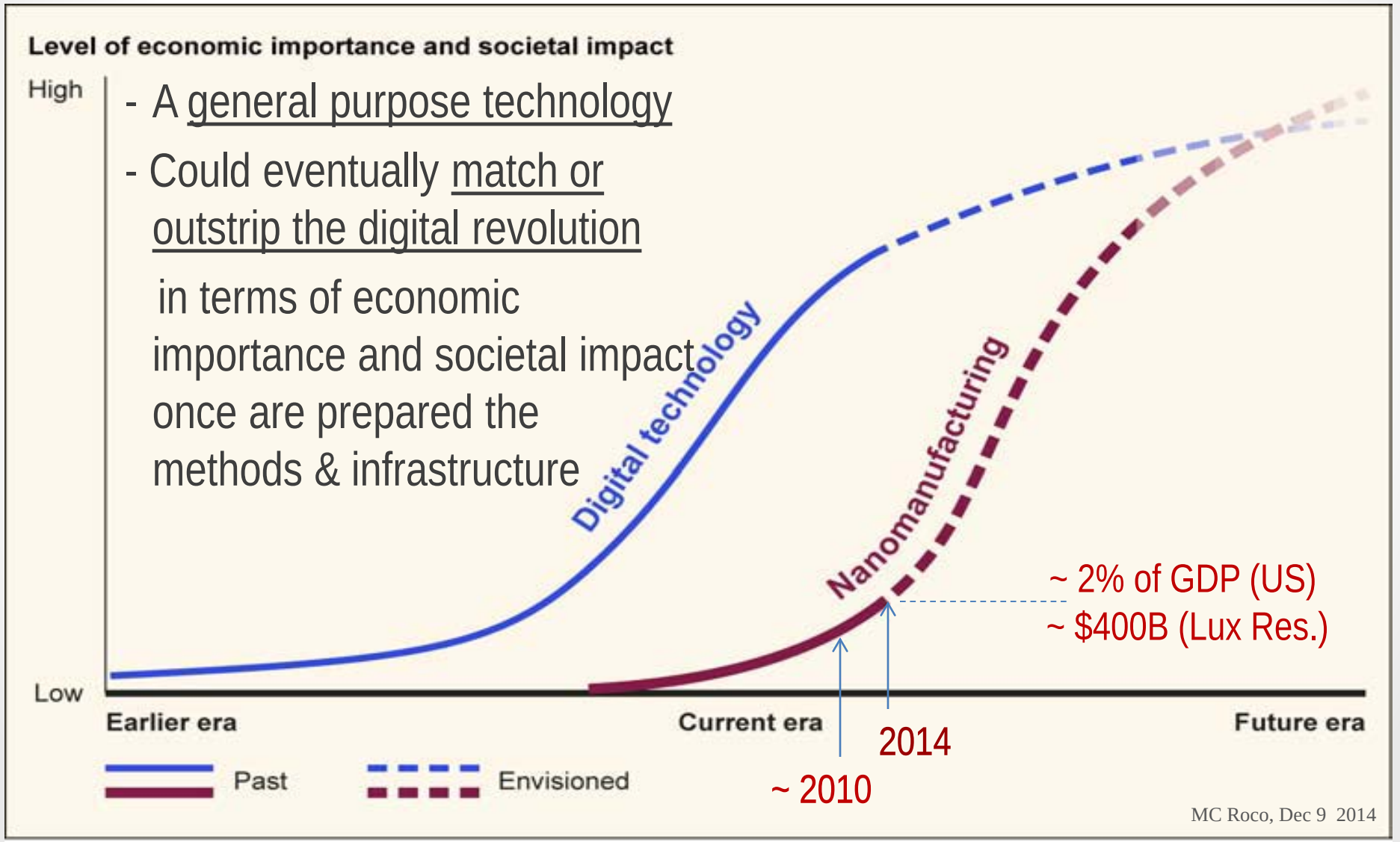
I. CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

GENERATIONS OF NANOPRODUCTS

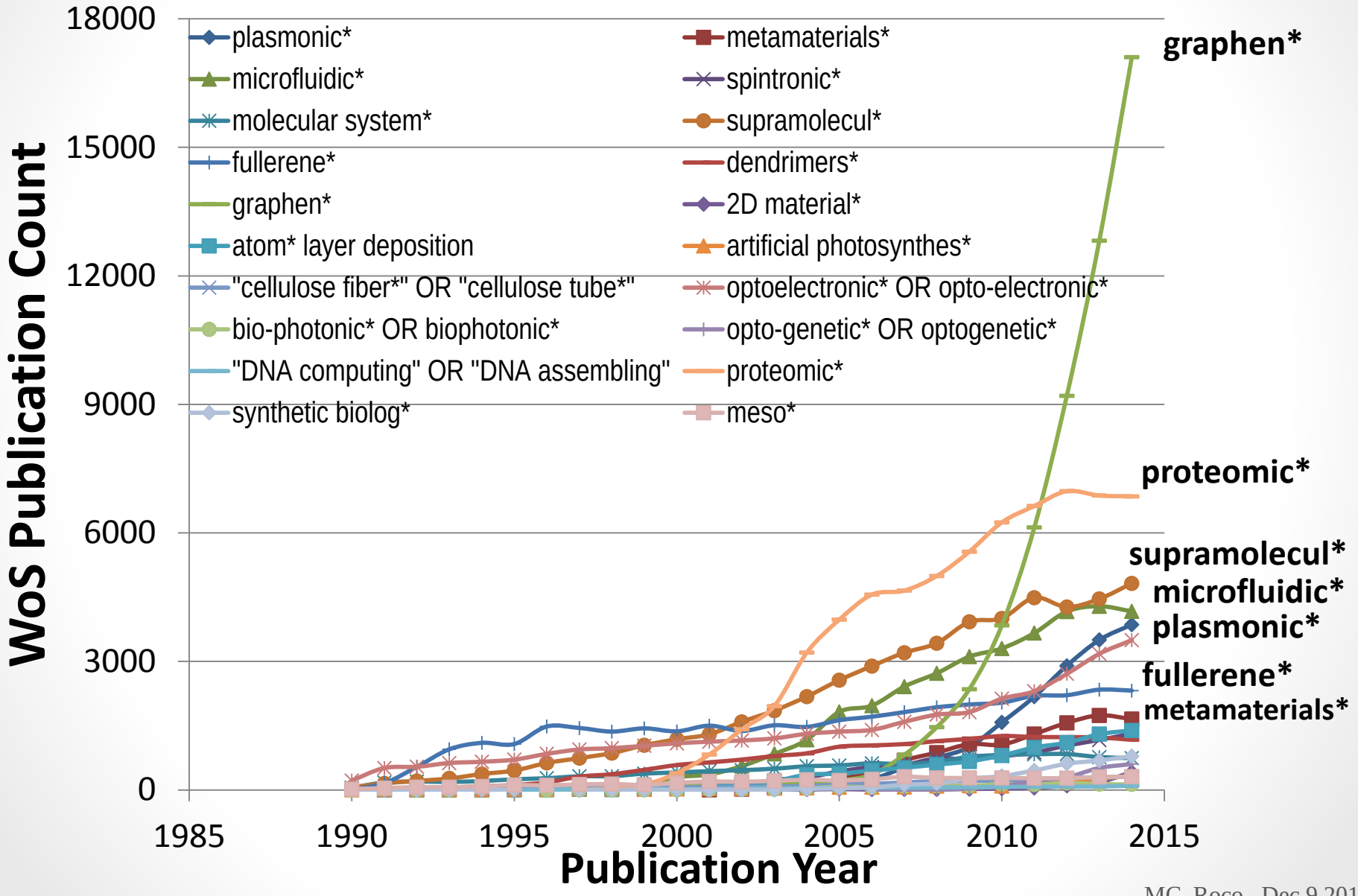


Conceptualization of "Nanomanufacturing" and "Digital Technology" megatrends: *S-curves*

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



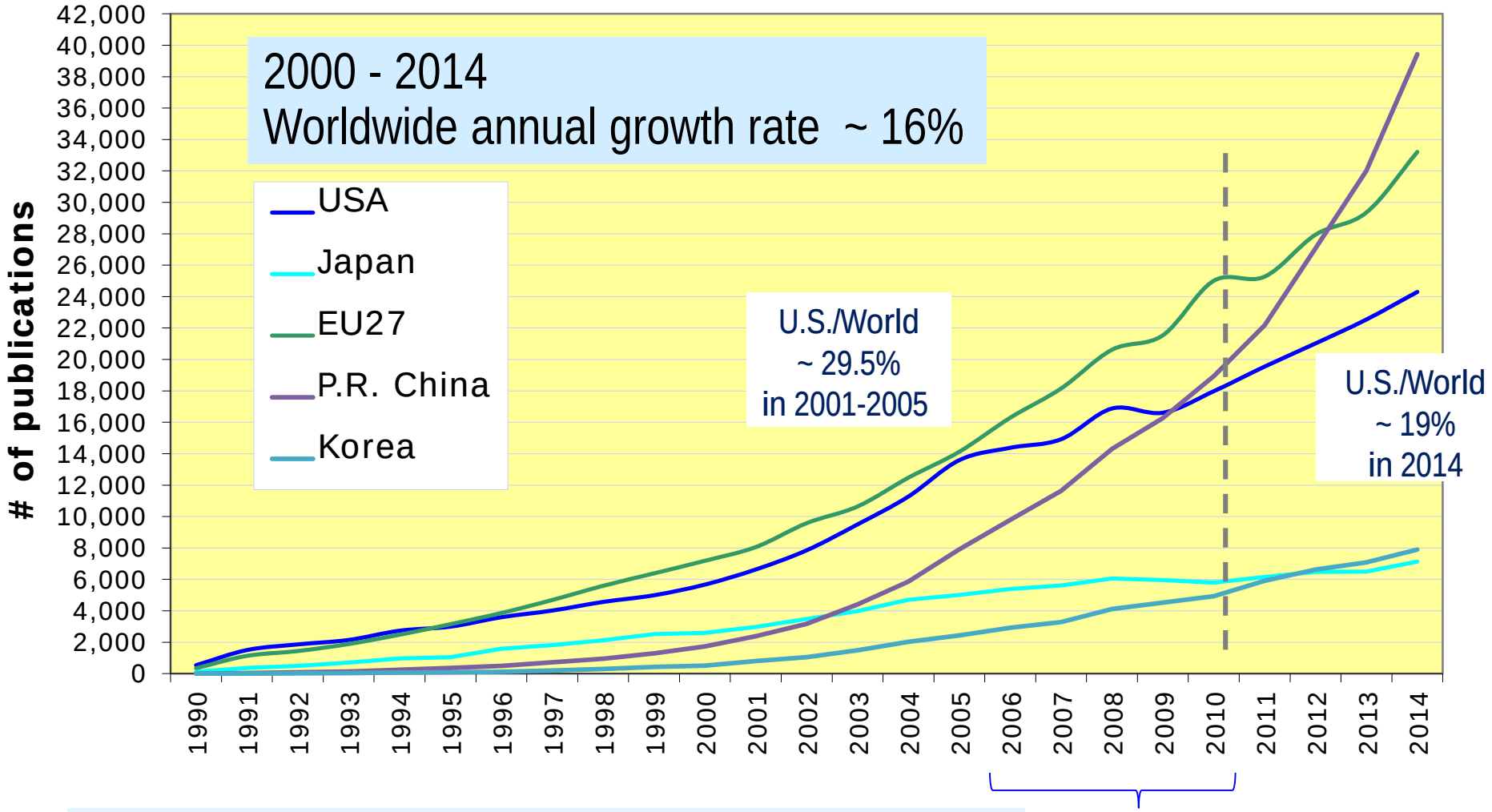
Number of World of Science publications on nano-extended 20 terms has increased



MC. Roco, Dec 9 2015

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))



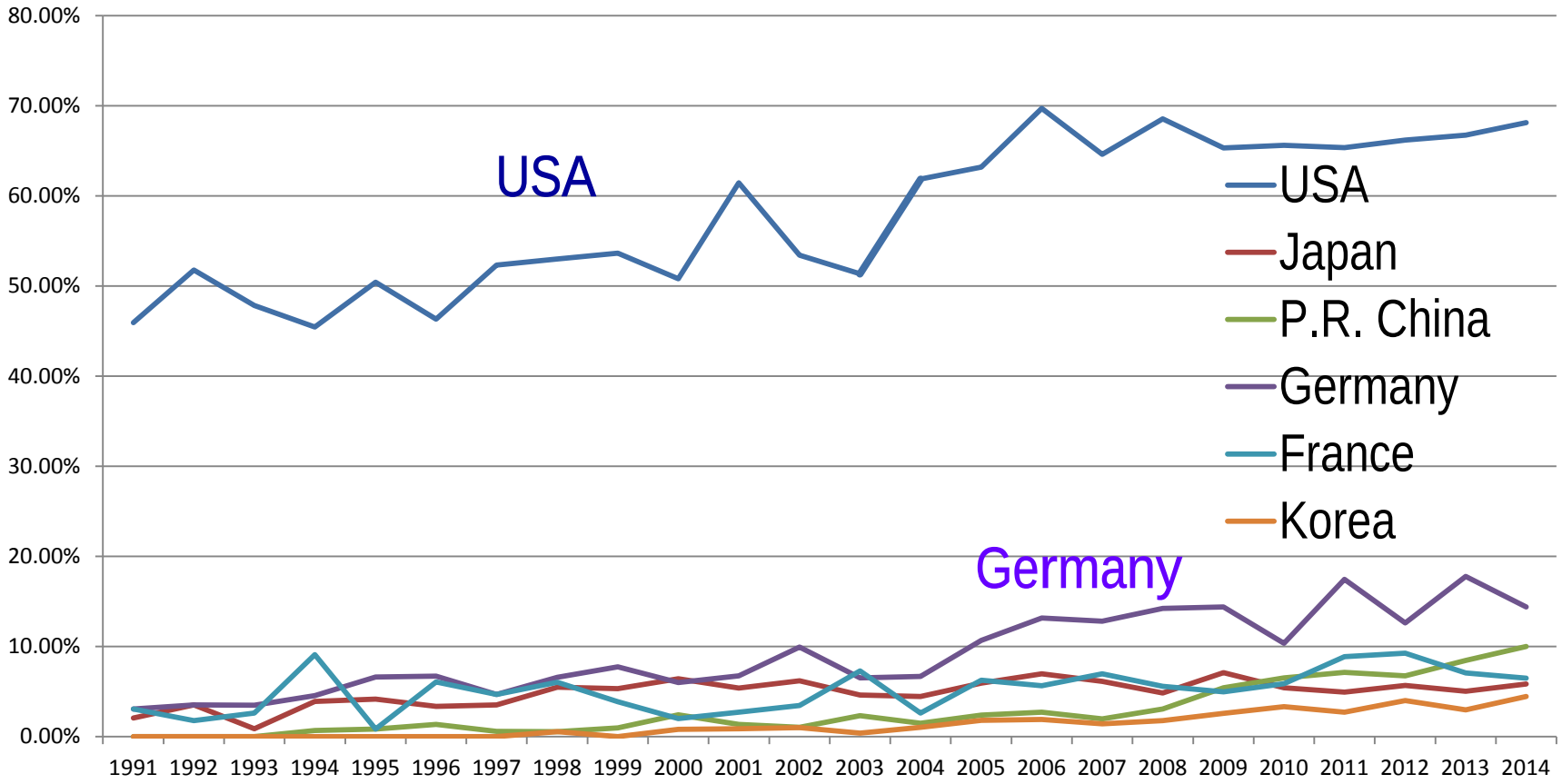
Rapid, uneven growth per countries

MC. Roco, Dec 9 2015

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))



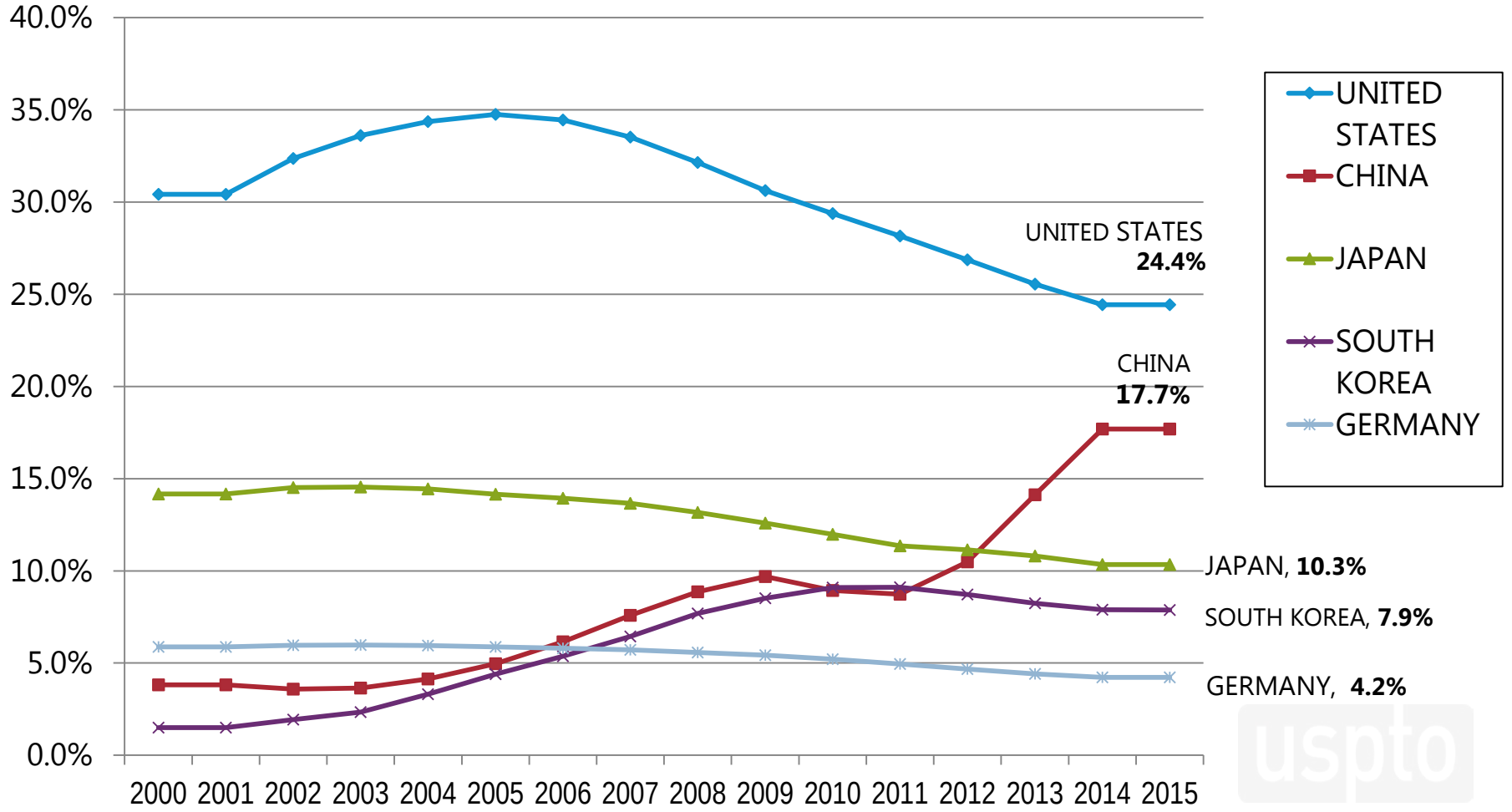
* Started to use Combined Keywords from 2014

MC. Roco, Dec 9 2015

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

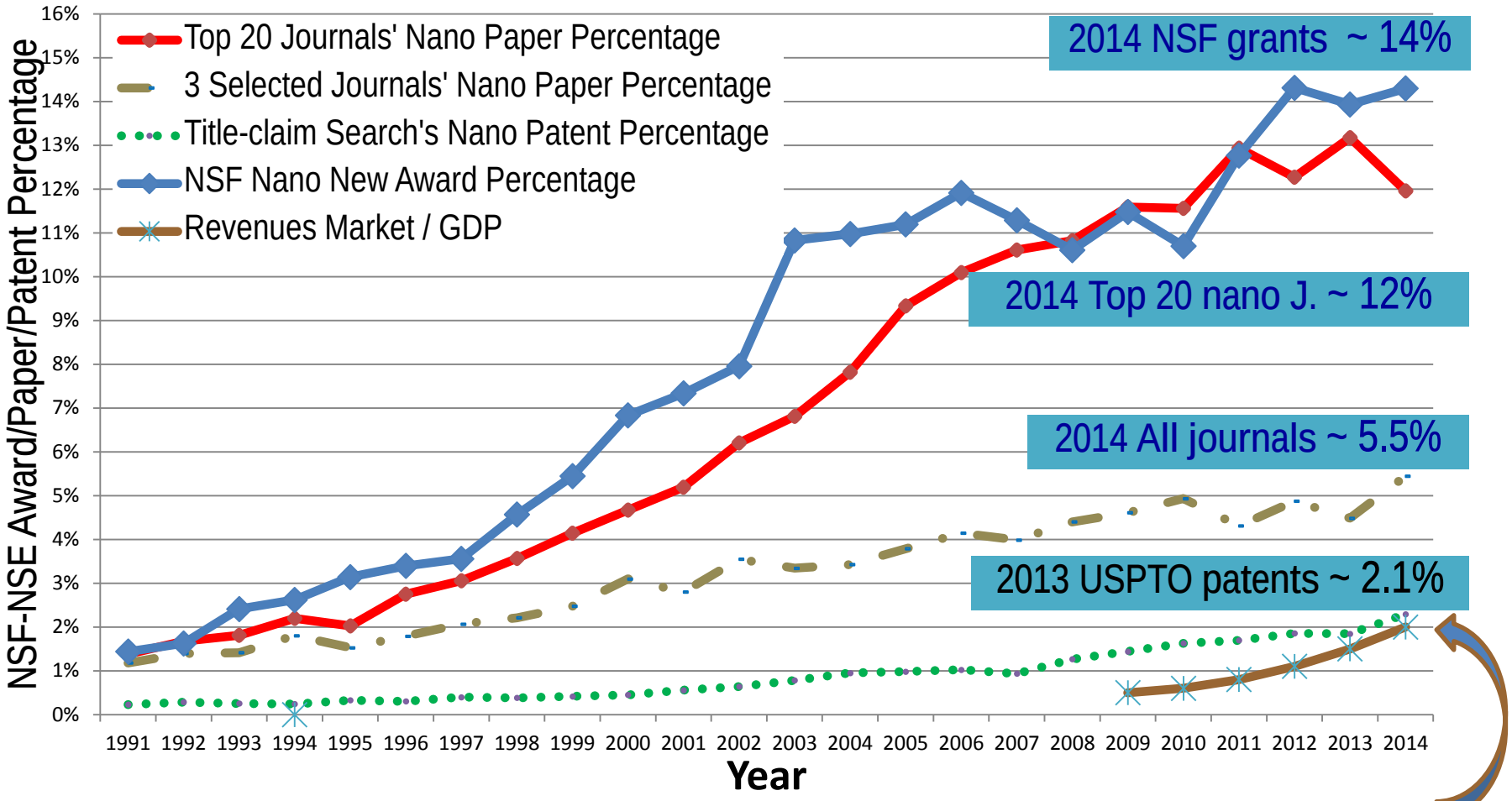
Nanotechnology Global Patent Statistics (First-Occurring Patent Publications): Top-5 Countries, Relative Percent of Total

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



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)



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

MC. Roco, Dec 9 2015

II. Nano-Bio-Info-Cogno Convergence

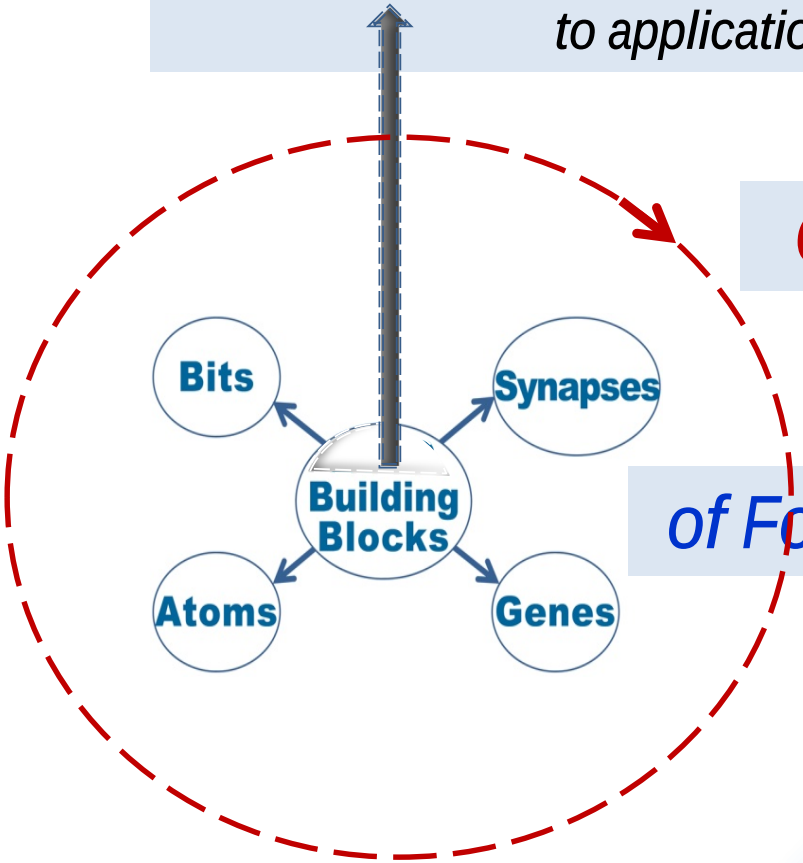
NBIC (Convergent new technologies) refers to the synergistic combination of emerging technologies with four major "NBIC" (nano-bio-info-cogno) most transformative provinces of S&T each of which is currently progressing at a rapid rate

The meaning of NBIC convergence

- Based on the unity of nature at the nanoscale
- Arising when the unification of science become possible
- Arising when accelerated improvement of human potential become possible
- Cognitive technologies are based on computer science, psychology, neuroscience, philosophy, anthropology, economics, sociology

Emergence & convergence of foundational N B I C

Emergence (from basic elements to applications)



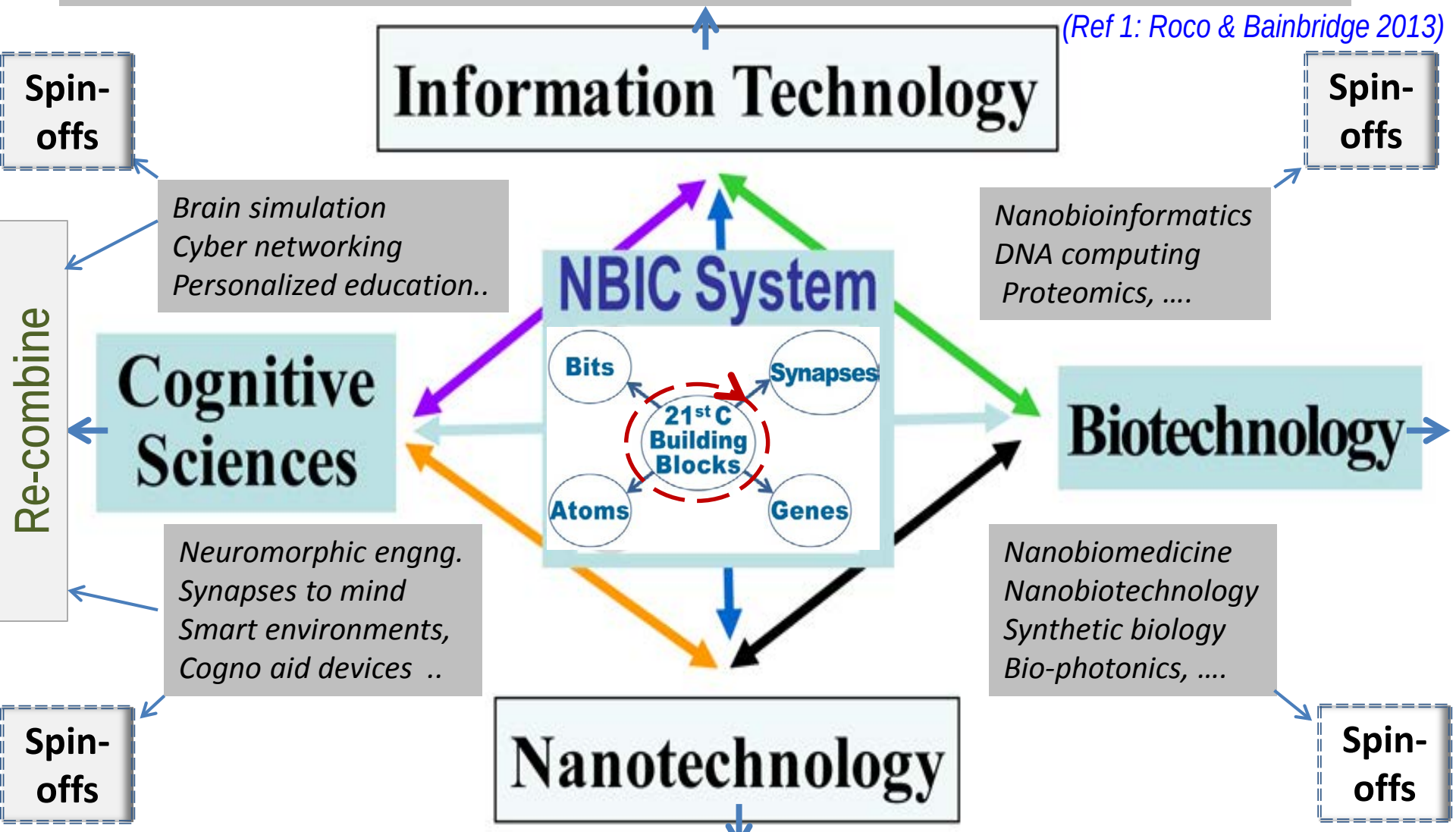
Convergence

of Foundational NBIC

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, ..

Examples of NBIC domains with NSF awards

2005-2015

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

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 8: Roco, "NBIC", in Handbook of S&T Convergence, 2015)

III. Convergence of Knowledge, Technology and Society

For societal benefit, human development

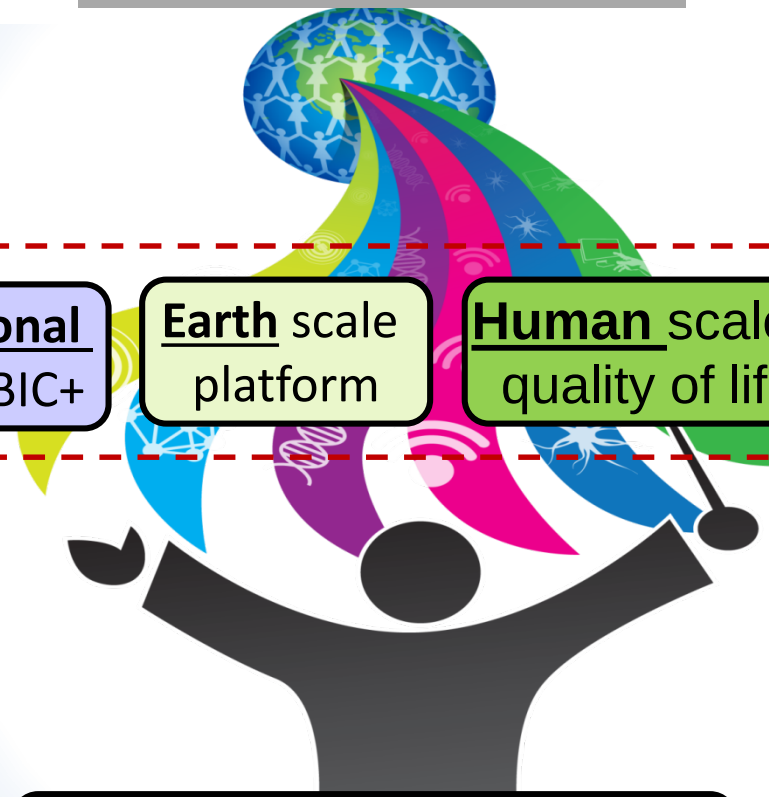
Innovation circuit

Foundational tools – NBIC+

Earth scale platform

Human scale & quality of life

Societal scale platform



System feedback

Innovative & responsible governance- **System behavior**

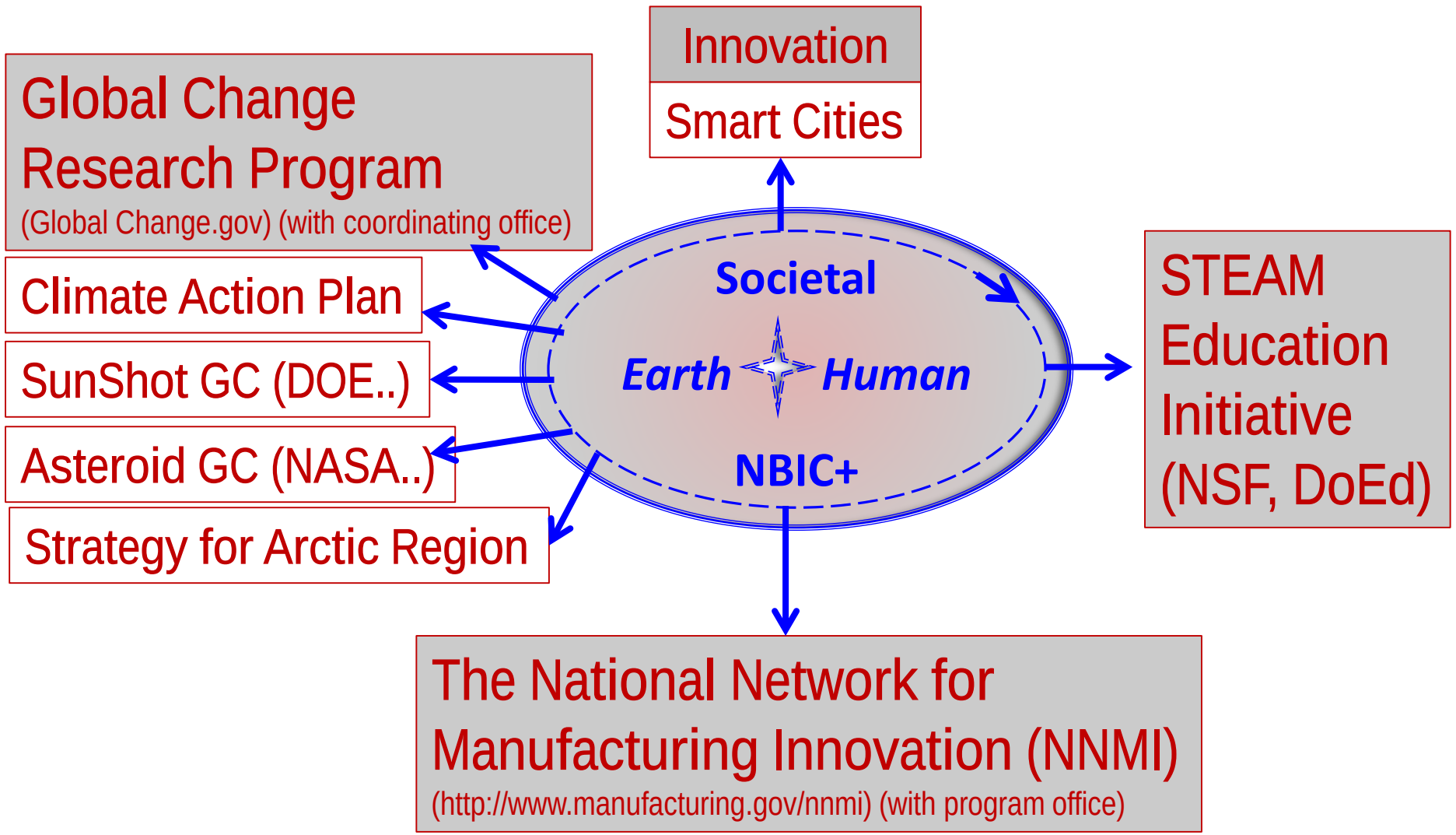
Societal values and needs

Human activity system

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

Ref: 6: "Convergence of knowledge, technology and society: Beyond NBIC" 2013

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



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

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

Nanoscale Science and Engineering at NSF

2001-2015

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

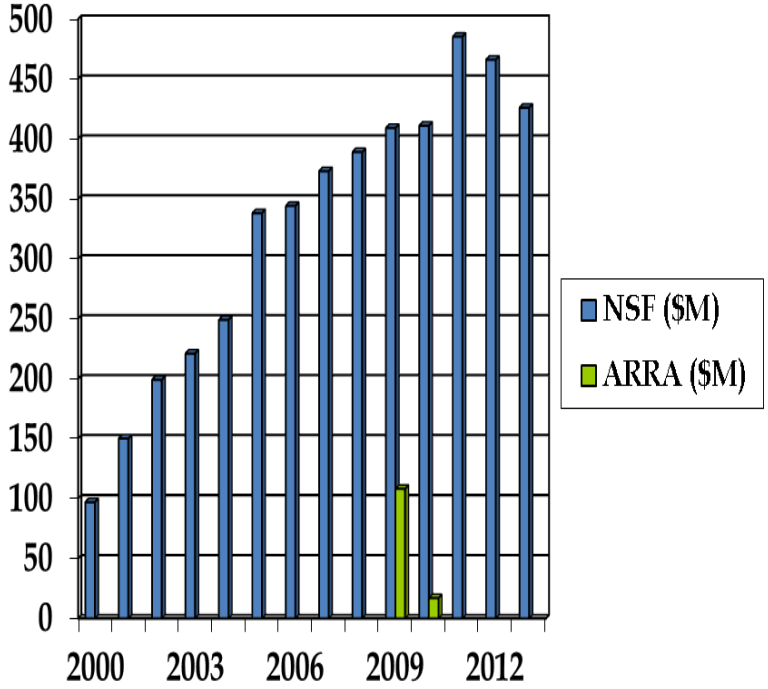
www.nsf.gov/nano , www.nano.gov

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

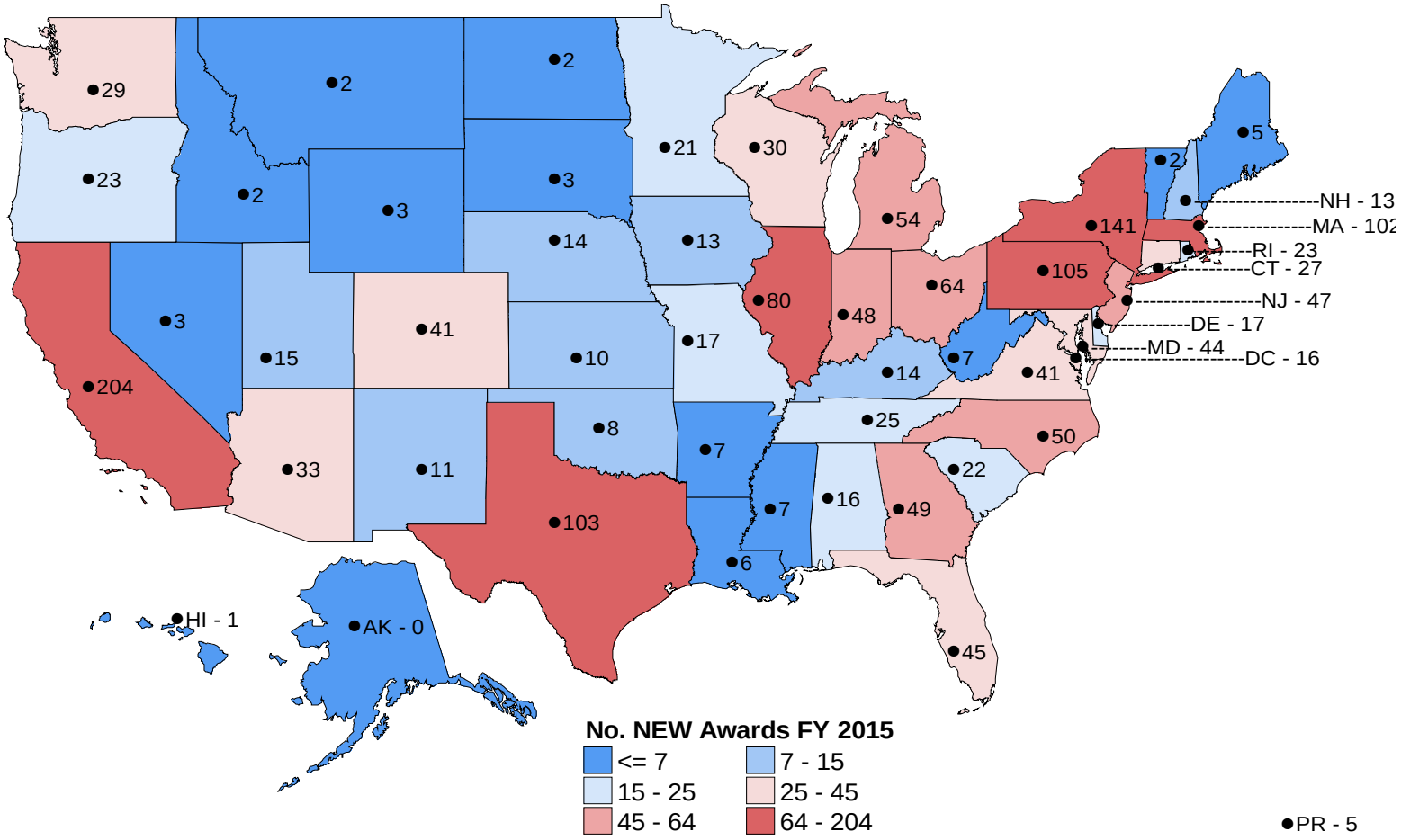


– Training and education
  > 10,000 students and teachers/y; ~ $30M/y

NSF's NSE number of new awards per state

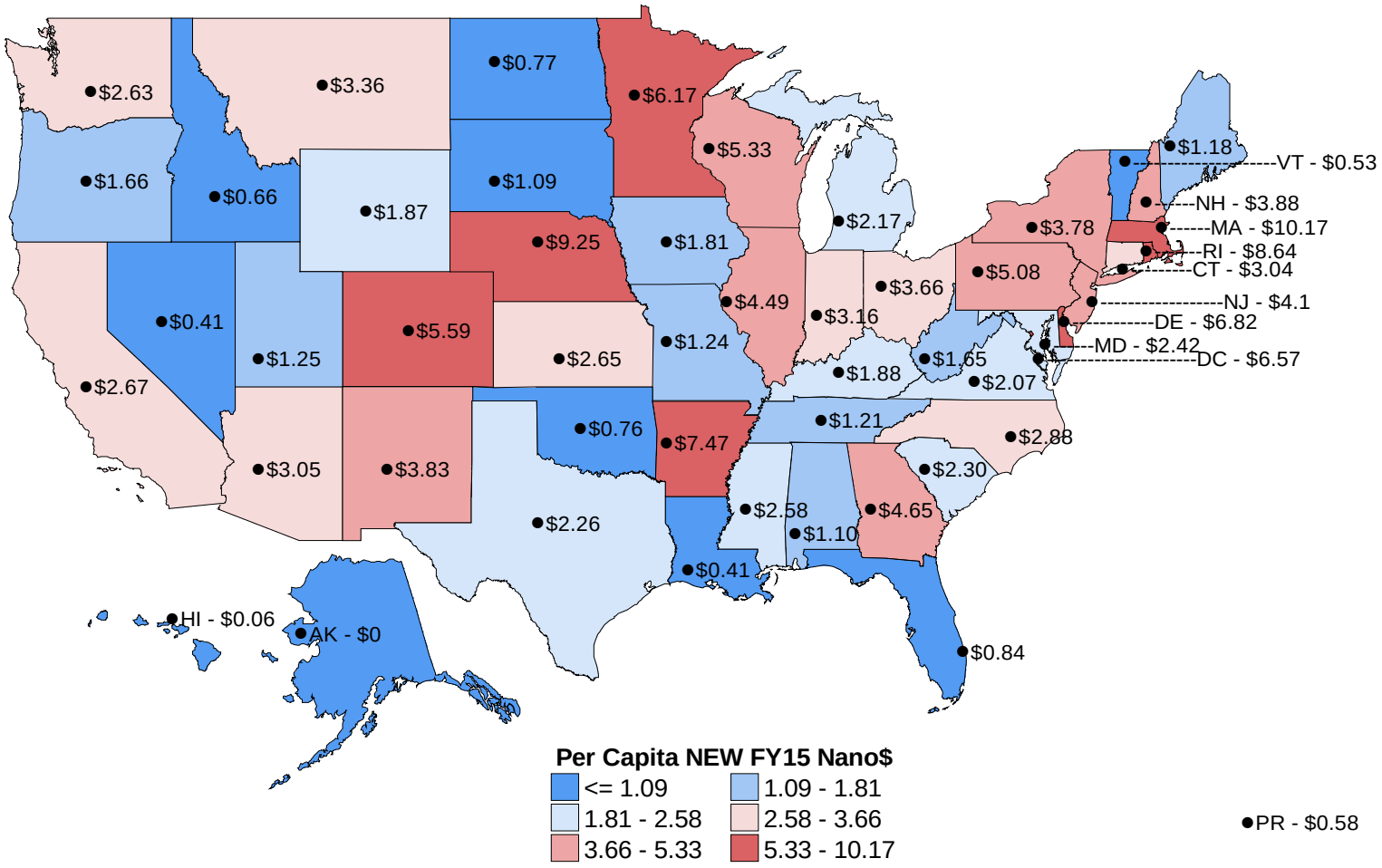
FY 2015: U.S. total new awards = 1,670

(total active awards over 6,000; abstracts on www.nsf.gov/nano)



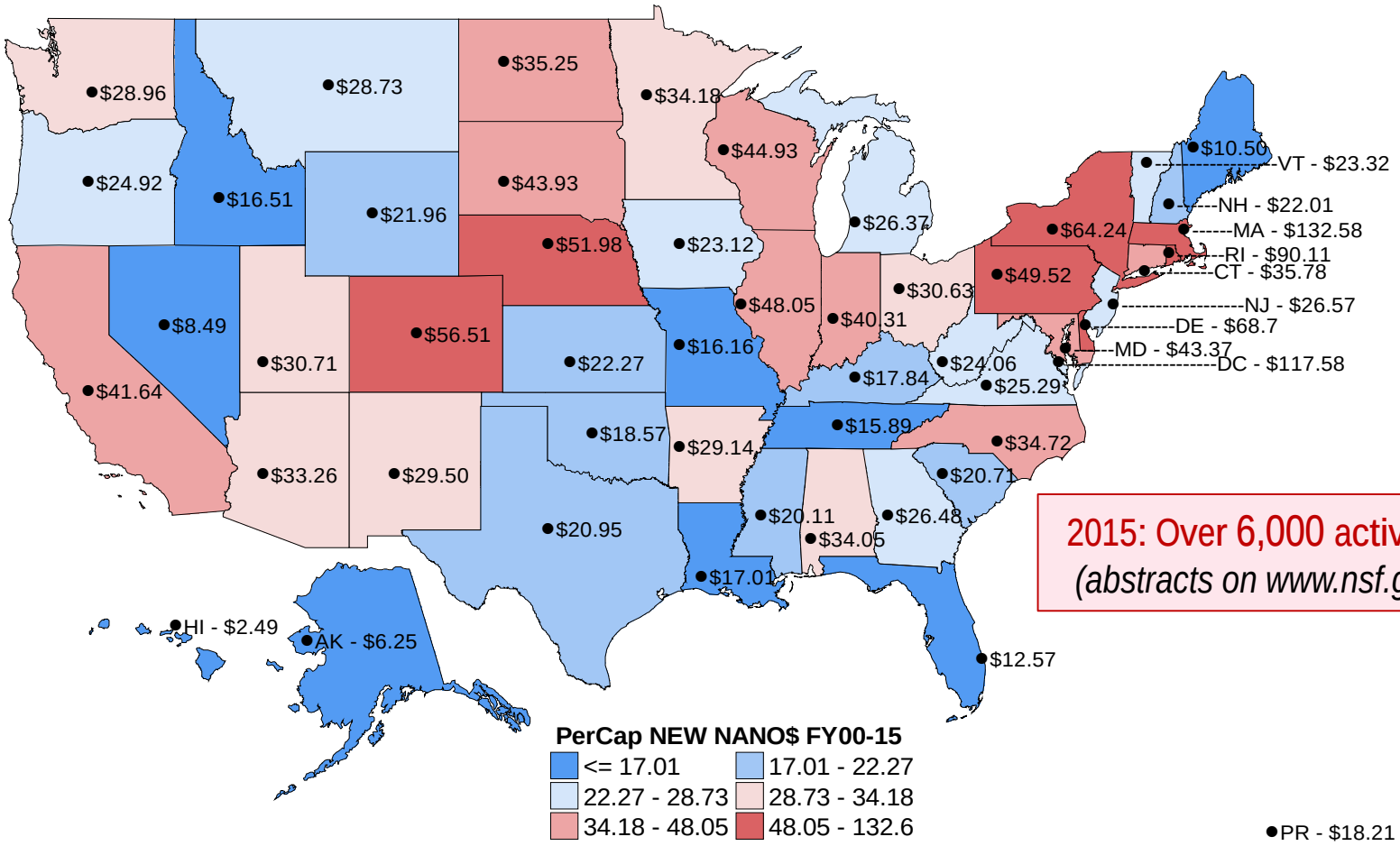
NSF's NSE amount new awards per capita, by state

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



NSF's NS&E amount new awards per capita

FYs 2000 - 2015: U.S. average amount ~ $35 / capita



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

#1 MA $132.58/capita

Several NSF NSE awards in FY 2015 (1)

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

Several NSF NSE awards in FY 2015 (2)

www.nsf.gov

- Core research in: BIO, CISE, E.H.R., ENG, GEO, MPS, SBE
- Materials Research Science and Engineering Centers (MRSEC)
- Science and Technology Centers (STC)
  $5M/year per center for 5+5 yrs
- Other centers in core programs (Ex: Center for Sustainable Development of Nanotechnology in CHE)
- Environmental, Health and Safety (EHS) (5-6% of NSF NNI)
- US (NNI)-EU (EC) Communities of Research (7 CORs) on nanoEHS (http://us-eu.org/)
- Part of Converging Knowledge and Technologies in Society (CKTS)

I (innovation)-Corps

Leveraging NSF investments in fundamental research by supporting education and networking to transcending the "valley of death" after research

(http://www.nsf.gov/pubs/2012/nsf12586/nsf12586.htm)

NSE examples in 2014-2015:

- High Quality Boron Nitride Nanotubes *(PI: Yoke Khin Yap, MTU) : Insulating heat sink materials for high-performance electronic devices and engines.*
- Photocatalysts for Water Remediation *(PI: Pelagia Gouma, SUNY): Ceramic nanocatalysts based on the CuO/WO3 system that are using the visible part of the solar energy to break down hydrocarbons in water*
- Targeted Drug Delivery *(PI: Rebecca Bader, Syracuse): Site-specific delivery of drugs by using polysialic acid (PSA)-based nanocarriers as platforms.*

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

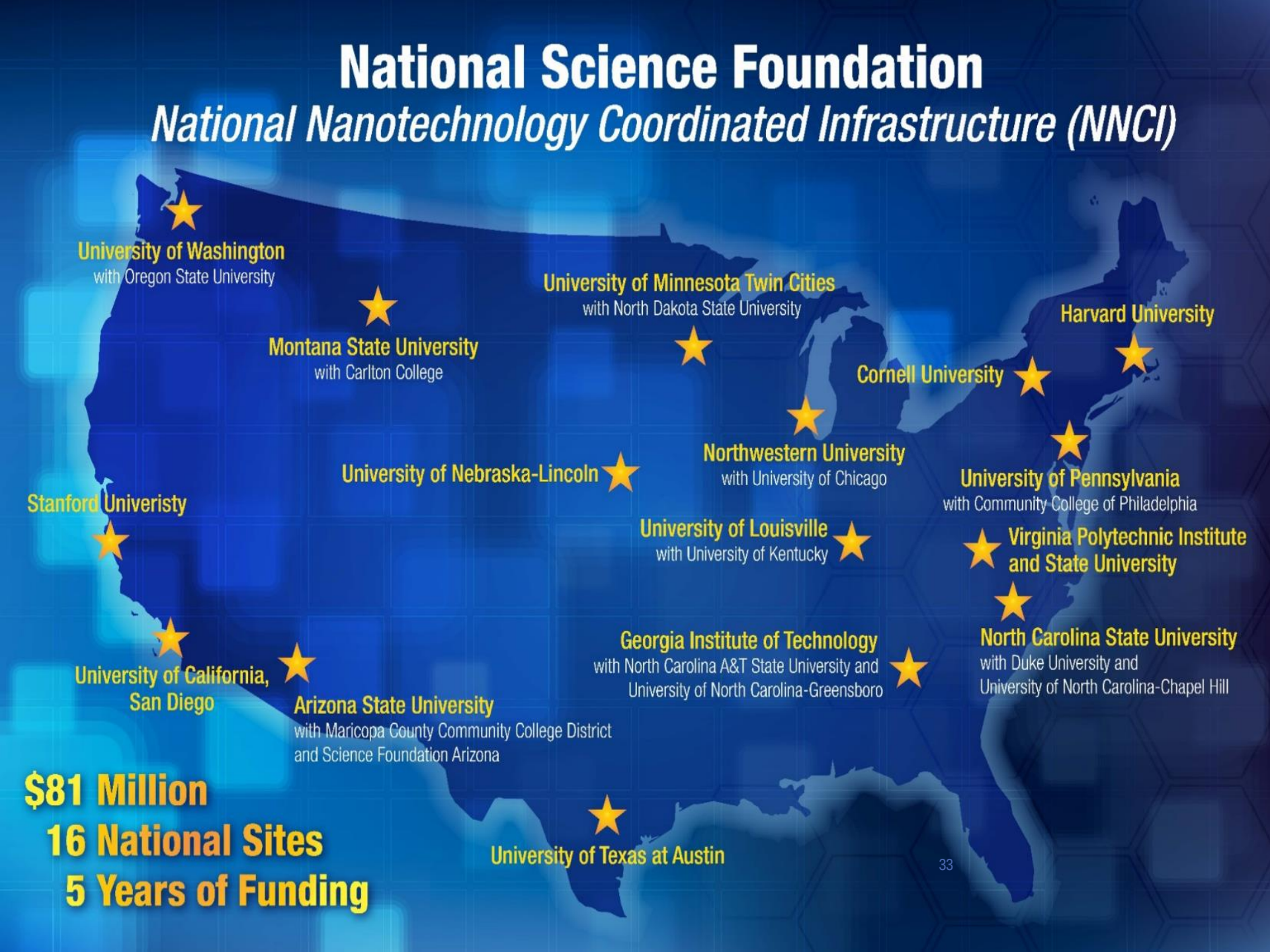
Breaking Reciprocity &Time-Reversal Symmetry (EFRI: NewLAW)

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

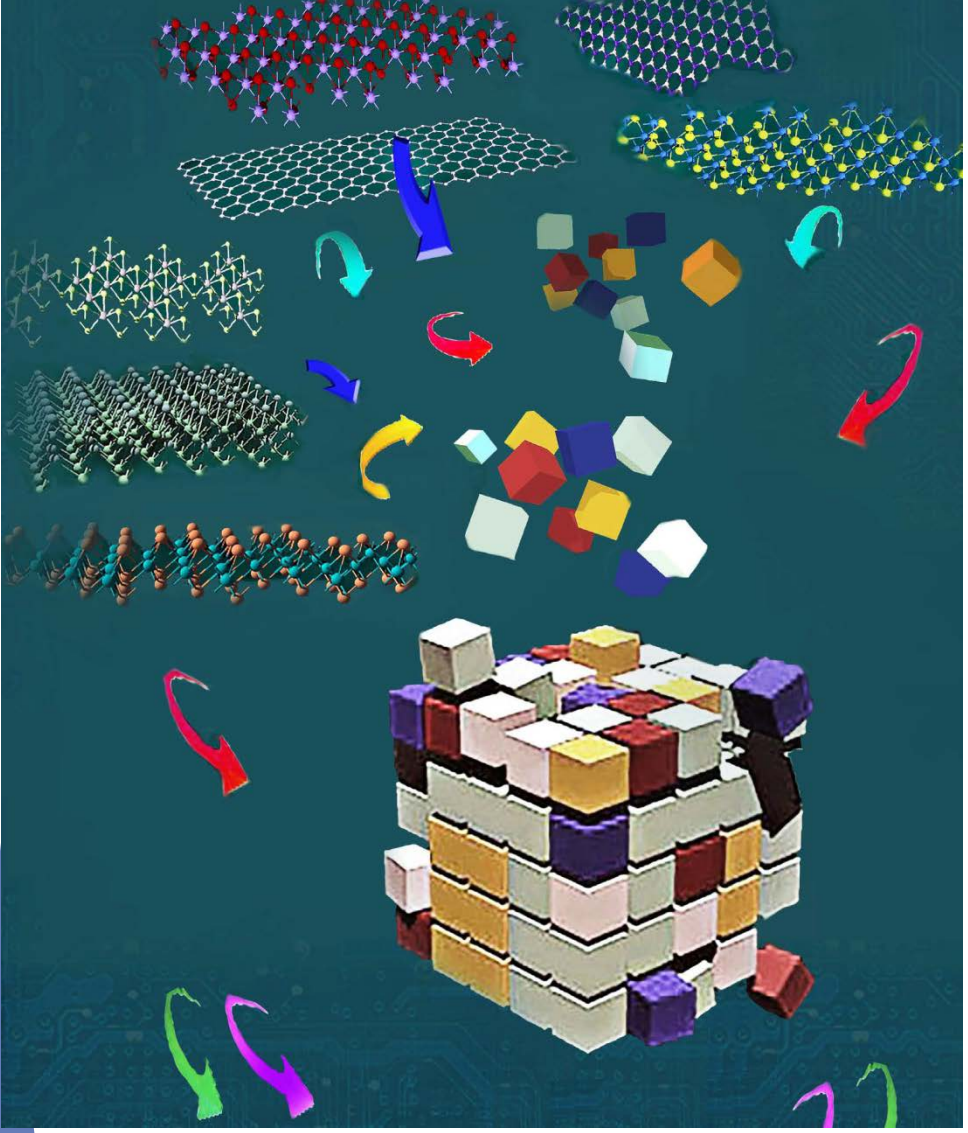
- Disruptive approach to design of electronic, photonic and acoustic devices, and enabler of totally new functionalities.
- Acoustic technologies, such as soundproofing and sonar stealth systems, energy absorbing materials, and imaging
- Integrated nanophotonic elements based on topological insulators,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

National Science Foundation

National Nanotechnology Coordinated Infrastructure (NNCI)

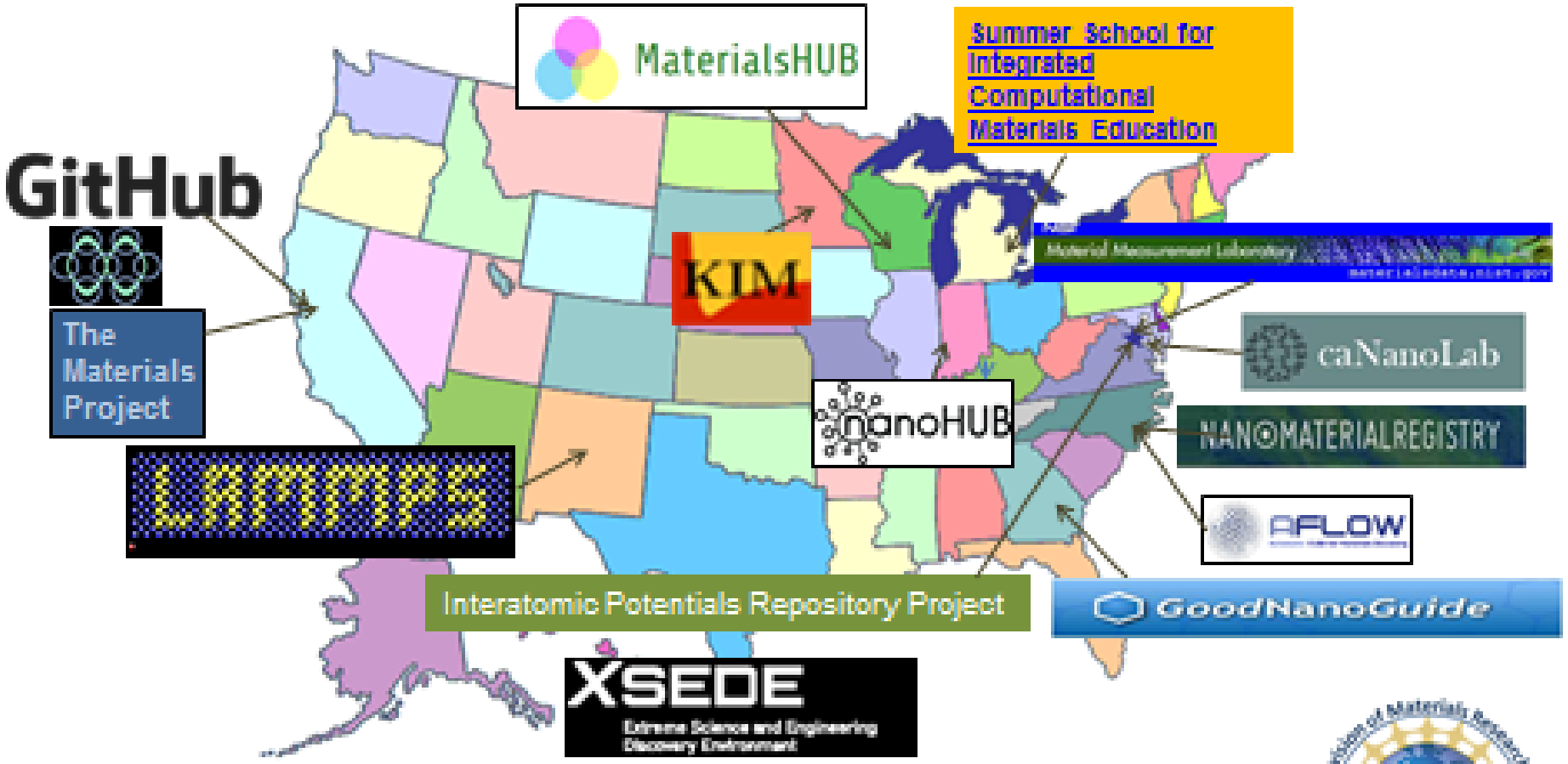


$81 Million
16 National Sites
5 Years of Funding



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

Some Components of the Nanotechnology Knowledge Infrastructure



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

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

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
- **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**

Nanotechnology Signature Initiatives

National Nanotechnology Initiative (NNI), 2011-2014 (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 for 2015:

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

"Brain like computing" combining

National Nanotechnology Initiative

National Strategic Computing Initiative

BRAIN Initiative

- *Nanotechnology-Inspired Grand Challenge for Future Computing* (DOD, DARPA, DOE, IARPA, NSF), announced by OSTP on Oct 21, 2015: http://www.nano.gov/futurecomputing

- Purpose: "Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain."

Also: pattern recognition, human like simultaneous perception of information from various sources including the five senses,

Several supporting workshops

(NSF sponsored)

Recently completed reports:

- ✓ Rebooting the IT Revolution, Report (2015-0901)

  https://www.src.org/newsroom/rebooting-the-it-revolution.pdf

- ✓ Workshop for Energy Efficient Computing (2015-1020)

  https://www.src.org/nri/energy-efficient-computing-workshop.pdf

Next:

Workshop for scenarios development (suggestions?)

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 scalable, modular, hybrid, on site
- Systems nanotechnology

FY 2015 NS&E Priorities Research Areas (3)

C. Integration of nanotechnology with other areas

- Nanomanufacturing for sustainable environment
- Replacing electron charge as the information carrier in electronics (Ex: Nanoelectronics Research Initiative)
- Energy conversion; water filtration / desalinization; food
- Nano-bio interfaces between the human body and manmade devices
- Nano-informatics for communication, nanosystem design
- Converging science, engineering and technology

FY 2015 NSF priority research areas (4)

D. Societal dimensions of nanotechnology

- Understanding and sustainable ENV, including research for natural / incidental / manufactured nanomaterials

  Key nano- EHS priorities at NSF
  - New instrumentation for nanoparticle characterization and nanotoxicity
  - Transport phenomena and physic- chem.- biological processes
  - Nano-bio interface: ecological and human health implications
  - Predictive models for nanomaterials interaction with cells/living tissues
  - Separation of nanoparticles from fluids
  - Safety of manufacturing nanoparticles

- Earlier formal and informal education
- Social issues and public engagement
- Long-term and convergence approach (government – wide)

FY 2015 NSF's NSE Grantees Conference

- Contents: Keynotes, posters and panels to facilitate exchanges, partnerships, networking, mutual evaluation and research planning – *on selected topics in 2015*
- Focus: progress in four fundamental nanobiology and biomedicine; NSECs and NNCI; increased complexity, system approach, identify research and education trends
- Meetings between researchers and program officers

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"* (JNR 2013a)
2. *"Global nanotechnology development from 1991 to 2012"* (JNR 2013c)
3. *NANO1: "Nanotechnology research directions: Vision for the next decade"* (Springer, 316p, 2000)
4. *NANO2: "Nanotechnology research directions for societal needs in 2020"* (Springer, 690p, 2011a)
5. *NBIC1: "Converging technologies for improving human performance: nano-bio-info-cognition"* (Springer, 468p, 2003)
6. *NBIC2: "Convergence of knowledge, technology and society: Beyond NBIC"* (Springer, 604p, 2013b)
7. *"Mapping nanotechnology innovation and knowledge: global and longitudinal patent and literature"* (Springer, 330p, 2009)
8. "Long View of Nanotechnology Development: the NNI at 10 Years"(JNR, 2011d)