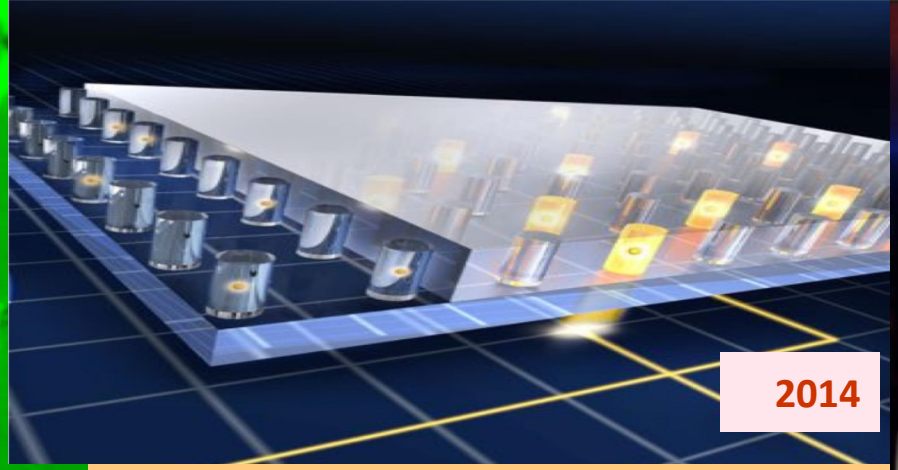
Nanoscale science and engineering update

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

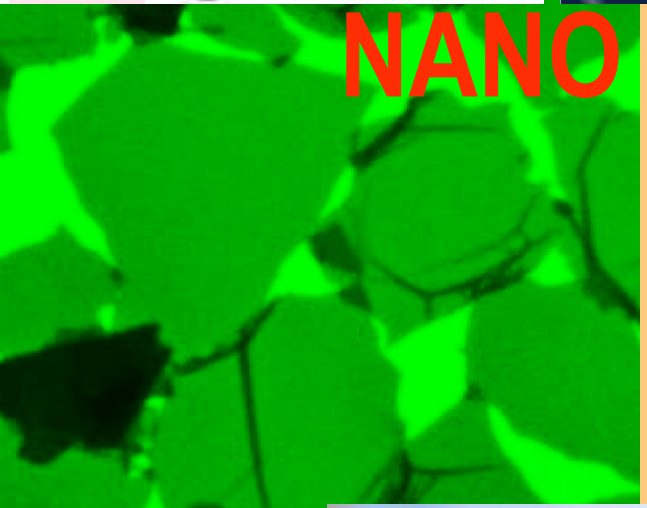
Sustainable Nanotechnology Organization, Los Angeles, November 5, 2017

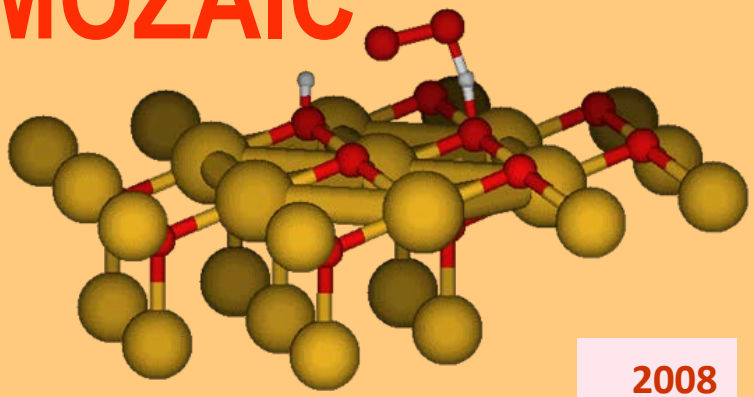

2012

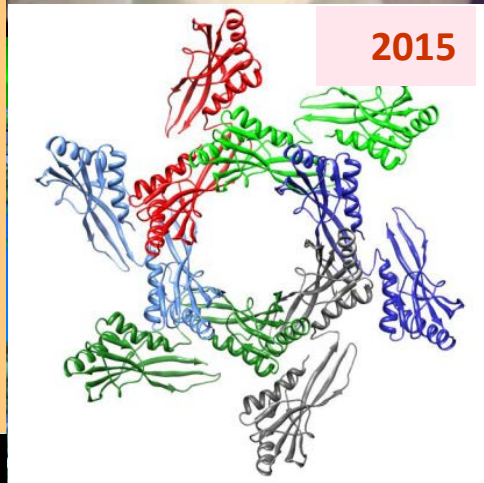

2014


2013

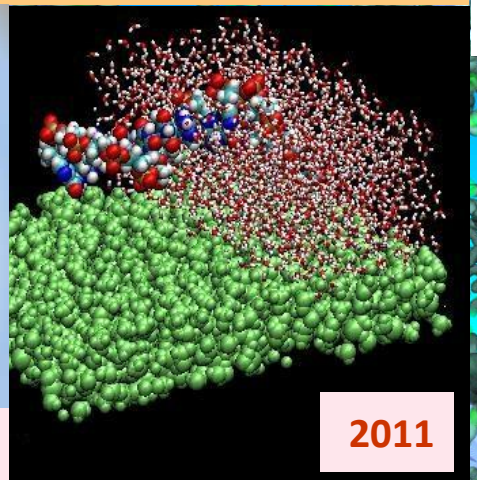
NANO MOZAIC

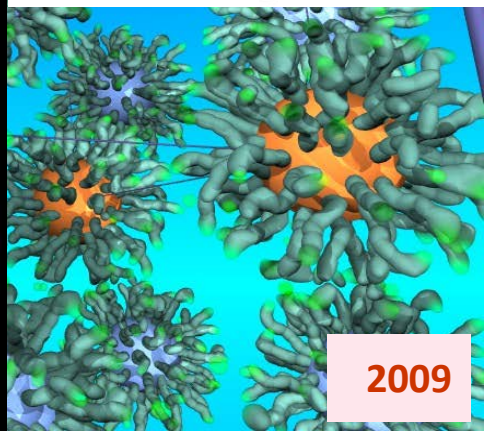

2010


2008

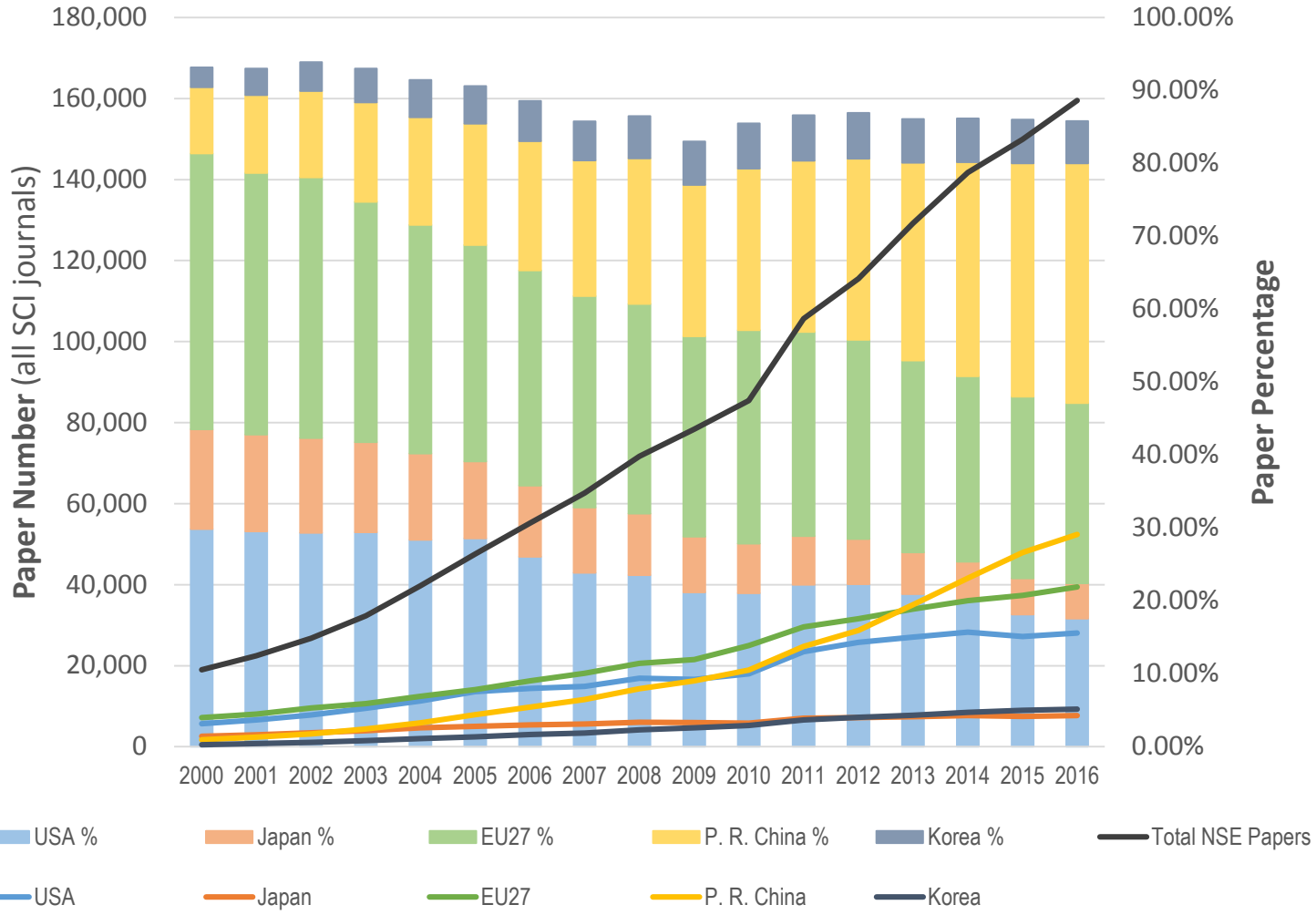

2015

2016


2011


2009

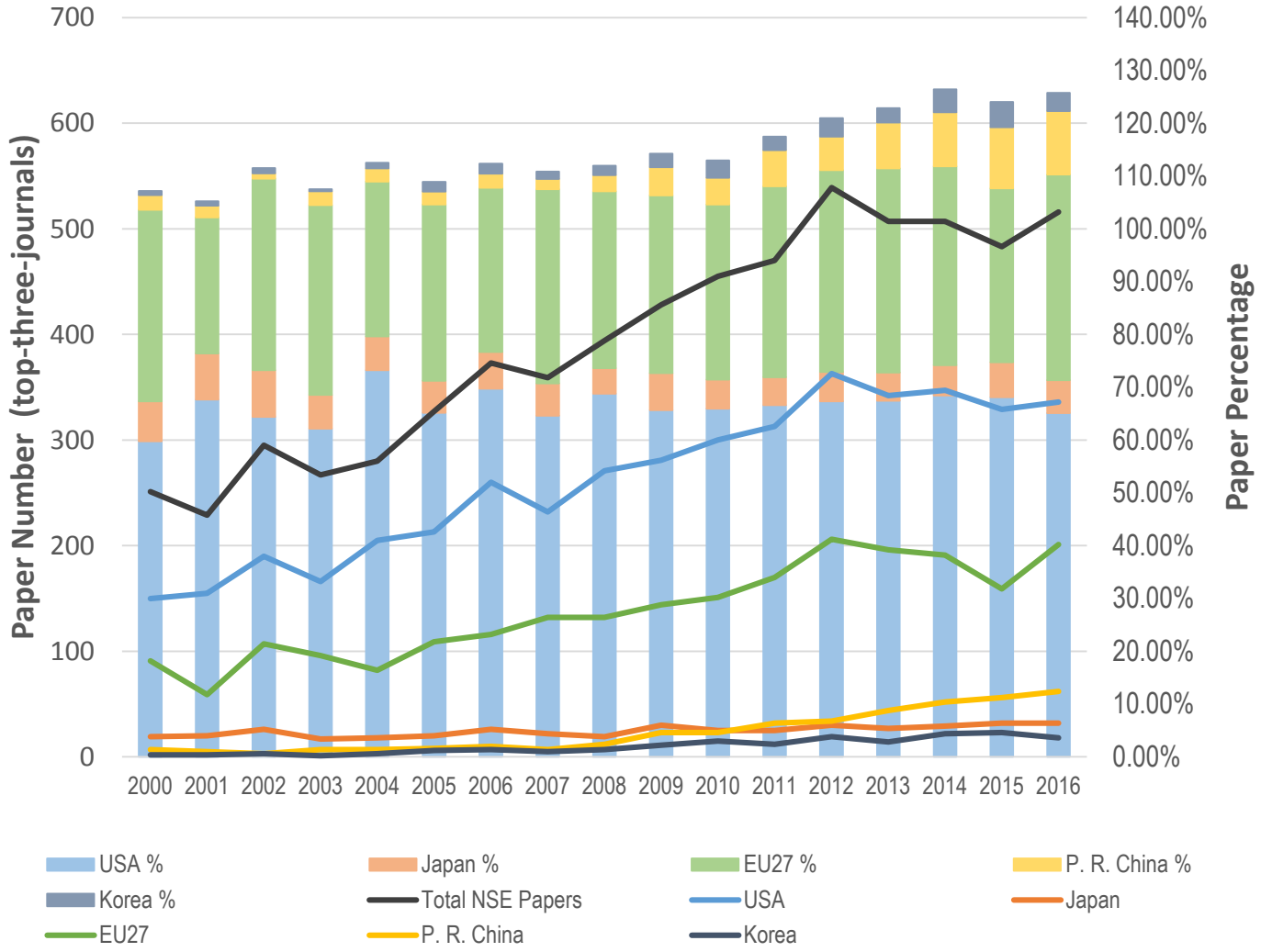
Nanotechnology papers in all SCI extended journals in the WoS, in 2000-2016, by five regions



(International perspective on nanotechnology papers, patents and NSF awards (2000-2016), J. Nanoparticle Research, Nov 5017); ("Title-abstract" search by keywords)

MC Roco, Nov 5 2017

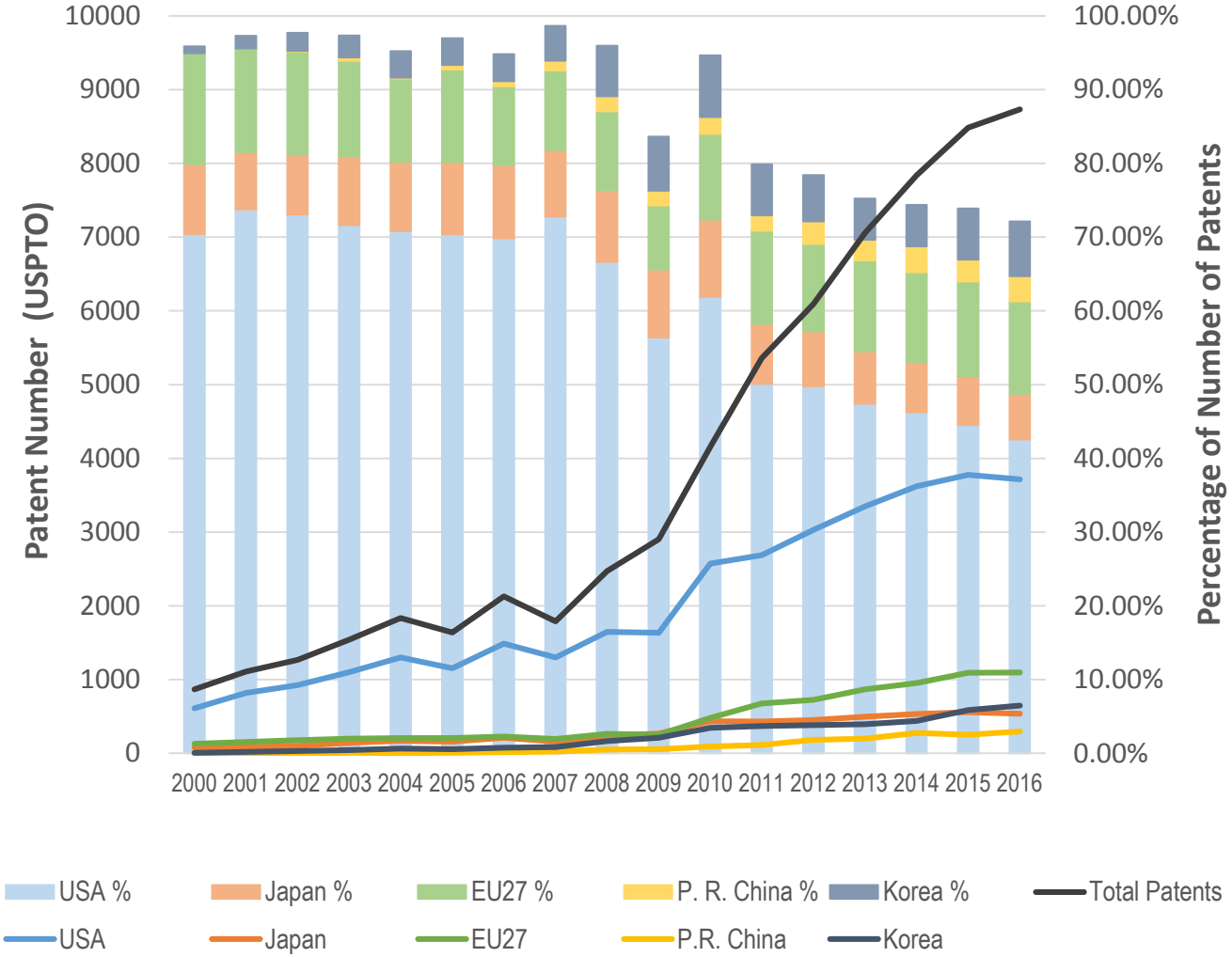
Nanotechnology papers in (Nature, Science, PNAS) searched by all authors in 2000-2016, by five regions



(International perspective on nanotechnology papers, patents and NSF awards (2000-2016), J. Nanoparticle Research, Nov 5017); ("Title-abstract" search by keywords)

MC Roco, Nov 5 2017

Nanotechnology patents published by USPTO in 2000-2016, by five regions



(International perspective on nanotechnology papers, patents and NSF awards (2000-2016), J. Nanoparticle Research, Nov 5017); ("Title-abstract-claims" search by keywords)

MC Roco, Nov 5 2017

Papers and patent publications per million capita in the five regions

(Notations: M = million, /MC = per million capita)

Region	US	Japan	EU27	P.R. China	South Korea	Totals numbers
Population on July 1, 2017	325M	128M	506M	1,410M	51M	(2,419 M)
2016 papers /MC	84	60	78	37	**185**	19,003
2016 Top-three-papers /MC	**1.04**	0.25	0.40	0.04	0.35	516
2016 USPTO patents /MC	11.5	4.2	2.2	0.21	**12.7**	8,732
2015 WIPO patents /MC	20.7	23.11	4.2	18.8	53.3	42,822

MC Roco, Nov 5 2017

Global revenue from nano-enabled products by sector

(Lux Research, updated in January 2016) (US / World ~ 32%)

Sector ***(all in US$ Billion)***	**2012** (survey)	**2013** (survey)	**2014** (survey)
Building materials	$28.837	$44.564	$66.891
Materials & manufacturing	$457.936	$625.508	$826.704
Electronics & IT	$265.306	$377.631	$527.137
Healthcare & life sciences	$74.742	$103,350	$139,597
Energy & Environment	$25,668	$38.478	$55.737
Total (world)	**$853**	**$1,190**	**$1,616**
Annual Increase Rate (%)		*40%*	*36%*

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

Sustainable and resilient society – many facets

- Social (population growth and needs, governance, enduring democracy)
- Economic ("more with less": knowledge, technology, materials, water, energy, food, climate, green chemistry)
- Resilient (infrastructure, emergency response, for life cycle)
- Maintaining quality of life and
- Environmental (clean, renewable, biodiverse) sustainability in planetary boundaries

Ref. 4: Nano 2020 Report, 2011

Nanotechnology-inspired grand challenges

- ✓ **Principles for progress via grand challenges (NNI, 2000-):**
  - **Planning long-term vision-inspired research**
  - **Facilitate S&T breakthroughs**
  - **Advance sustainable development**
  - **Support convergence processes**

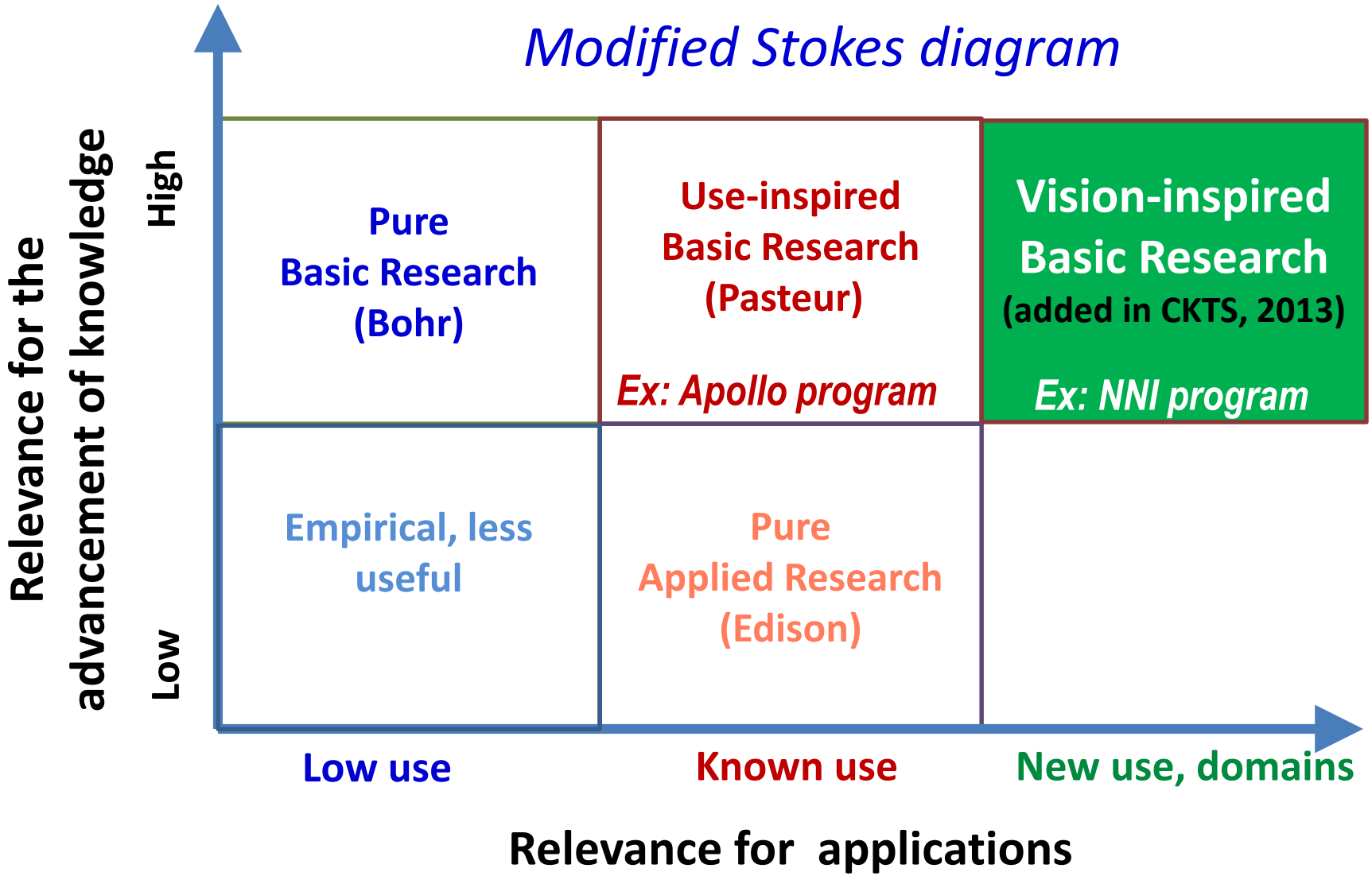
- ✓ **Several U.S. priorities in 2017 - 2018**

  Nanotechnology Signature Initiatives (re: sustainability)
  Sustainable Food-Energy-Water Systems
  Nanotechnology-inspired Brain-like Computing
  Convergence of S&T, Intelligent Cognitive Assistants
  National Network for Manufacturing Innovation

Long-term vision-inspired research

Focus on conceptual, synthetic goals

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



Ref 5: Roco and Bainbridge, 2013 , Fig 9

S&T breakthroughs underpin Grand Challenges

(examples of novel concepts targeted by NNI in 2000 "in 20-30 years")

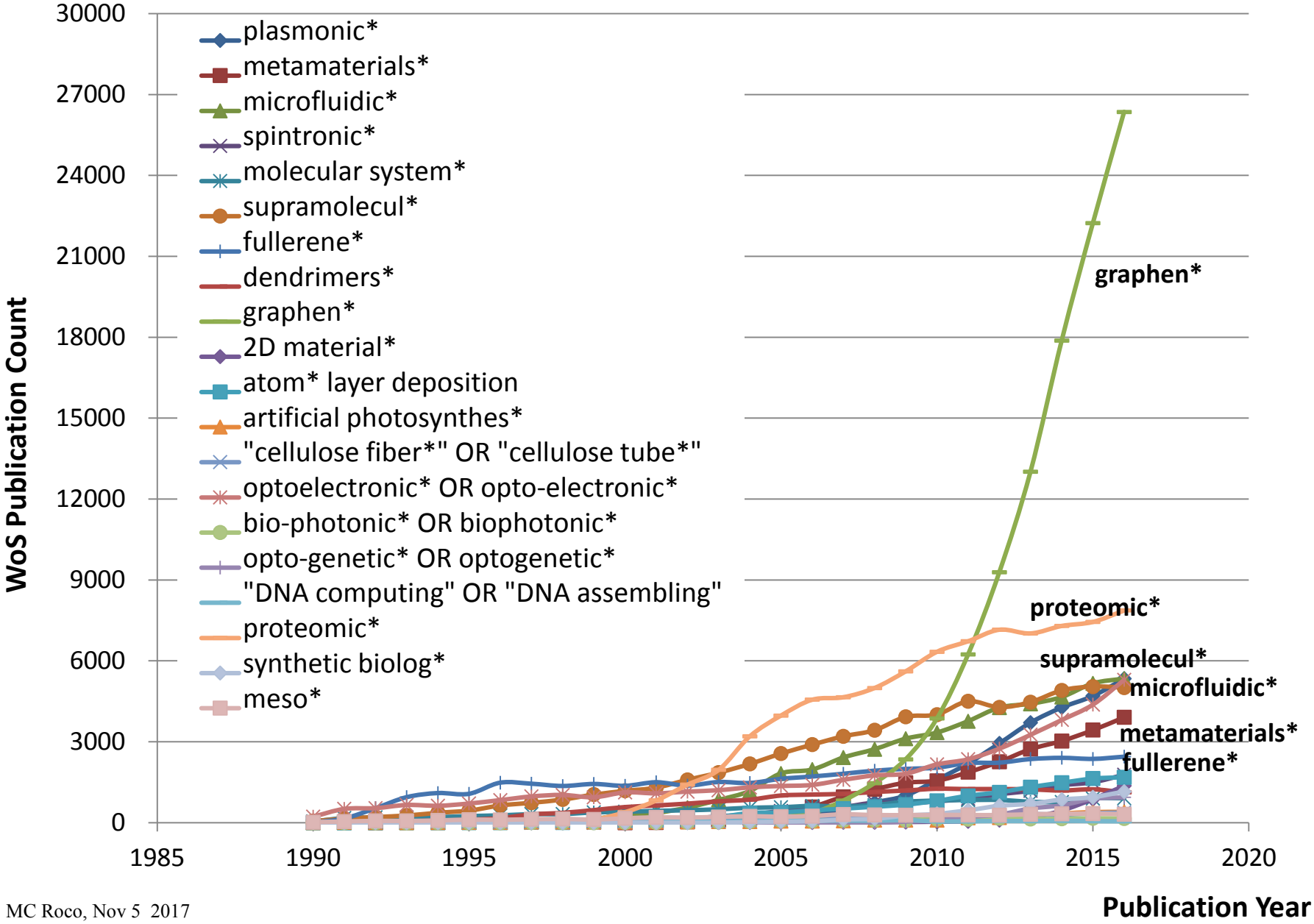
- **Library of Congress in a "one cubic cm" memory device**: target 30-40 atoms (2000); Realized 12-atom structure (IBM, 2012), DNA structure (Harvard, 2012; in "one cubic mm"). "*Millions times smaller*"
- **Molecular cancer detection and treatment** (first gold-shells, Rice, 2002 - 2016 many other solutions in progress) *"Not possible before"*
- **Materials 10 times strength of steel, fraction of weight**; before 2015
- **Exploit nano-photonics:** change direction and frequency of light (2004, then succession of solutions); negative diffraction of light / electrons in meta-metamaterials (2004) & 2D mat (2007). "*New phenomena and devices*"
- **Quasi-frictionless nanocomponents**: quantum fluctuations between selected material surfaces (first Harvard, 2008). "*Almost frictionless*"
- **Magnetic computing** close to the lowest Landauer fundamental limit of energy dissipation under the laws of thermodynamics (STC Berkeley, 2016). *"Millions times less energy consumption"*

S&T breakthroughs underpin Grand Challenges

(examples of novel concepts targeted by NNI in 2000 "in 20-30 years")

- **The promised smallest transistor in 2000 100 nm; realized 1nm in 2016** (Desei et al., Science, Stanford U): "*Hundred times smaller*"
- **Quantum communication at room temperature with few photons** (STC Harvard, Westervelt et al. 2014): "Single photon memory device"
- **Promised to develop a predictive approach with case studies for nanotoxicity:** *"UC CEIN Predictive Toxicological Platforms"*
- **Promised evaluation and governance using convergent methods:** *"Duke CEINT Governance Platform"*
- **Formulation nano-ELSI and establish International nano-ELSI:** *"ASU and UCSB international CNS platform"*
- **Mass-media dissemination of nanotechnology in society:** *"NCLT; NISE (>500 sites in 2015); NBC videos; Nano-Generation"*

Number of World of Science publications on 20 nano-extended terms has increased (1990-2016)



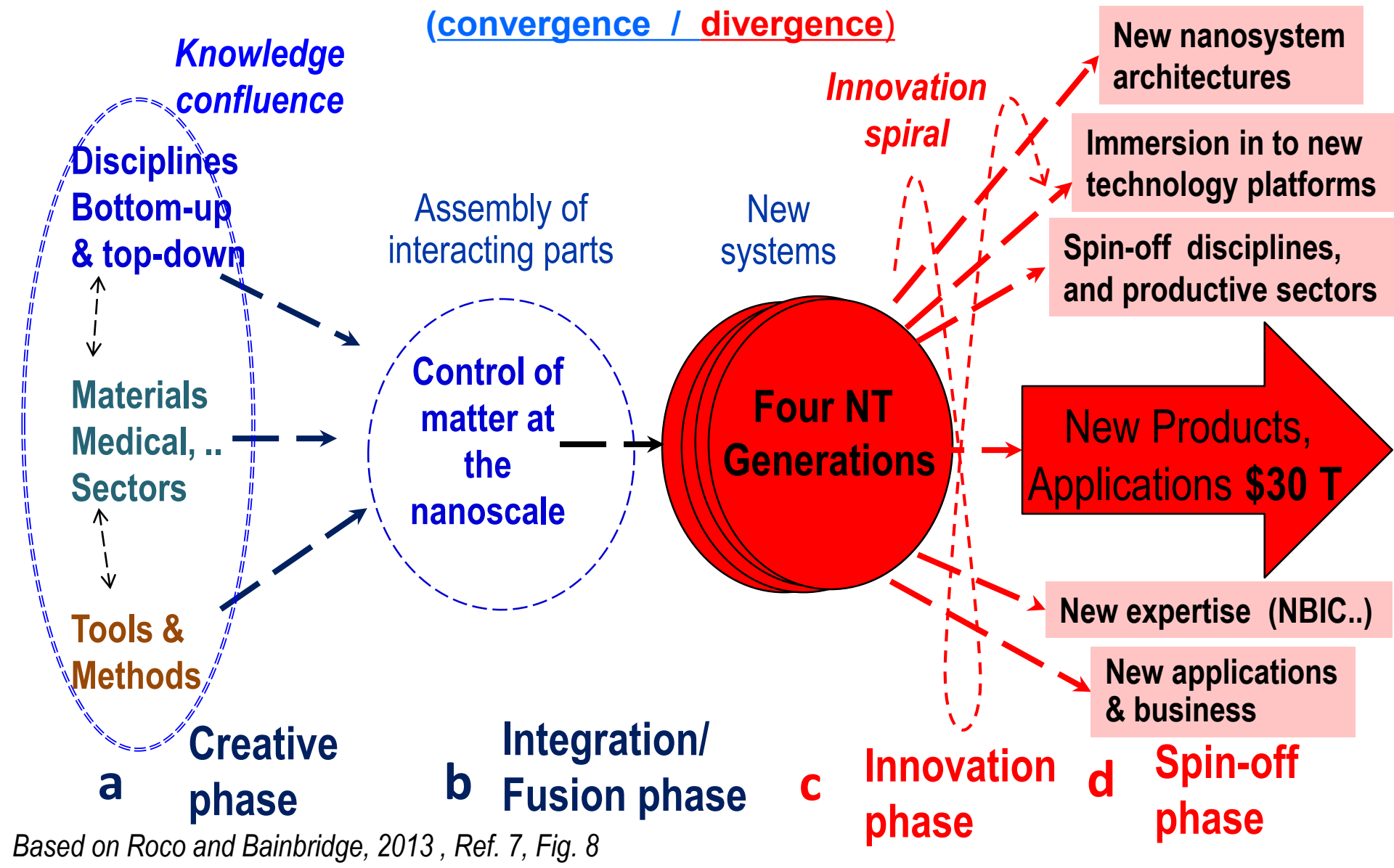
MC Roco, Nov 5 2017

Nanotechnology for sustainable society

Examples of long-term targets

- **Nanosystems design and separations methods for economic desalinization to make available water at any quantity at any place near oceans**
- **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**

2000-2030 Convergence-Divergence cycle for global nanotechnology development



Based on Roco and Bainbridge, 2013 , Ref. 7, Fig. 8

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

GENERATIONS OF NANOPRODUCTS

Based on NANO 2020, Fig. 5 (Ref. 3)

2030

DIVERGENCE

New socio-economic capabilities

nano3 Technology divergence

2020-2030

To general purpose technology

nano2 System integration

2010-2020

CONVERGENCE

Create library of nanocomponents

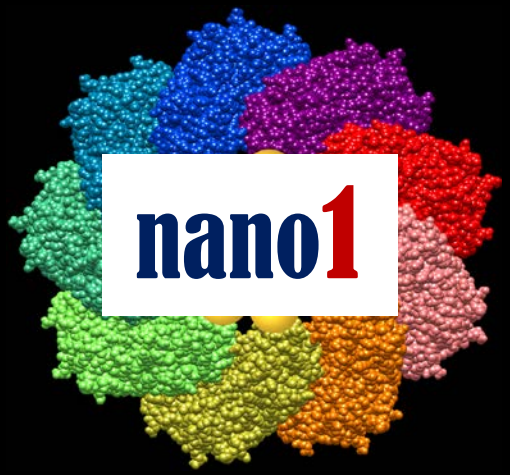
nano1 Component basics

2000-2010

2000

- Nanosystem Conv. Networks
- NBIC Technology Platforms
- Molecular Nanosystems
- Systems of Nanosystems
- Active Nanostructures
- Passive Nanostructures

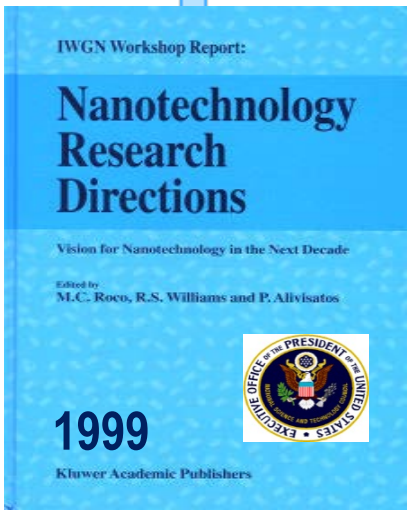
2000

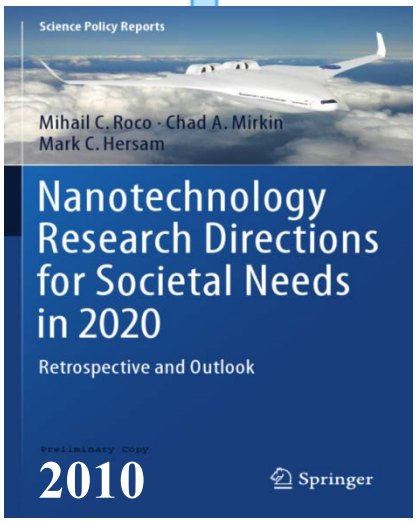


2010

2020

2030

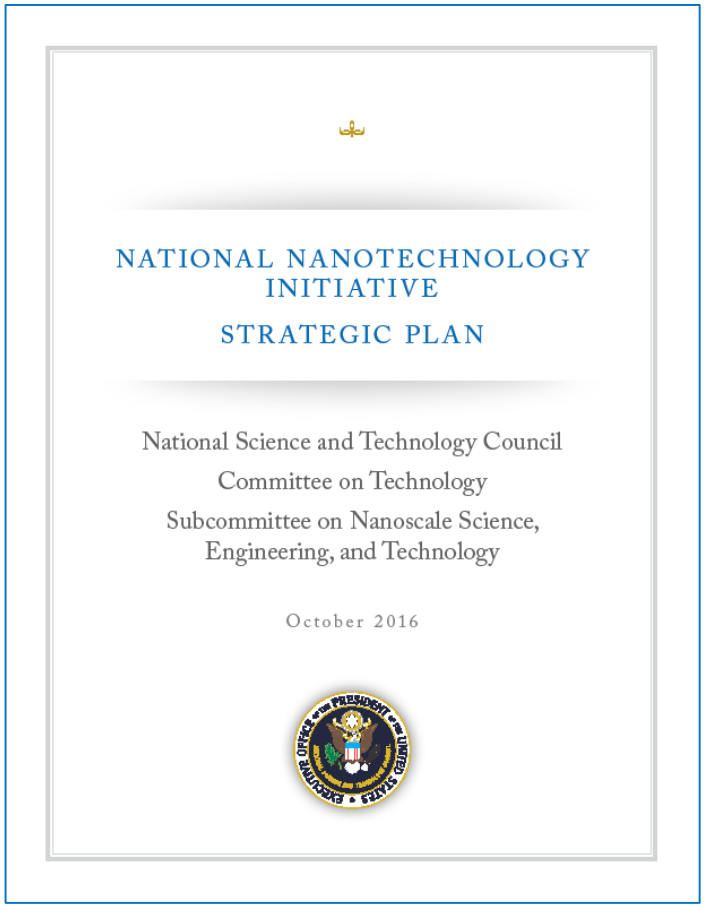




30 year vision to develop nanotechnology in three stages changing focus and priorities

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

Preparations for National Nanotechnology Initiative in 2018


NATIONAL NANOTECHNOLOGY INITIATIVE

STRATEGIC PLAN

National Science and Technology Council

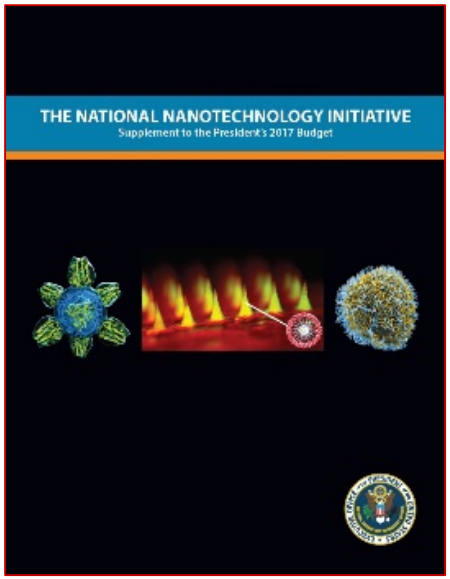
Committee on Technology

Subcommittee on Nanoscale Science, Engineering, and Technology

October 2016

2016-2019 NNI Strategic Plan approved by WH and submitted to Congress

(available on www.nano.gov)



2017 NNI Supplement to the President's Budget (including NSF, NIH, DOE, …)

PCAST report on NNI

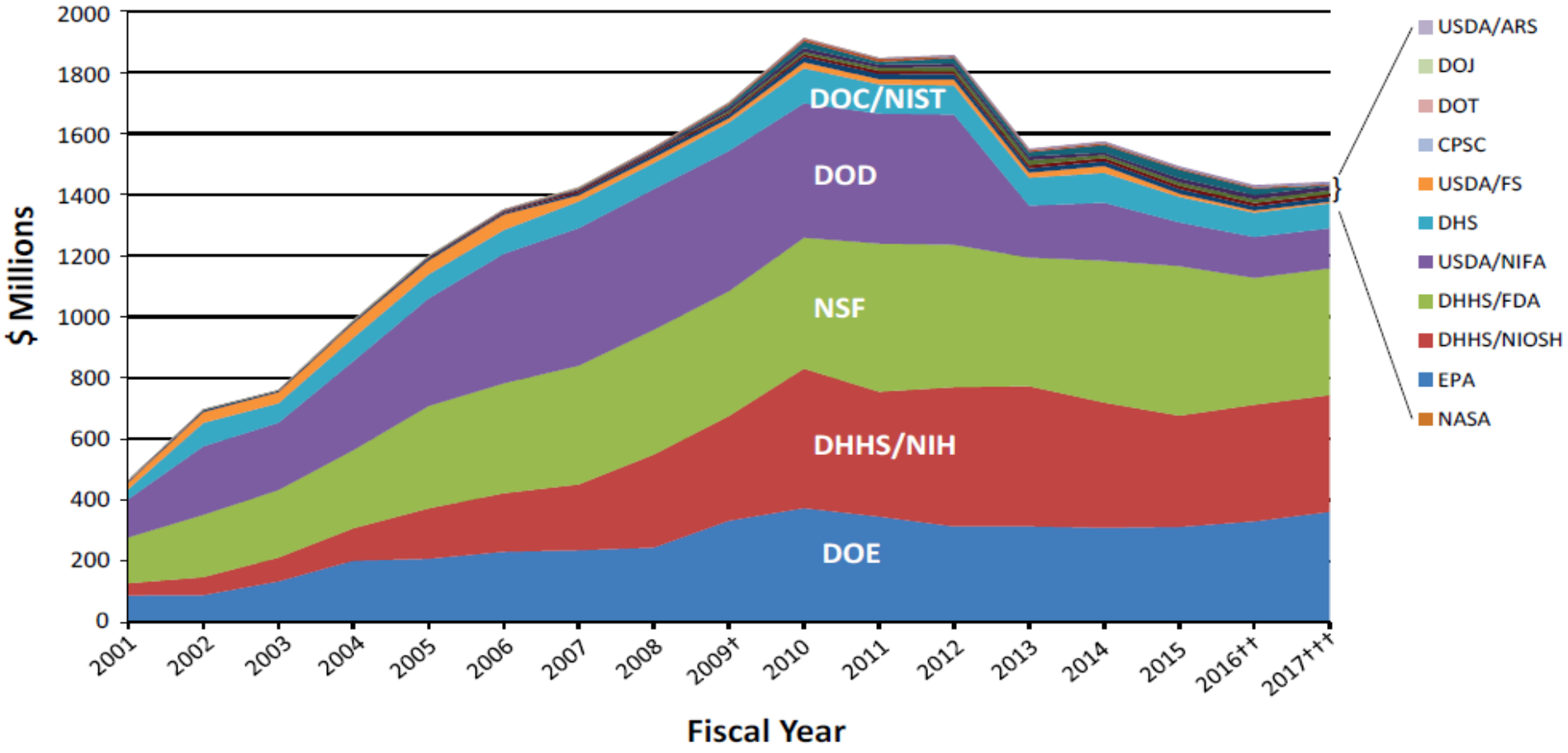
NAS/NRC report on NNI

- Sustainable Nanomanufacturing
- Nanoelectronics for 2020 and Beyond
- Water Sustainability Through Nanotechnology
- Nanotechnology for Sensing
- Nanotechnology Knowledge Infrastructure

Signature Initiatives (2017-)

NNI Funding by Agency 2001-2017

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



† 2009 figures do not include American Recovery and Reinvestment Act funds for DOE ($293 million), NSF ($101 million), NIH ($73 million), and NIST ($43 million)

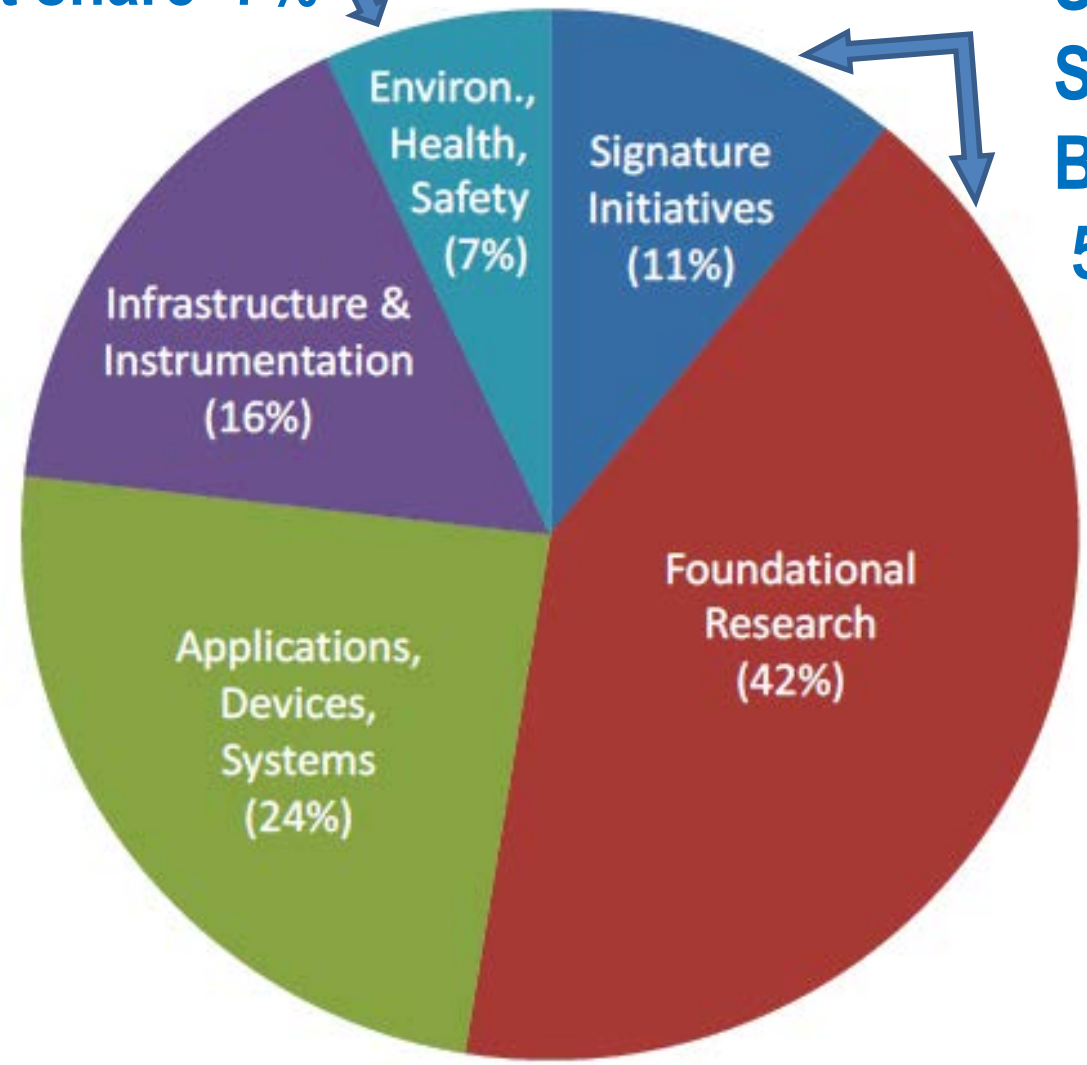
†† 2016 estimated funding is based on 2016 enacted levels and may shift as operating plans are finalized.

††† 2017 Budget.

Breakout of NNI funding by program component areas in the 2017 Budget Request: evolving with priorities

EHS budget share 7%

Supporting S&T Breakthrough 53%



I. National Nanotechnology Initiative, 2016

Nanotechnology Signature Initiatives

Sustainable Nanomanufacturing

www.nano.gov/NSINanomanufacturing

Nanoelectronics for 2020 and Beyond

www.nano.gov/NSINanoelectronics

Water Sustainability through Nanotechnology

www.nano.gov/node/1577

Nanotechnology Knowledge Infrastructure

www.nano.gov/NKIPortal

Nanotechnology for Sensors

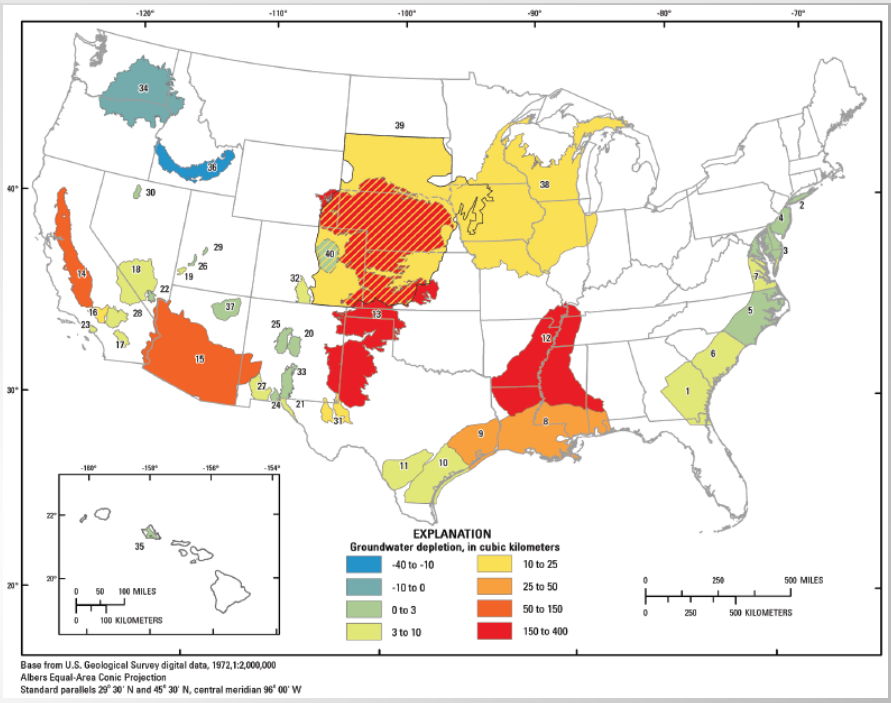
www.nano.gov/SensorsNSIPortal

Other considered topics are related to: nanomodular systems, nanomedicine, nanocellulose, nanophotonics, nano-city.
Completed: Nanotechnology for Solar Energy (2011-2015)

Water Sustainability through Nanotechnology

Research thrusts

- **Increase water availability**
  (ex: double the throughput membrane separation systems within 5 years)

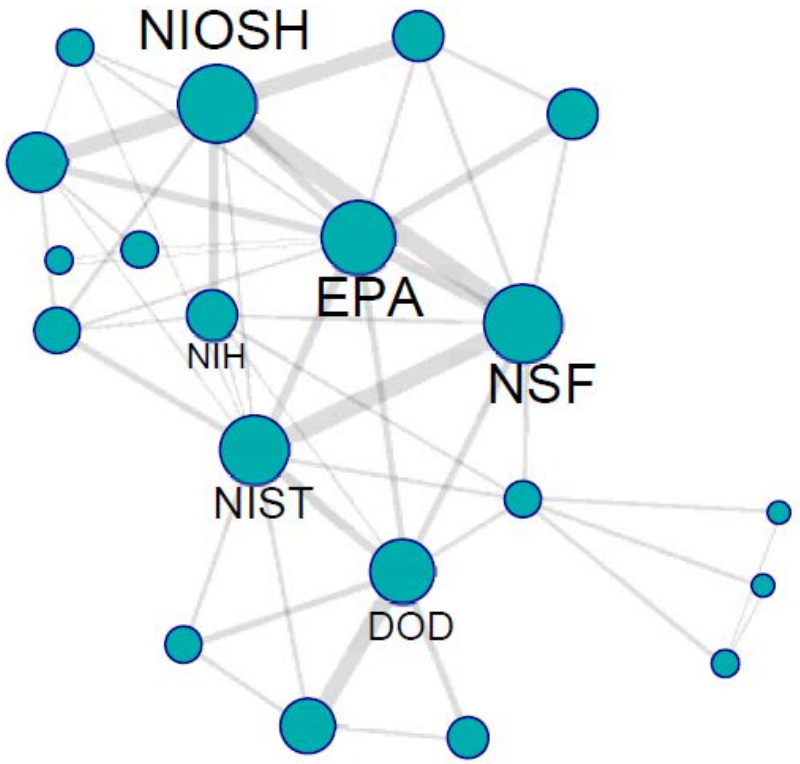


- **Improve the efficiency of water delivery and use**
  (ex: Develop within 5 years nanotechnology-enabled coatings that reduce by 50% the amount of energy)

- **Enable the next-generation water monitoring systems with nanotechnology** (ex: continuous, real-time measurement of water quality that are more sensitive, more reliable, use sensors)

NNI collaboration: formal agreements dominated by environmental aspects

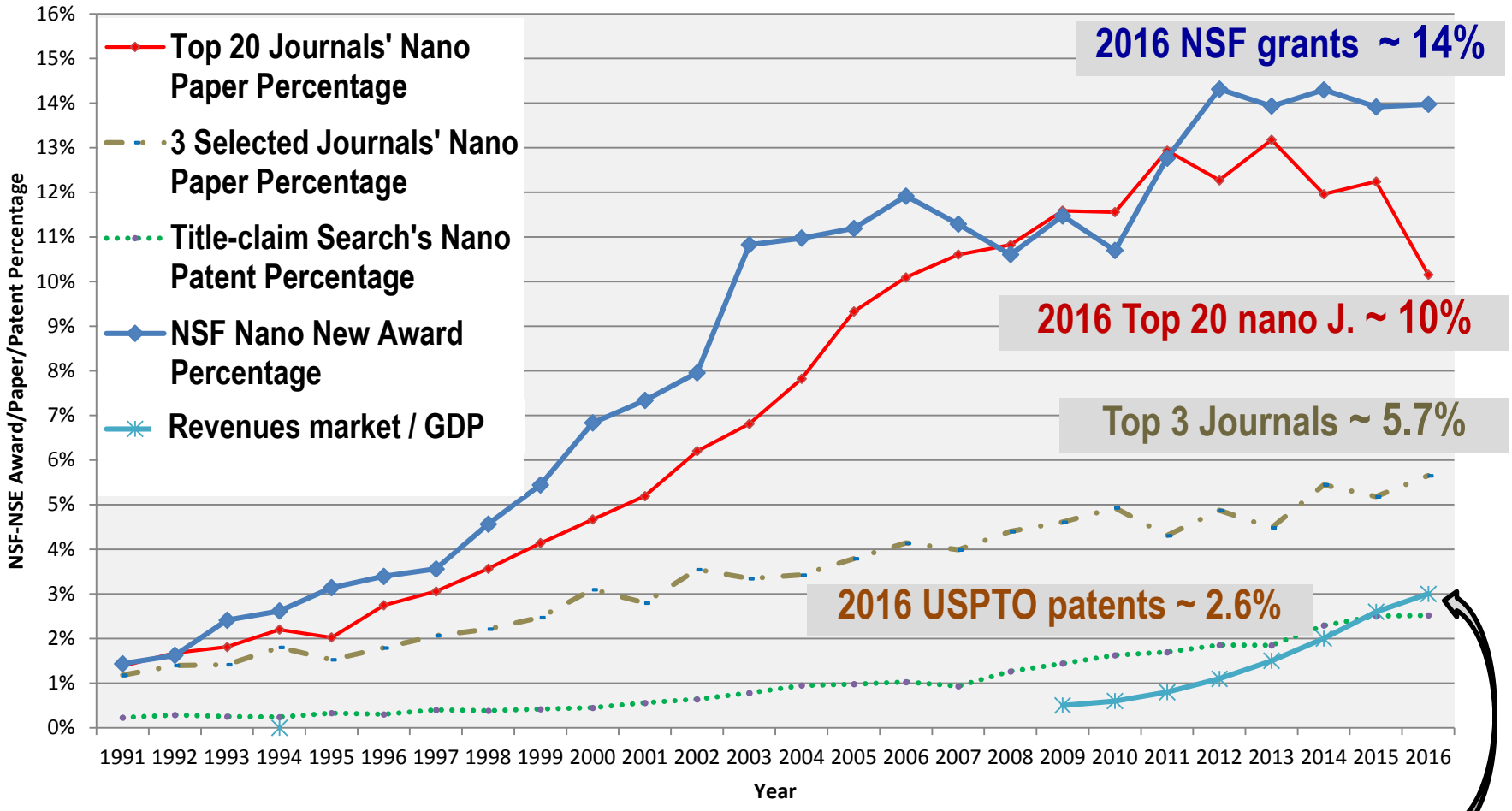
PCAST (Oct 2014):



159 collaborations
FY2013-FY2014

Percentage rate of penetration of nanotechnology in NSF awards, WoS papers and USPTO patents (1991-2016)

Searched by keywords in the title/abstract/claims (update Encyclopedia Nanoscience, Roco, 2016)



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

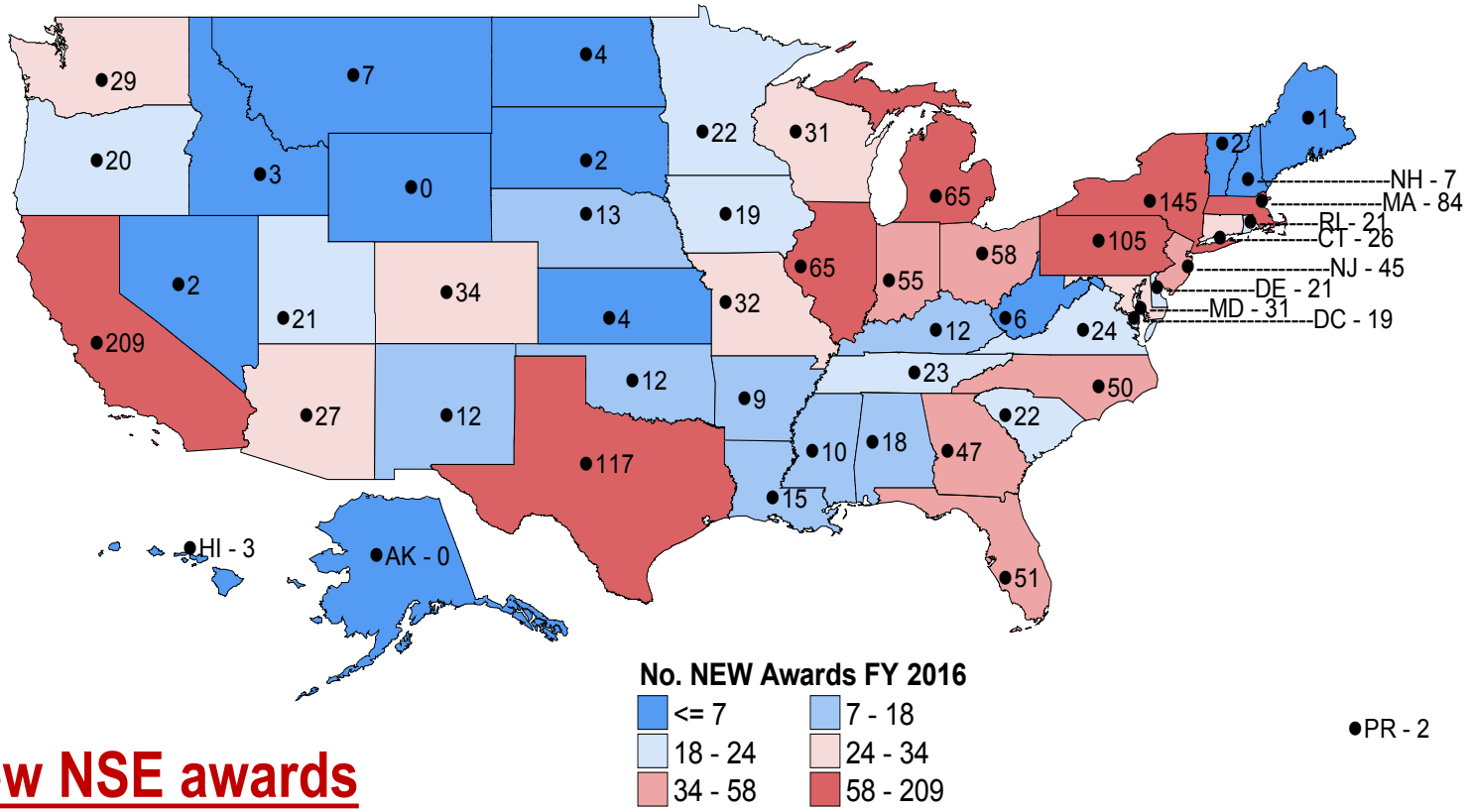
MC Roco, Nov 5 2017

NSF's NSE number of new awards per state

FY 2016: U.S. total new awards = 1,662

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

Rank	No. FY 16 NEW Awds.
1	CA
2	NY
3	TX
4	PA
5	MA
6	IL



#1 CA 209 new NSE awards

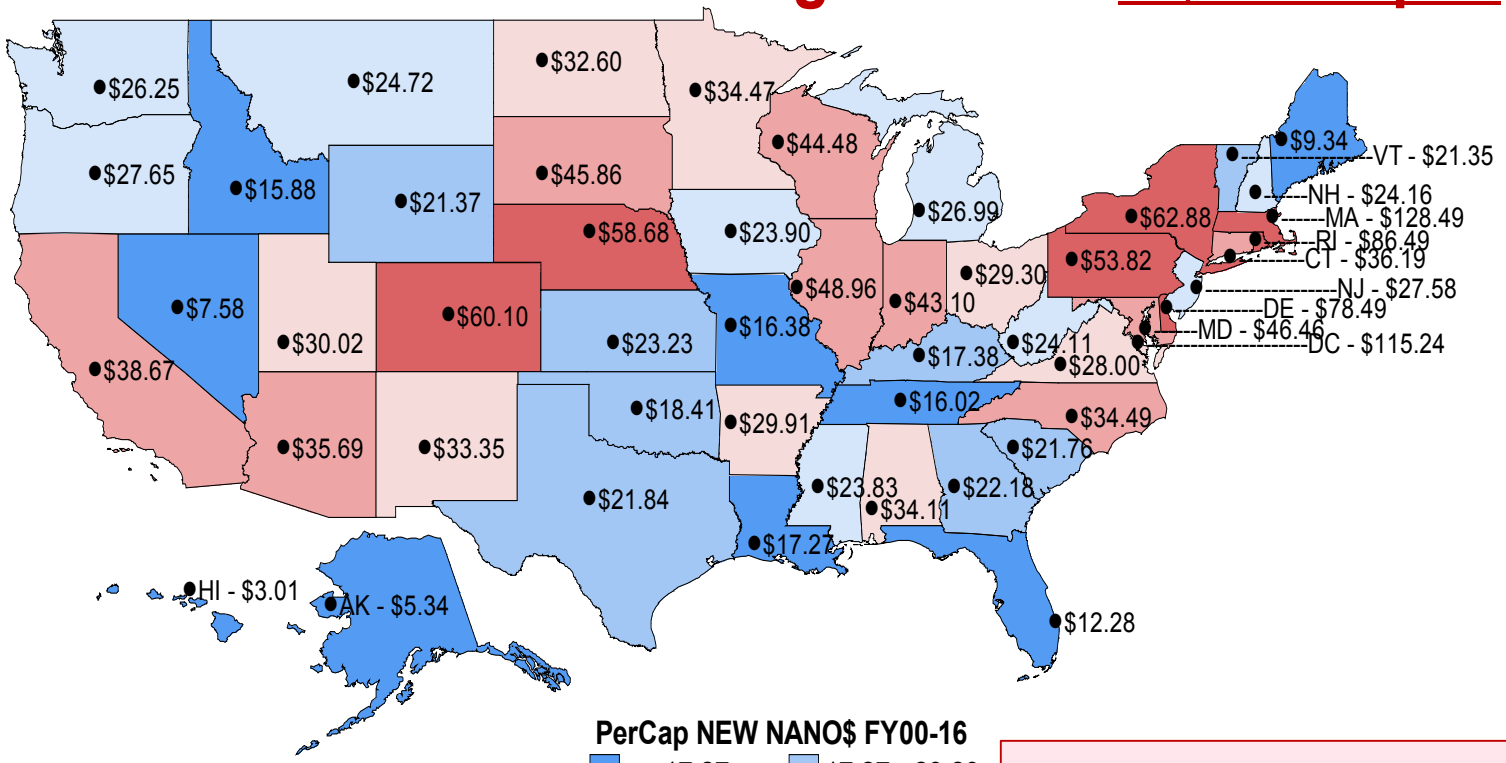
AK 0; AL 18; AR 9; AZ 27; **CA 209**; CO 34; CT 26; DC 19; DE 21; FL 51; GA 47; HI 3; IA 19; ID 3; IL 65; IN 55; KS 4; KY 12; LA 15; **MA 84**; MD 31; ME 1; MI 65; MN 22; MO 32; MS 10; MT 7; NC 50; ND 4; NE 13; NH 7; NJ 45; NM 12; NV 2; **NY 145**; OH 58; OK 12; OR 20; **PA 105**; PR 2; RI 21; SC 22; SD 2; TN 23; **TX 117**; UT 21; VA 24; VT 2; WA 29; WI 31; WV 6; WY 0

MC Roco, Nov 5 2017

NSF's NS&E amount new awards per capita

FYs 2000 - 2016: U.S. average amount ~ $35 / capita

Rank	FY 2000-2016 NEW Amt.
1	MA
2	DC
3	RI
4	DE
5	NY
6	CO



2016: Over 6,000 active awards
(abstracts on www.nsf.gov/nano)

#1 MA $128.49/capita (2000-2016)

AK 5.34; AL 34.11; AR 29.91; AZ 35.69; CA 38.67; **CO 60.1**; CT 36.19; **DC 115.24**; **DE 78.49**; FL 12.28; GA 22.18; HI 3.01; IA 23.9; ID 15.88; IL 48.96; IN 43.1; KS 23.23; KY 17.38; LA 17.27; **MA 128.49**; MD 46.46; ME 9.34; MI 26.99; MN 34.47; MO 16.38; MS 23.83; MT 24.72; NC 34.49; ND 32.6; NE 58.68; NH 24.16; NJ 27.58; NM 33.35; NV 7.58; **NY 62.88**; OH 29.3; OK 18.41; OR 27.65; PA 53.82; PR 18.48; **RI 86.49**; SC 21.76; SD 45.86; TN 16.02; TX 21.84; UT 30.02; VA 28; VT 21.35; WA 26.25; WI 44.48; WV 24.11; WY 21.37

MC Roco, Nov 5 2017

Several NSF NSE awards in FY 2017-2018 (1)

www.nsf.gov

- National Nanotechnology Coordinated Infrastructure, NNCI
- Network for Computational Nanotechnology, nanoHUB et al.
- Scalable nanomanufacturing, SNM (2017)
- "Two-Dimensional Atomic-layer Research and Engineering, 2-DARE"; "Advancing Communication Quantum Information Research in Engineering (ACQUIRE)" and "NewLAW", 2017
- 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

Several NSF NSE awards in FY 2017-2018 (2)

www.nsf.gov

- Core research in: BIO, CISE, E.H.R., ENG, GEO, MPS, SBE
- Materials Research Science and Engineering Centers (MRSEC); Nanotechnology Engineering Research Centers (NERC)
- Science and Technology Centers (STC) (Ex: UCB, Harvard U., MIT-GA Tech, U. Colorado-Boulder, U. Penn) $5M/year/center
- 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, Technologies & Society (CKTS)
- Translational: GOALI; I/UCRP; PFI; Nano-ERC; I-Corps

Supporting studies for future of *nanotechnology* and *brain-like computing*

NANO 2020: "Nanotechnology Research Directions: for Societal Needs in 2020" (Springer, 2011)

Report: www.nano.gov/node/948 (Ref. 4)

CKTS 2030: "Converging Knowledge, Technology and Society: Beyond NBIC" (Springer 2013)

Report: http://www.wtec.org/NBIC2-Report/ (Ref. 6)

RITR: Rebooting the IT Revolution (NSF, SRC & SIA; Sept. 2015)

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

NNI-GC: Nanotechnology-Inspired Grand Challenge for Future Computing (OSTP, 2015): ttp://www.nano.gov/futurecomputing; https://www.nano.gov/grandchallenges.

ICA: Intelligent Cognitive Assistants,

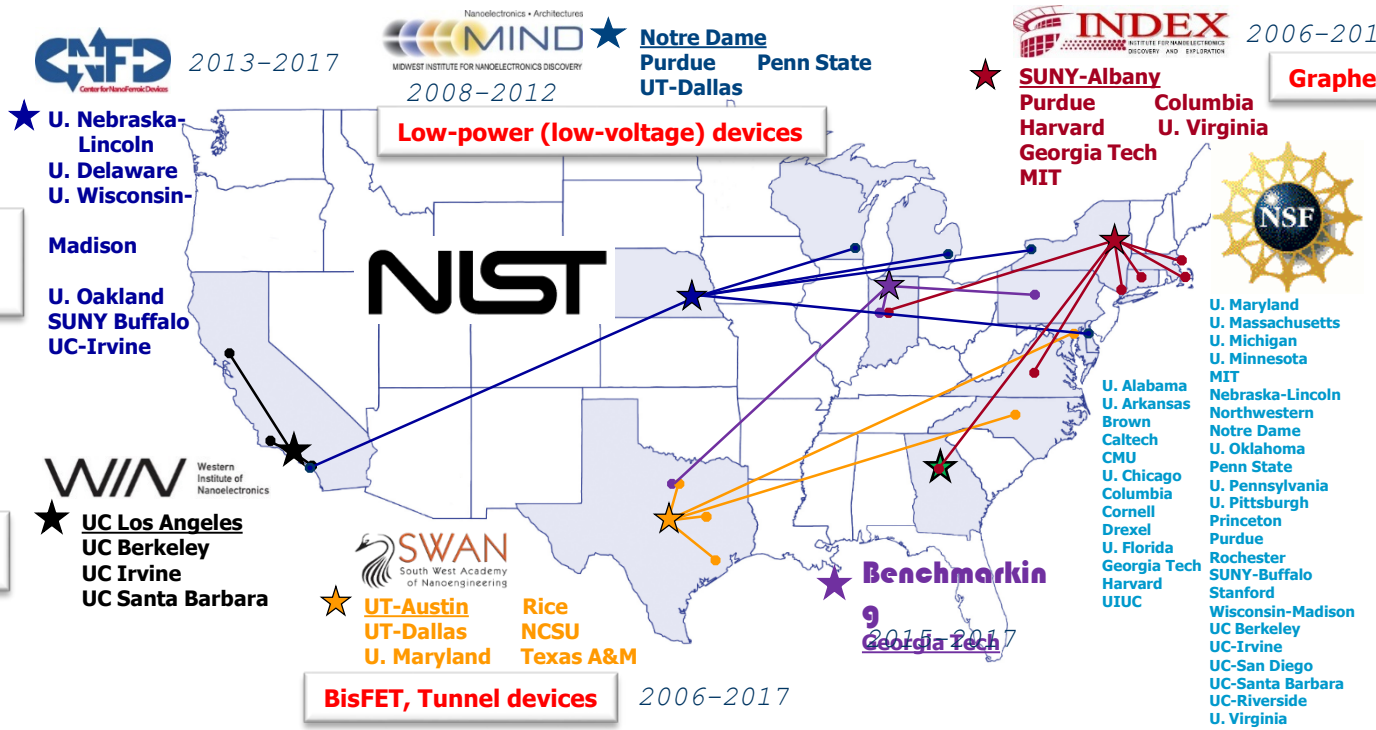
(NSF, SRC & SIA: ICA1 - Oct. 2016; ICA2 –Nov 14-15, 2017)

www.nsf.gov/nano/ and www.semiconductors.org/issues/research/research/

Nanoelectronics Research Initiative (NRI), 2017

"Taking computing beyond the limitations of current technology"

- > 1500 journal papers
- > 40 patents
- > 300 Ph.D. /post-doc



MRSEC supplement

NEB2020

E2CDA

Non-Academic Research Internships for Graduate Students (INTERN)

- **INTERN** Dear Colleague Letter (DCL): https://www.nsf.gov/pubs/2017/nsf17091/nsf17091.jsp
- Offered as supplemental funding to any active NSF Research Grant
- Supported in FY18 and FY19

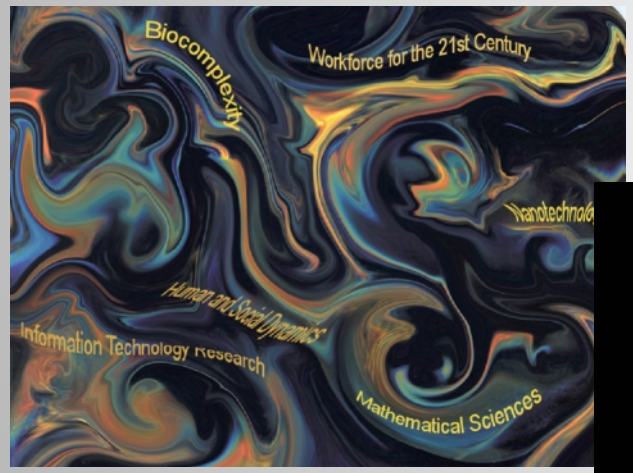
INTERN DCL – Highlights

- Internships for NSF funded Graduate Students on research assistantships
- Up to 6 months per internship
- Host organization describes internship/mentoring plan
- Need an IP agreement governing internship activities
- INTERN DCL support funds go to the academic institution

Defining convergence

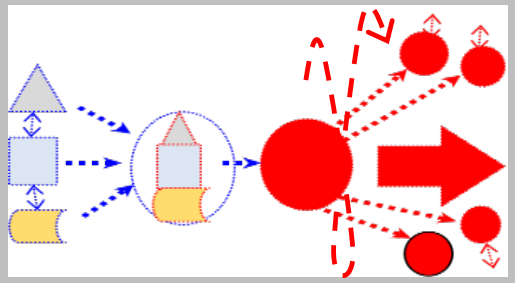
Evolution in nature, science, technology, society is

- *Increasingly turbulent*
- *Coherent*
- *Emergent*



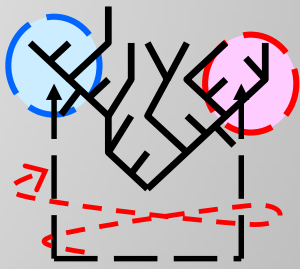
S&T trends

(Ref. 1-5) Coherence cycle



Education trends

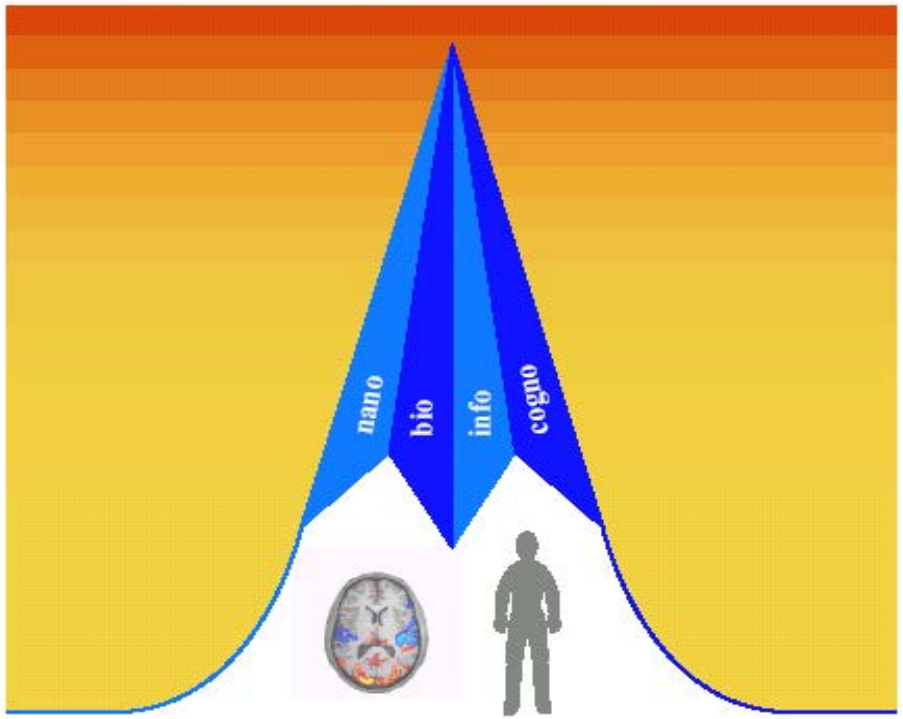
(Ref. 1-5) Ex: Trading zones



Convergence is a general strategy to holistically understand and transform a system for reaching a common goal

Seven reports on convergence

2003, 2006 and 2007 Springer; 2004 NYAS; 2004; 2013 (worldwide), 2016 (handbook)



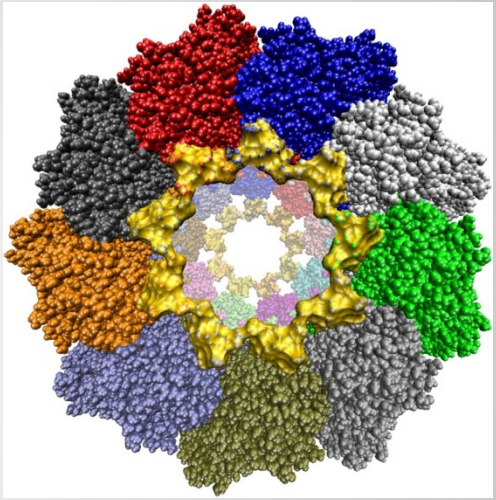
CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

Workshop, Dec. 2001
NSF-DOC Report 2002

(includes sections on sustainability)

Coevolution of Human Potential and Converging New Technologies



In: **Annals of the New York, Academy of Sciences, Vol. 1013, Report 2004**

(M.C. Roco and C. Montemagno)

Convergence of Knowledge, Technology, and Society:

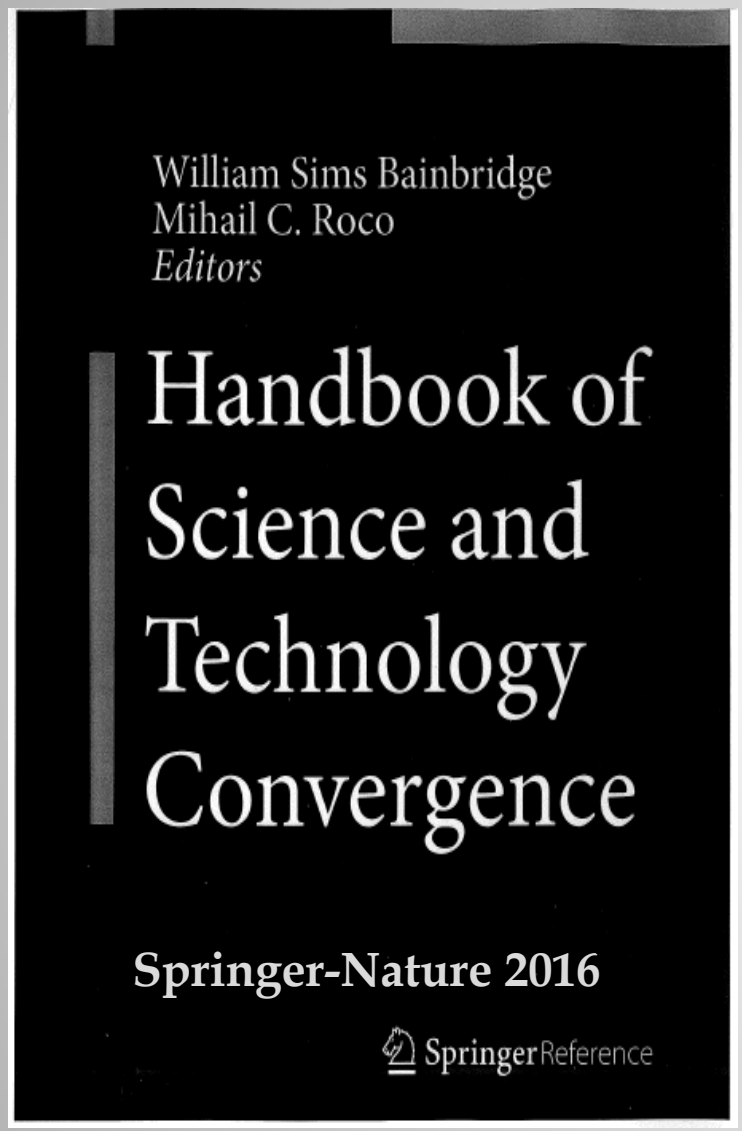
Beyond Convergence of Nano-Bio-Info-Cognitive Techologies

www.wtec.org/NBIC2-Report; M. Roco et al.

INTERNATIONAL BENCHMARKING of METHODS and APPLICATIONS

Springer-Nature, Report 2013

(includes chapters on sustainable development)



Convergence Science: focus on principles, methods and case studies

applied to

75 science and technology, research, education, sustainability and other societal applications

*Ref 10: "**Science and technology convergence**, with emphasis for nanotechnology-inspired convergence" (Bainbridge & Roco, JNR, 2016)*

Reports driven by various application domains

- **National Academies**: Convergence for Life Sciences, Physical Sciences, Engineering, and Beyond (2014)
- **MIT-Harvard**: Biomedical applications of convergence (paper 2011), and The Future of Health (report 2016)
- **OECD Bio, Nano, and Converging Technologies group:** BNCT series of reports (2014-)
- **NSF-SRC-industry**: Intelligent Cognitive Assistants (2016-)
- **NSF portal:** Convergence for research and education (2016-)
- **National Academies:** Convergent ERC centers (2017)
- **NSF Ad-Com on Environmental Research and Education**: Convergence for sustainable development (2017)

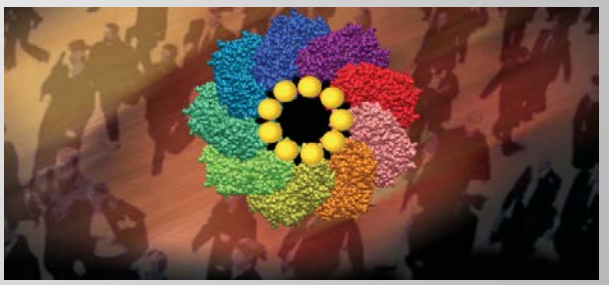
1. Defining S&T convergence

(Ref 6: "Convergence of Knowledge, Technology and Society", Springer, 2013)

Convergence is deep integration of knowledge, tools, domains and modes of thinking, driven by common goal

- **leading to a new framework, paradigm or ecosystem** - that allows to answer questions, resolve problems and build things that isolated capabilities cannot *(convergence stage of changing the system),*

- **that creates novel pathways, opportunities & frontiers** – in competencies, knowledge, technologies and applications *(divergence stage)*



Convergence science – Creating/ changing an ecosystem for a goal based on *10 theories, 6 convergence principles, and specific methods*

Convergence of knowledge, technology and society is guided by six general principles

A. The interdependence in nature and society

B. Evolutionary processes of convergence and divergence

C. System-logic deduction in decisions

D. Higher-level cross-domain languages

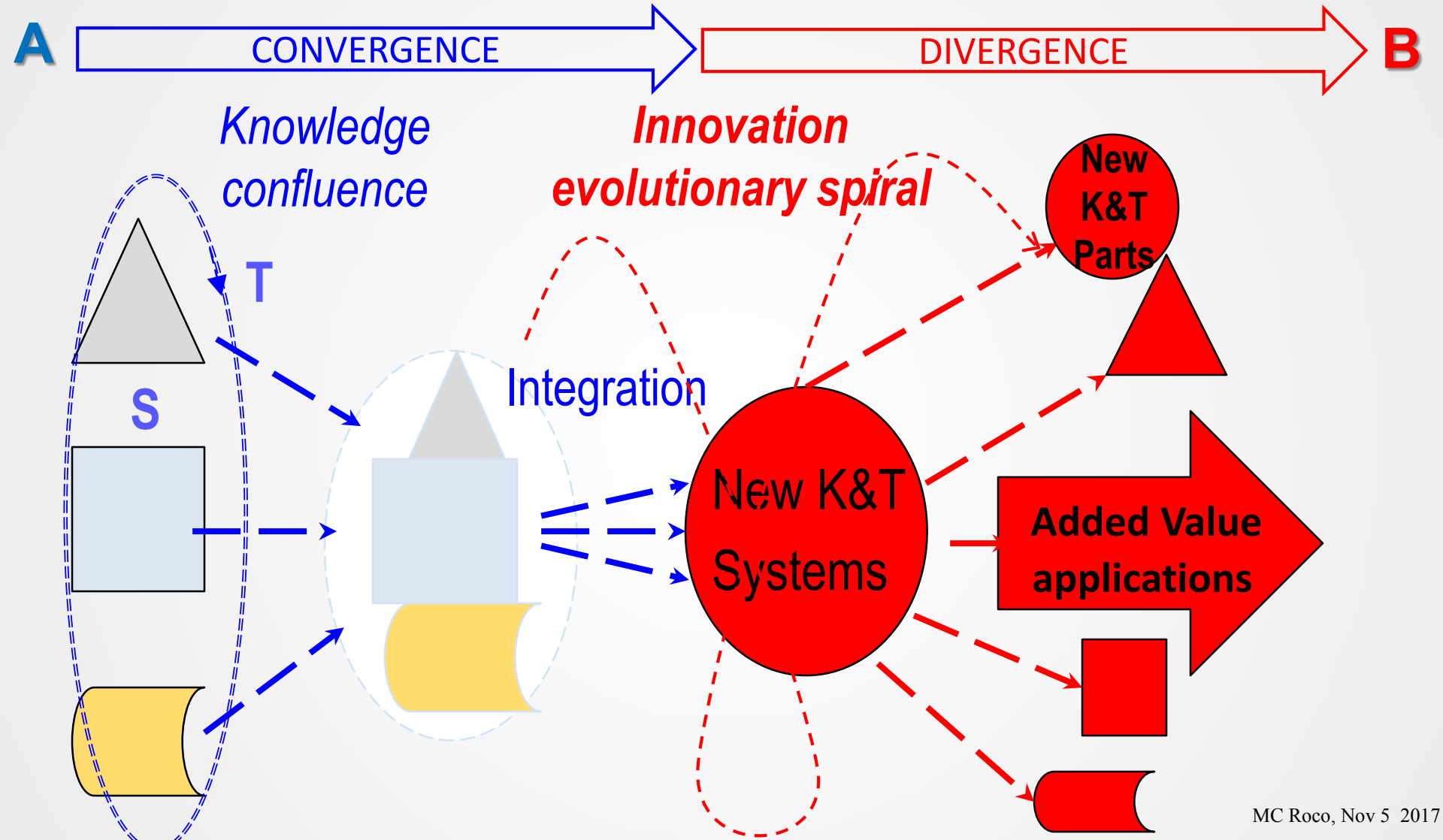
E. Confluence of resources leading to system changes (S curve)

F. Vision-inspired basic research for long-term challenges

PRINCIPLES FOR CONVERGENCE

Ref. 8

Evolutionary processes of convergence and divergence in S&T



MC Roco, Nov 5 2017

The spiral is driven by the added-value goal through the convergence of domains S, in the external context ENV (imagine a **"tornado"** or "**hurricane**" with surrounding air flow and Earth rotation). After Refs. 1 (Roco 2002) and 6 (CKTS Report 2013)

Three implemented stages of S&T Convergence

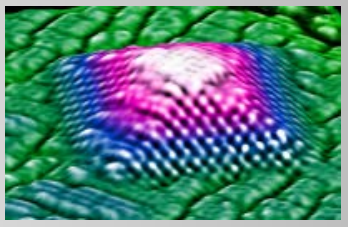
- Nano, NBIC, Society ecosystem -

Three stages of convergence

(Ref 6: CKTS, Springer, 2013)

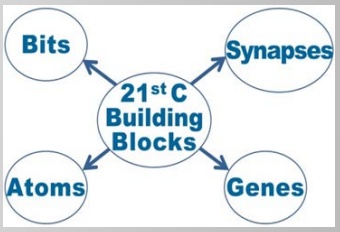
I. Nanoscale Science, Engineering and Technology "Nanotechnology"

Integrates disciplines and knowledge of matter from the nanoscale



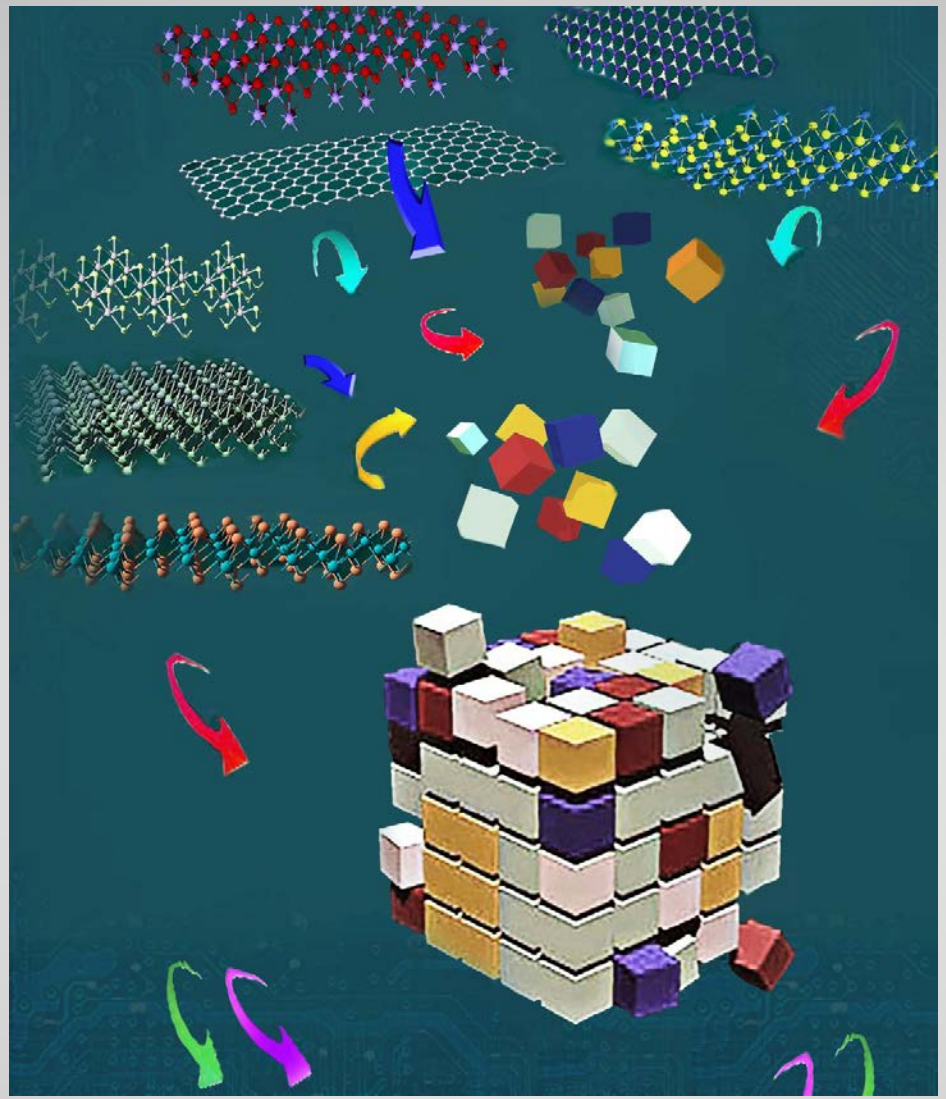
II. Nano-Bio-Info-Cognitive Converging Technologies "NBIC"

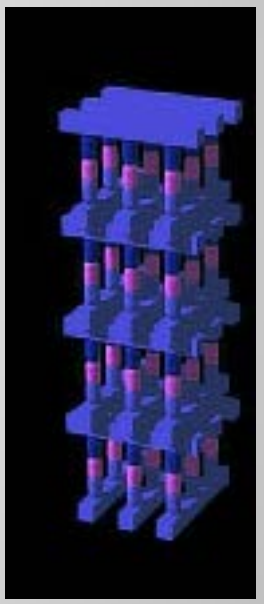
Integrates foundational and emerging technologies from basic elements using similar system architectures



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

Integrates the essential platforms of human activity using five convergence principles





Ex I: NanoModular Materials and Systems by Design, NSF/WTEC, 2016

http://www.wtec.org/nmsd/docs/NMSD-FinalReport-Web-Lowres.pdf

Ex I: Energy-Efficient Computing: from Devices to Architectures (E2CDA)

E2CDA invests in radical new approaches – from brain- inspired architectures to hybrid digital-analog designs

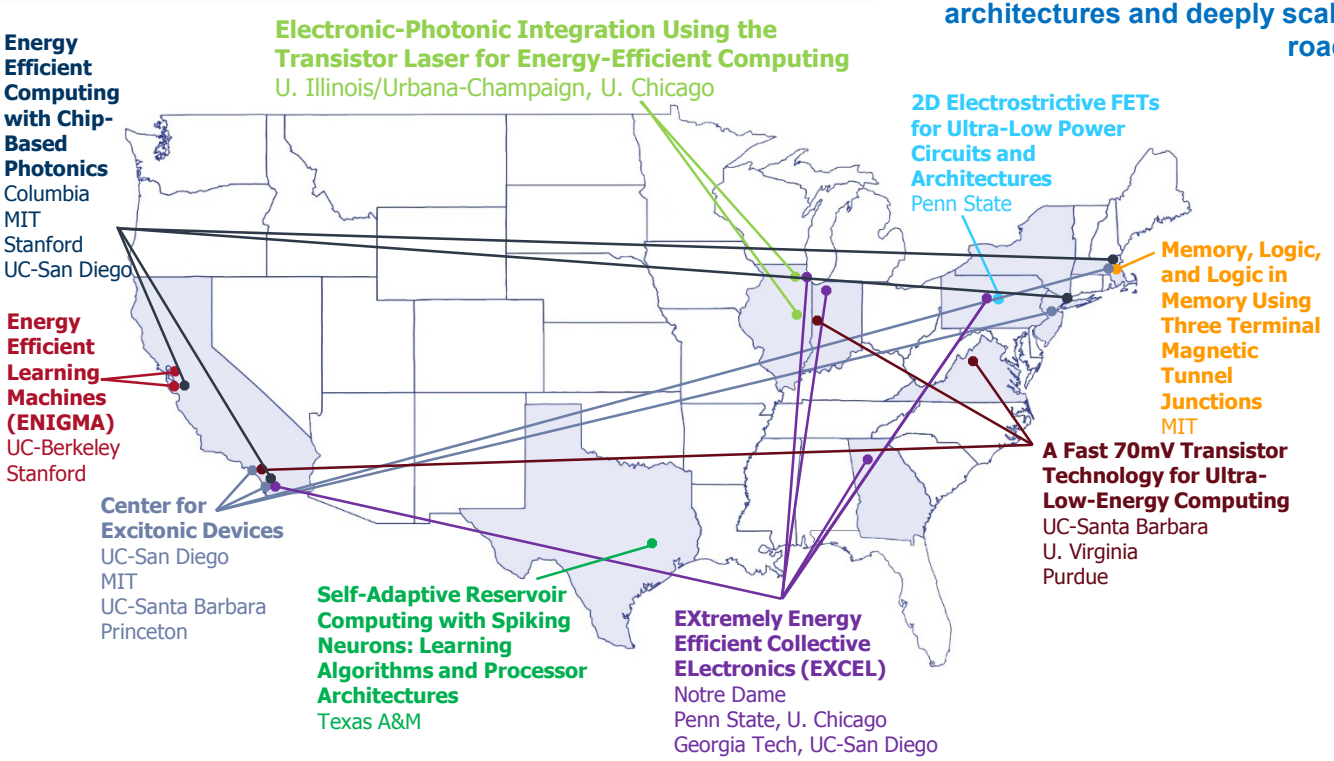
Partnership between NSF (ENG and CISE) and Semiconductor Research Corporation (SRC)

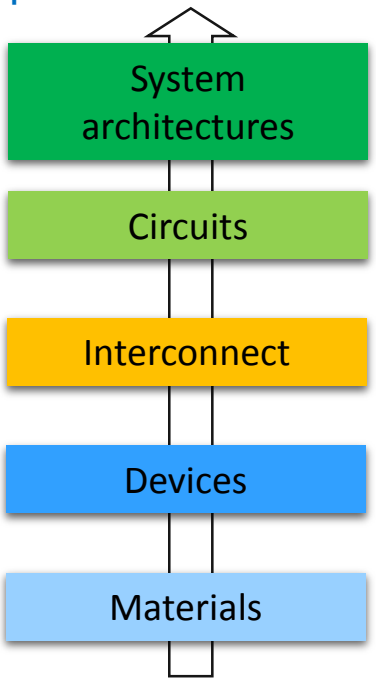
SRC-NSF Initiative: E2CDA

Co-optimizing emerging devices and architectures

Energy-Efficient Computing from Devices to Architectures

Target a 100X reduction or more in energy per delivered operation as compared to projected performance of conventional CMOS architectures and deeply scaled technology at the end of the roadmap





nano2 Twelve global nano 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**

II. Nano-Bio-Info-Cognitive Converging Technologies

Workshop (NSF, 2001): *"Converging Technologies for Improving Human Performance: Nano-Bio-Information-Cognitive"*

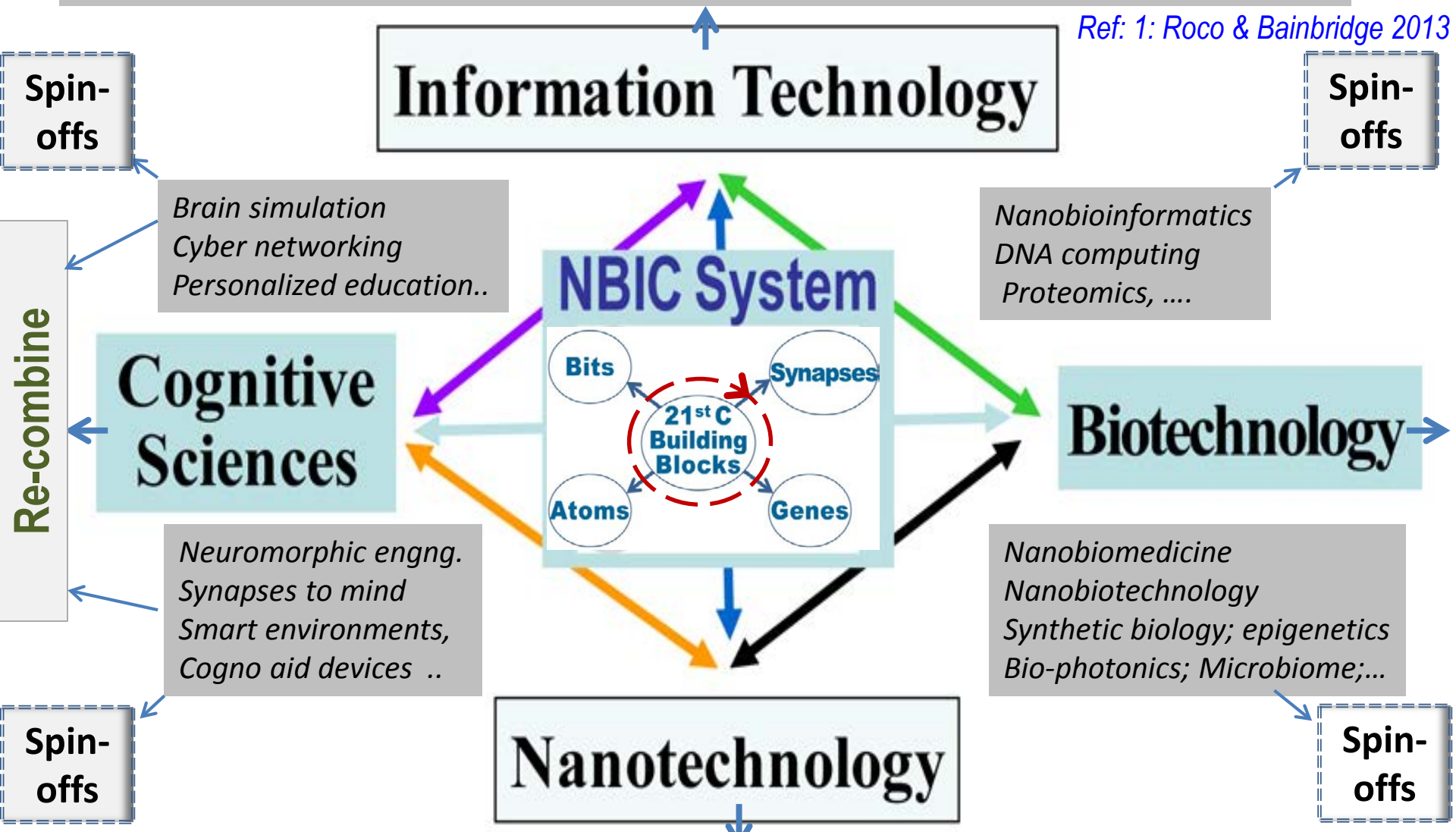
NBIC: **Synergistic combination of four foundational emerging fields from their basic elements (atoms, bits, genes, and neurons) up and using similar system architecture concepts, for common core goals such as learning, productivity & aging**

On this basis: 20 visionary scenarios for 20 years ahead

II. Emergence & divergence 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*

II. U.S. emerging S&T initiatives

OSTP

Brain–like Computing; Smart systems

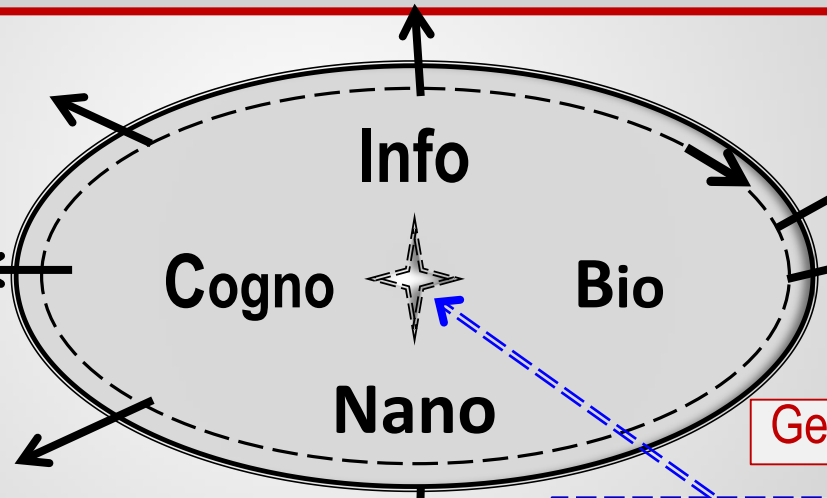
Big Data | National Strategic Computing Initiative

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

Artificial Intelligence

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

National Robotics Initiative



Biology centered

Biomedical / Health focus

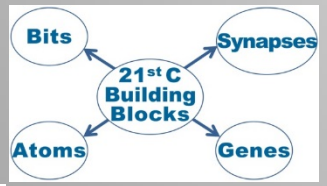
Precision Med

Genome(s) | Microbiome

Architecture, Life, Human-technology

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

Materials Genome | Photonics | NNI Grand Challenges



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

Ex. II: Nanotechnology-inspired Grand Challenge

"Brain like computing"

combining National Nanotechnology Initiative (NNI),
National Strategic Computing Initiative (NSCI) & 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

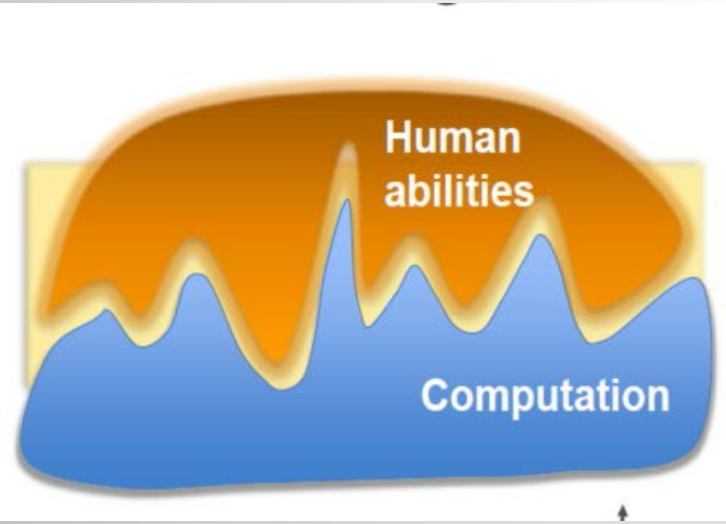
- Purpose: "**Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.**"

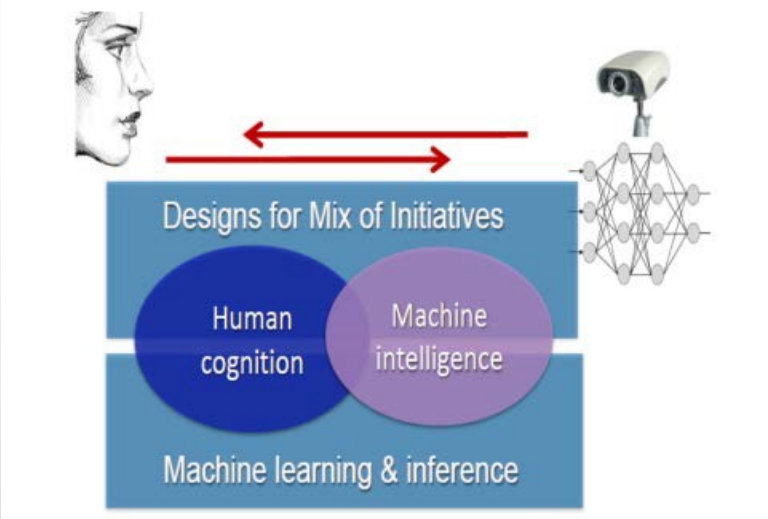
Also: pattern recognition, human like simultaneous perception of information from various sources including the five senses, intelligence from the bottom with materials that compute (like tissues & neuromorphics), simultaneous actions, natural communication.

Ex II: Intelligent cognitive assistants

2016 workshop (sponsored by NSF, SIA, SRC)

Systems that are highly useful to humans, specifically on the topic of Harnessing Machine Intelligence to Augment Human Cognition and Human Problem-Solving Capabilities – e.g., research that drives towards "Intelligent Cognitive Assistants"





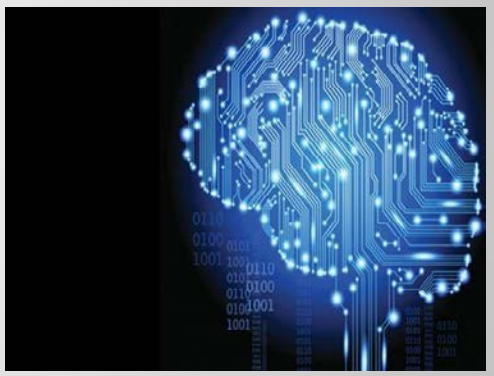
Ref: **Intelligent Cognitive Assistants (ICA) report, 2016**
The report is available on www.nsf.gov/nano (4th item) and www.semiconductors.org/issues/research/research/

Ex II: Human Centered Cognitive Engineered Systems

Machines ⇒ **Smart Machines** ⇒ **Human Centered Cognitive Engineered Systems**

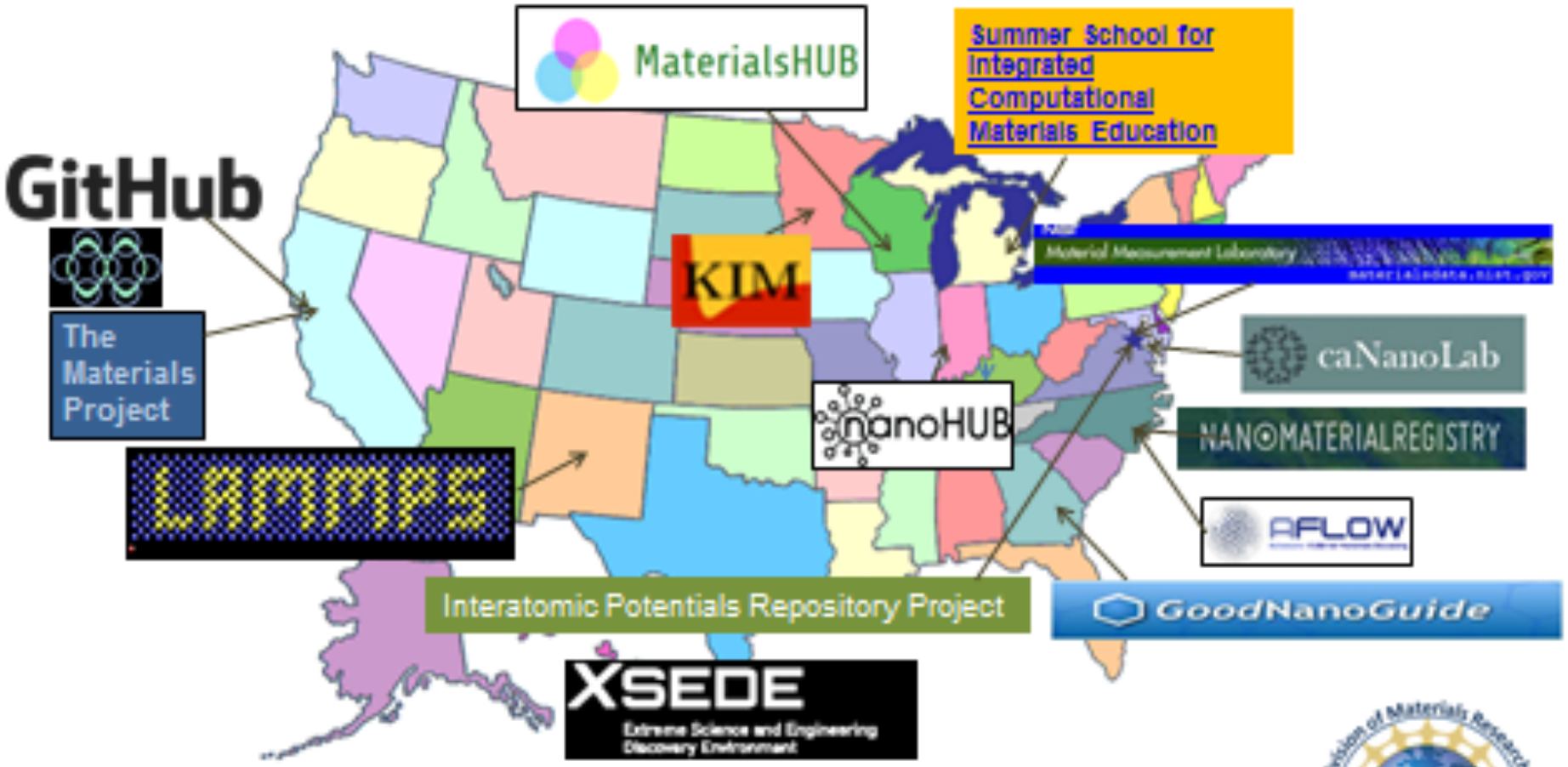
- Achieve functionality
- Improve productivity/consistency/ quality

- Achieve functionality
- Improve productivity/ consistency/ quality
- Has some learning/decision making capacity



- Achieve functionality
- Improve productivity/ consistency/quality
- Has greater learning/decision making capacity
- Collaborate with humans
- Evolve in time as they learn

Some Components of the Nanotechnology Knowledge Infrastructure



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

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

II. NBIC
Examples initiatives in 2017

Spin-offs enabled by NBIC (in U.S.)

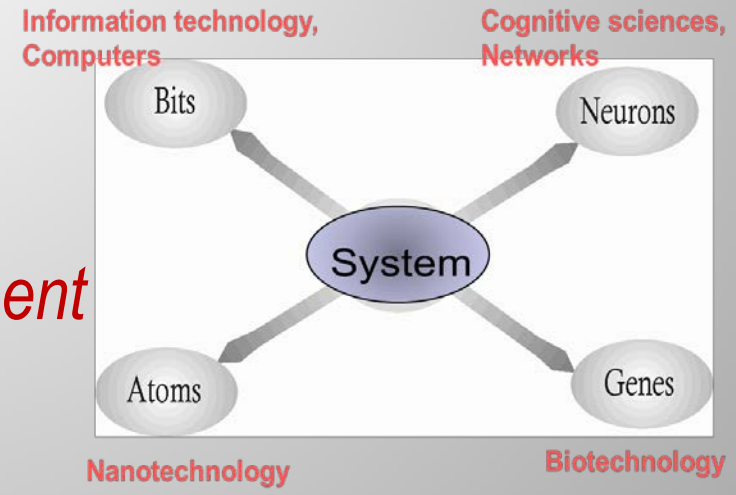
- **National Nanotechnology Initiative** (Brain- and Bio-inspired Computation Methods)
- **National Information Technology R&D** (NSCI, Supercomputing)
- **Human health; Precision Medicine; Microbiome Initiative**
- **BRAIN Initiative** (also international)

In Core NBIC system:

- *Requirements for life*
- *DNA control and implications*
- *Human-technology frontier*
- *Digital society and universal big data*

Twelve challenging ideas from 2001 NBIC Report that are reality or in development in 2017

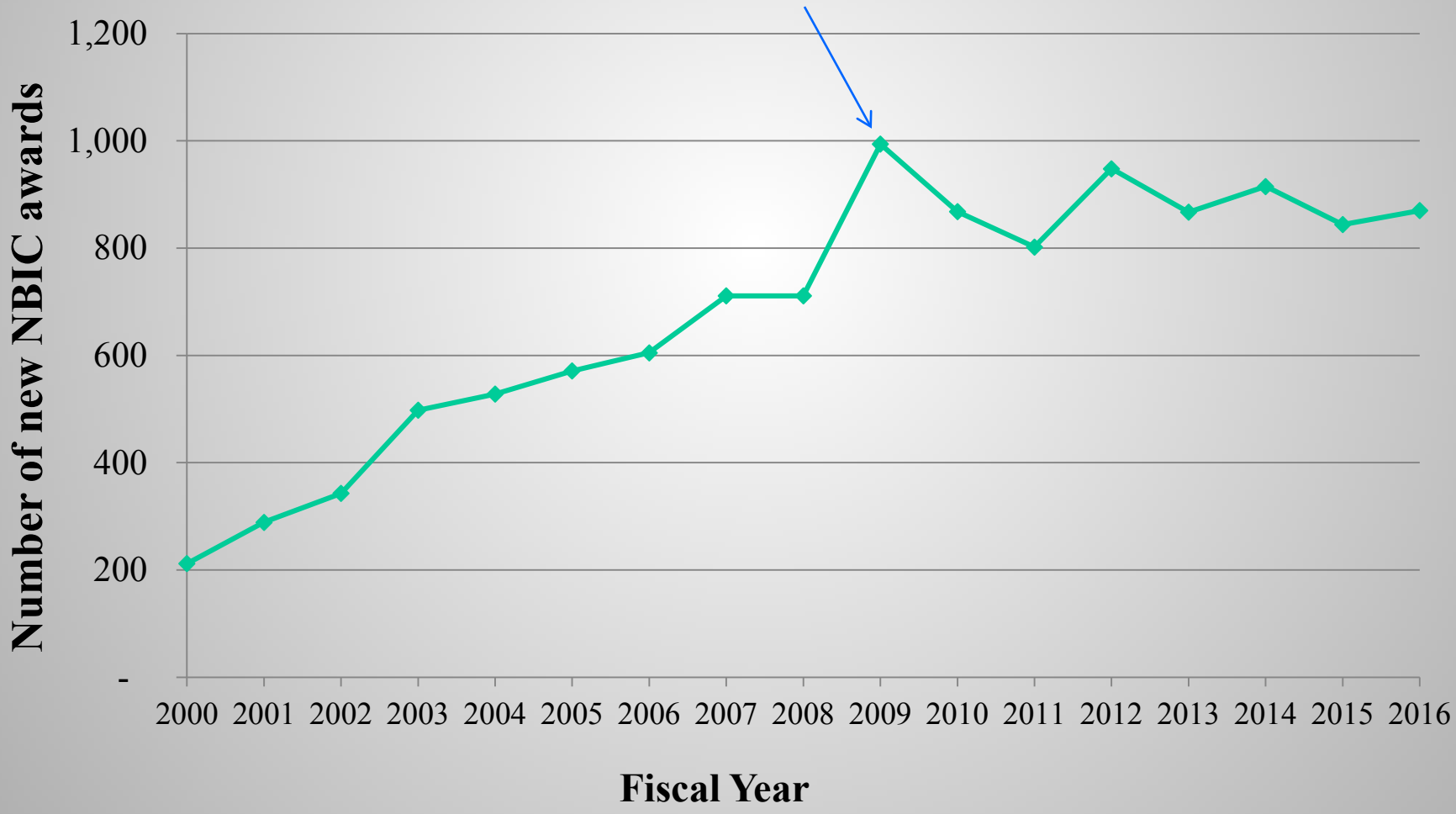
- Hierarchically interconnected world – *a reality in 2015*
- Non intrusive brain-to-brain communication – *accepted*
- Computer Personal advisor – as laptop or cell – *at beginning*
- Brain machine and brain robotics systems – in development
- From physics/chemistry to mind and education – in BRAIN R&D
- Centers of leaning: for brain to education methods – in function
- Regenerative medicine, Gene editing, 3-D print parts - accepted
- Nano-info-biomedical developments
- Proteases activated by brain - *done*
- Education earlier for NBIC - *modules*
- Intelligent environments – *in development*
- ELSI community – *organized in 2013*

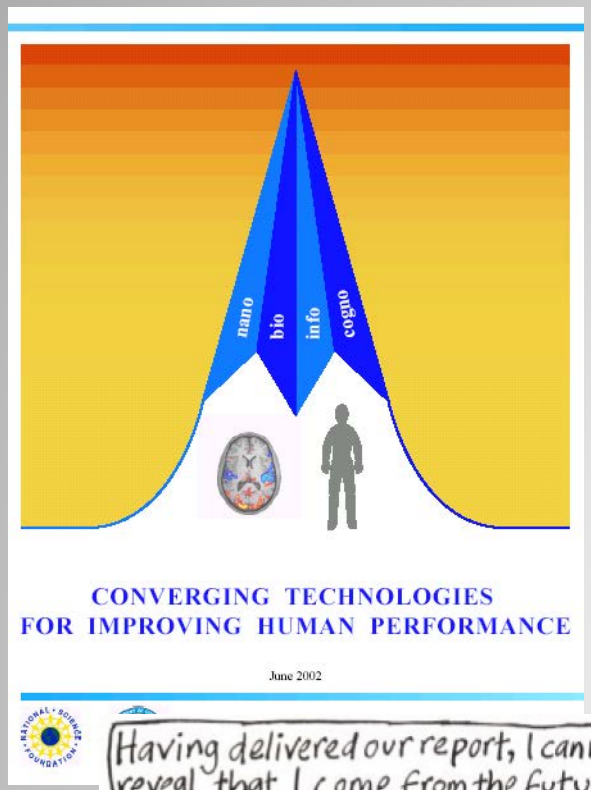


Number of NBIC Awards at NSF (2000-2016)

Abstract search by combined keywords

Since 2009, about **5% of total NSF new awards on NBIC**





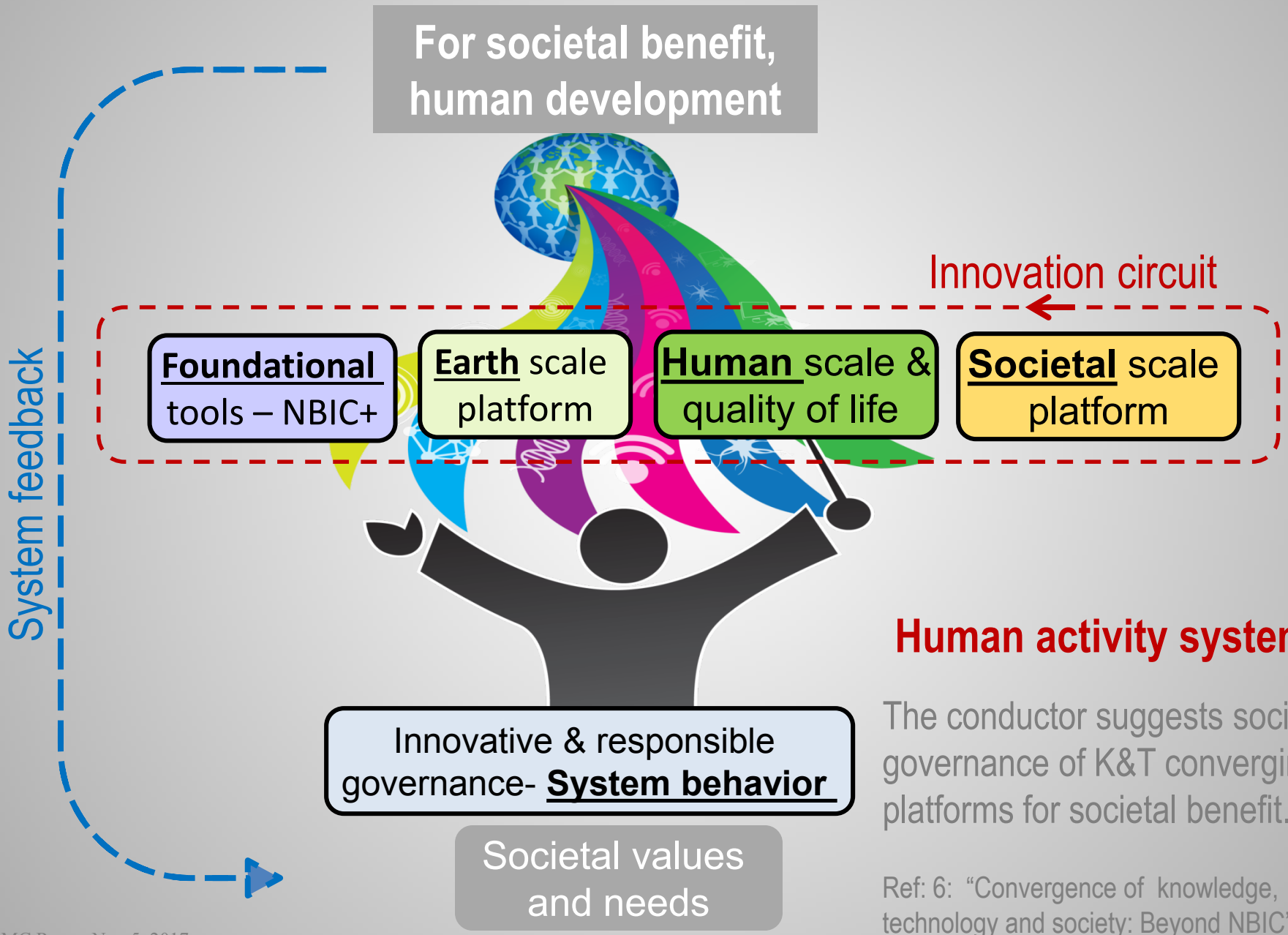
Nature (2002): 'Too visionary'

"**Direct brain-to-brain communication and the transfer of minds between bodies seem more like the stuff of Hollywood movies than of government reports** — but these are among the advances forecast in a recent report by the US National Science Foundation and Department of Commerce."

"Improving human performance has been a dream for centuries," says Mihail Roco, chairman of the government-funded NNI, and lead author of the study. … the report — ***Converging Technologies for Improving Human Performance***, — says that the **convergence of nanotechnology, biotechnology, computer science and cognitive science** may help to break those limits **in the next 20 years**."

NATURE|VOL 418 | 25 JULY 2002 |www.nature.com/nature

III. Convergence of Knowledge, Technology and Society



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

OSTP

Convergence of Knowledge and Technology (CKTS) leads to

III. U.S. global society-oriented initiatives

SunShot GC (DOE..)

Climate Action Plan

Strategy for Arctic Region

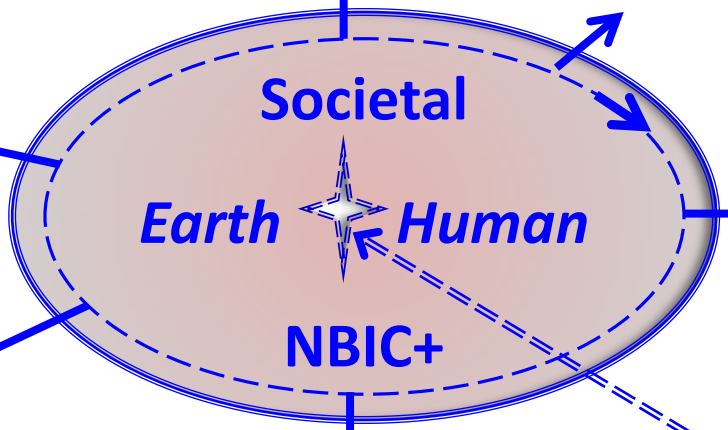
Smart and Connected Communities

I-Corps

Innovation

Aging Population

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



STEAM Education Initiative (NSF, DoEd)

Asteroid GC (NASA..)

Space Station (NASA..)

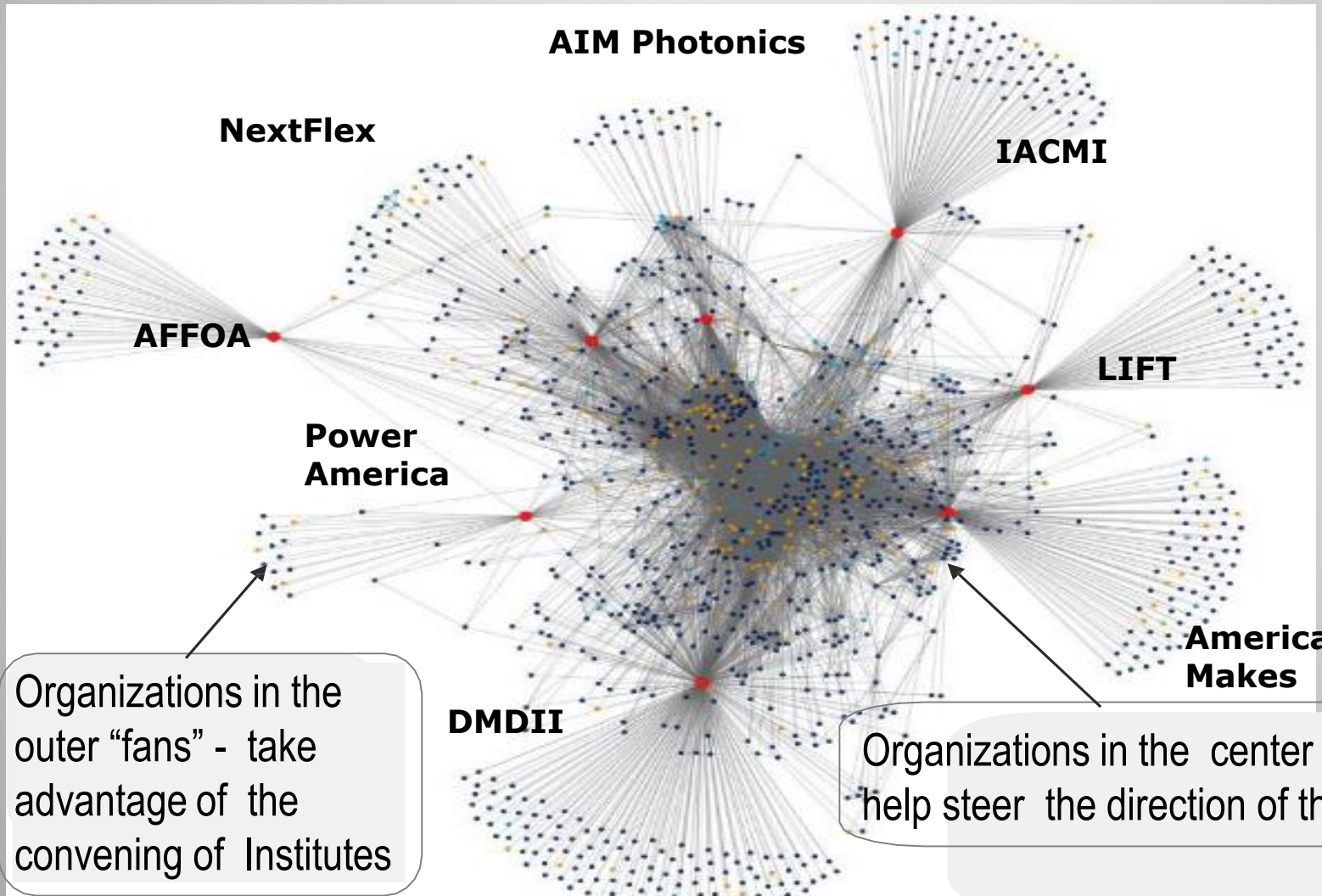
Productivity, Sustainability, Equality, Safe

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

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

Ex III: 14 Manufacturing USA Institutes

Deloitte report (2017): The Power of Connections is a Key Advantage



Addressing the "valley of death" **~ 1,200 core organizations** in an inter-industry Network comprised of **> 9,000 organization** networked/ coordinated

Organizations in the outer "fans" - take advantage of the convening of Institutes

Organizations in the center of the network - help steer the direction of the network.

III. Global Society: Examples of initiatives in 2016

Spin-offs enabled by CKTS (in U.S.)

- **Global Change: Clean Energy**
- **The National Network for Manufacturing Innovation**
- **STEAM Education**
- **Smart and Connected Communities**

In CKTS core system

- Origin of Universe and Earth evolution
- Societal sustainability and stability
- Convergence for production and wellness
- Morality aspects (conflict resolution, inequalities, safety)

Defining convergence for research and education at NSF

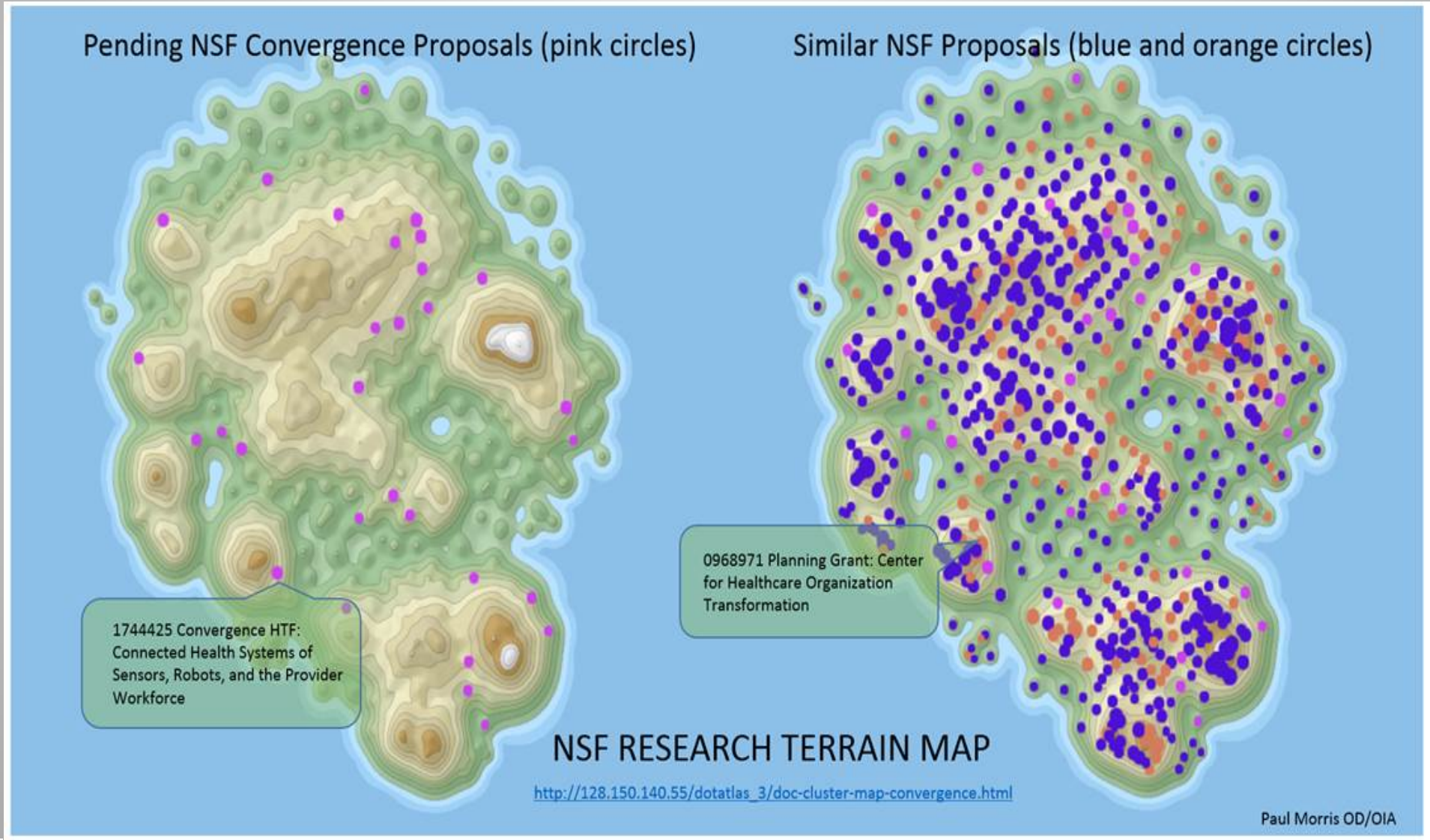
Convergence characterization in research and education (at NSF, 2017)

***Convergence is the deep integration of knowledge, techniques, and expertise to form new and expanded frameworks for addressing scientific and societal challenges and opportunities, with* two primary characteristics:**

1. ***Deep integration across disciplines****, from which new* frameworks, paradigms or disciplines can form from sustained interactions across multiple communities.
2. ***Driven by a specific and compelling challenge or opportunity***, whether it arises from deep scientific questions or pressing societal needs.

www.nsf.gov/od/oia/convergence/index.jsp

Convergence award topics “in the valleys” between traditional topics



Convergence-Divergence process (**upstream**): **Germination:** Germination of Research Ideas for Large Opportunities and Critical Societal Needs

- To design learning frameworks, platforms, and/or environments to enable participants to conceive research ideas and questions with potentially transformative outcomes
- NSF 16-028 Dear Colleague Letter: Sought EAGER proposals with exploratory ideas to design learning frameworks, platforms, and/or environments

Convergence-Divergence process (**downstream**):
Innovation Corps (I-Corps™)

- Provides experiential entrepreneurial education to capitalize on NSF investments in basic research
- Supports I-Corps™ Teams, Sites, and Nodes to build, utilize, and sustain a national innovation ecosystem
- Plans approximately 230 new I-Corps™ Teams, up to 71 active Sites, and up to 9 active Nodes in FY 2017
- Scaling via partnerships and networks: Federal agencies, states, private sector; and National Innovation Network

Innovations for Food, Energy, and Water Systems

- Quantitative and computational modeling
- Real-time, cyber-enabled interfaces
- Innovative solutions to critical FEW problems
- Workforce and education

Illustration credit: Nicolle R. Fuller, Sayo-Art LLC

NSF Advisory Committee on Environmental Research and Education

NSF Ad-Com (2017): Convergence can be characterized as

- Bringing an **end-to-end approach to problem solving**, from the most basic understanding to the science that underpins treatments and solutions. It thus encompasses what has become known as solution science in the sustainability literature

- The **transformative effect** that the transfer of tools, methods, theory, and understanding from one field to another can have,

- Often associated with developing the **science needed to address large, complex, and critical social issues. I**t integrate team science, deep interdisciplinary approach and ecological psychology

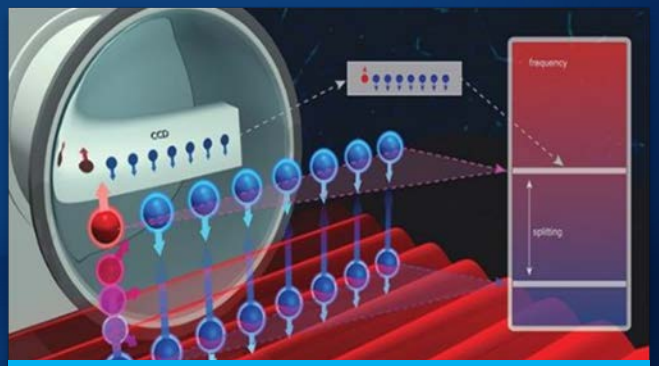
10 BiG IDEAS
- Pushing the Boundaries of Knowledge (3)



Windows on the Universe: The Era of Multi-messenger Astrophysics

Understanding the Rules of Life: Predicting Phenotype

NSE



The Quantum Leap: Leading the Next Quantum Revolution

NSE

10 BIG IDEAS
- Seizing New Opportunities (3)

Harnessing Data for 21st Century Science and Engineering

NSE

Navigating the New Arctic

Work at the Human-Technology Frontier: Shaping the Future

NSE

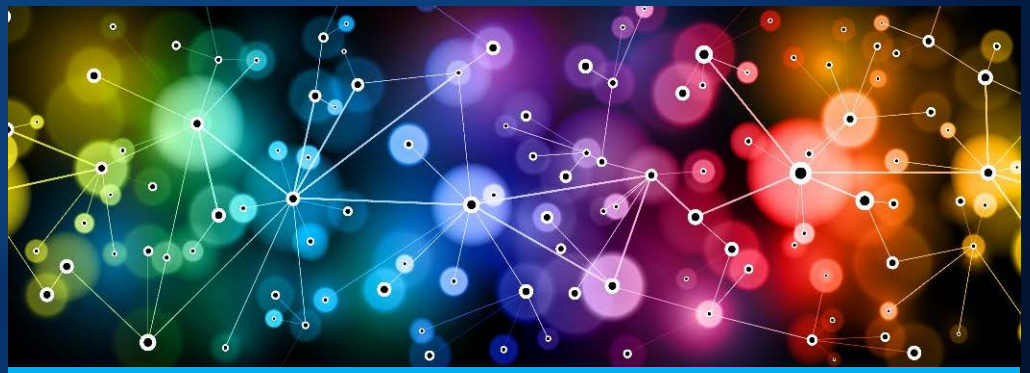
10 BIG IDEAS

- Identifying and Closing Gaps (4) NSE

NSF INCLUDES

NSF 2026

Mid-scale Research Infrastructure



Growing Convergent Research at NSF

NSF's Global Presence
(sustainability well represented)

Global action possibilities for convergence

- **International Grand Challenges: Nano, Brain, others**
- **An international convergence CKTS network**
- **Government coordination needed**: *"science of convergence", "convergence technology platforms", "collaborative culture"*
- **Production- , cognition-, biomedicine- current convergence**
- **Cross-domain programs** in universities & funding agencies
- Principles of convergence & **culture for conflict resolution**
- **OECD new committee on convergence** created in 2014

Several sustainability challenges

- Are **renewable** water/energy/food/materials sources **sufficient**?
- **Thermonuclear energy** will be controlled, economically used?
- **New technology convergence platforms** will be sustainable?
- How "smart systems" (incl. AI, NBIC) will change sustainability
- **DNA control** and hybrid nanobiodevices will have safe regulations and suitable organizations? Life security.
- **International collaboration and competition**: NBIC production (OECD), US-EU collaboration, databases, labeling
- Societal sustainability is the **overarching criterion**

Others topics to be discussed in the following SNO Panels

Selected publications for nano and convergence

(5 reports with R&D recommendations for 2020)

1. ***"Coherence and Divergence of Megatrends in Science and Engineering"*** *(Roco, JNR, 2002)*
2. ***"Nanotechnology: Convergence with Modern Biology and Medicine",*** *(Roco, Current Opinion in Biotechnology, 2003)*
3. ***NANO1: "Nanotechnology research directions: Vision for the next decade"*** *(Roco, Williams & Alivisatos, WH, 1999, also Springer, 316p, 2000)*
4. ***NANO 2020: "Nanotechnology research directions for societal needs in 2020"*** *(Roco, Mirkin & Hersam, Springer, 690p, 2011a)*
5. ***NBIC: "Converging technologies for improving human performance: nano-bio-info-cognition"*** *(Roco & Bainbridge, Springer, 468p, 2003)*
6. ***CKTS 2030: "Convergence of knowledge, technology and society: Beyond NBIC"*** *(Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)*
7. ***The new world of discovery, invention, and innovation: convergence of knowledge, technology and society"*** (Roco & Bainbridge, JNR 2013a, 15)
8. ***"Principles and methods that facilitate convergence"*** *(Roco, Springer Reference, Handbook of Science and Technology Convergence, 2015)*
9. ***HSTC: "Handbook of Science and Technology Convergence"*** *(Bainbridge & Roco, 2016)*