Nanotechnology and Information Technology Convergence

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

US-Korea NanoForum, September 11-12, 2017

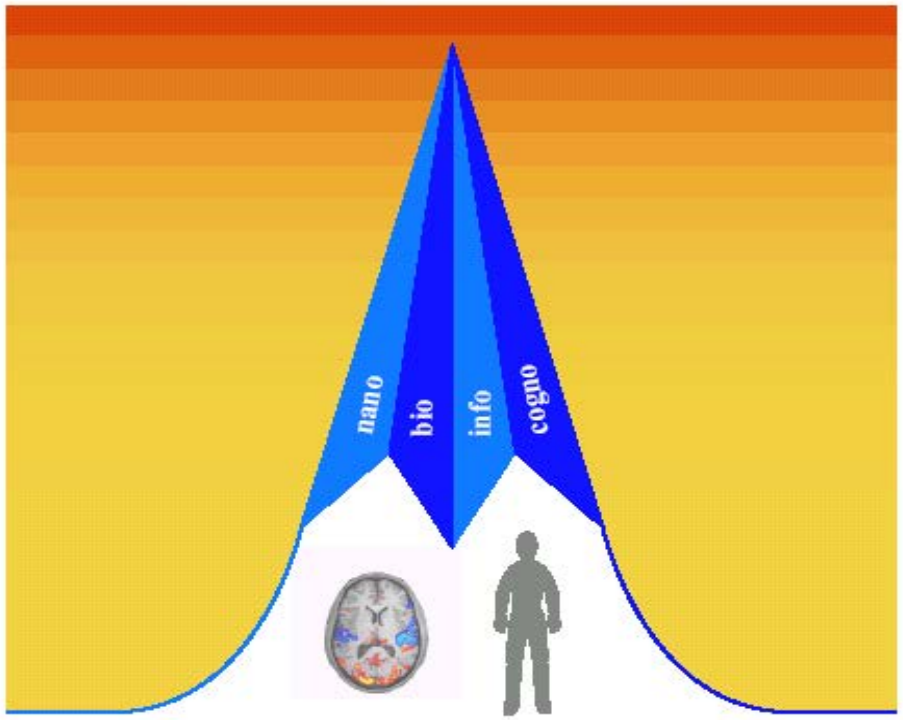
Convergence is a core opportunity for progress, and NT-IT convergence already has confirmed it

- ✓ Defining convergence
  - in science, technology and innovation
  - basic concepts: theory, principles and methods
- ✓ NT & IT convergence
- ✓ NSF programs at NT & IT convergence

Earlier studies on technology convergence

Seven reports on convergence

2003, 2006 and 2007 Springer; 2004 NYAS; NSF 2004; 2013 (world view), 2016 (handbook)



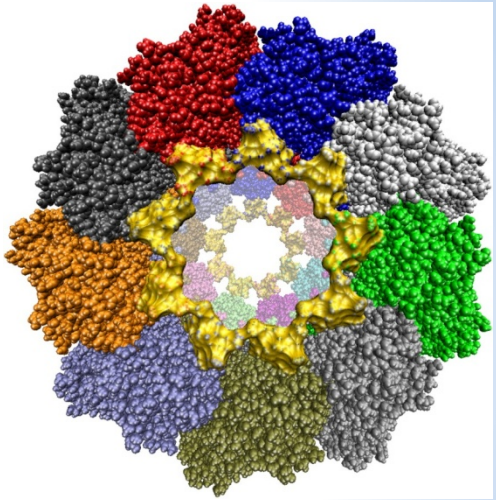
CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

Workshop, Dec. 2001
Volume Springer, 2003

Ref. 5

Coevolution of Human Potential and Converging New Technologies

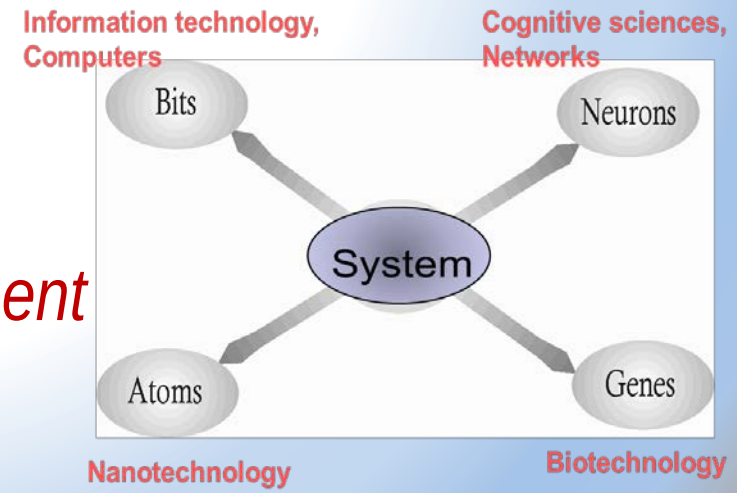


In: Annals of the New York, Academy of Sciences, Vol. 1013, 2004

(M.C. Roco and C. Montemagno)

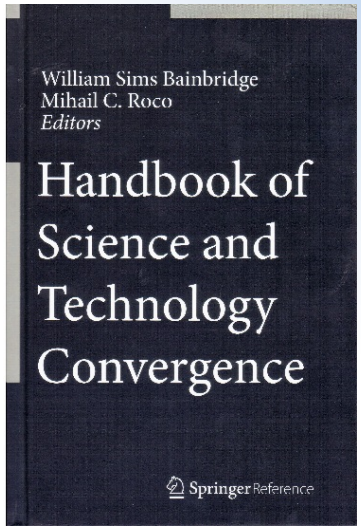
Twelve challenging ideas from 2001 NBIC Report that are reality or in development in 2017

- 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*



Several U.S. activities related to convergence

- NSF reports for S&T *(2001-2016)*
- Programs at US agencies : NSF Big Ideas, DARPA, EPA, NIH, AFOSR
- Academy study: Convergence - Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond (*2014*)
- *MIT-Harvard convergence for health (Biomed & S&E;2016)*
- *NSF priority areas: human-technology frontiers, microbiome, BRAIN, quantum computing systems, citizens science, longitudinal "science of education", convergence in governance of S&T*



Defining convergence

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 unified 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 new pathways, opportunities and frontiers – in competencies, knowledge, technologies and applications *(divergence stage)*

Convergence science – Creating or changing the unified ecosystem based on *10 theories, 6 convergence principles, and specific methods*

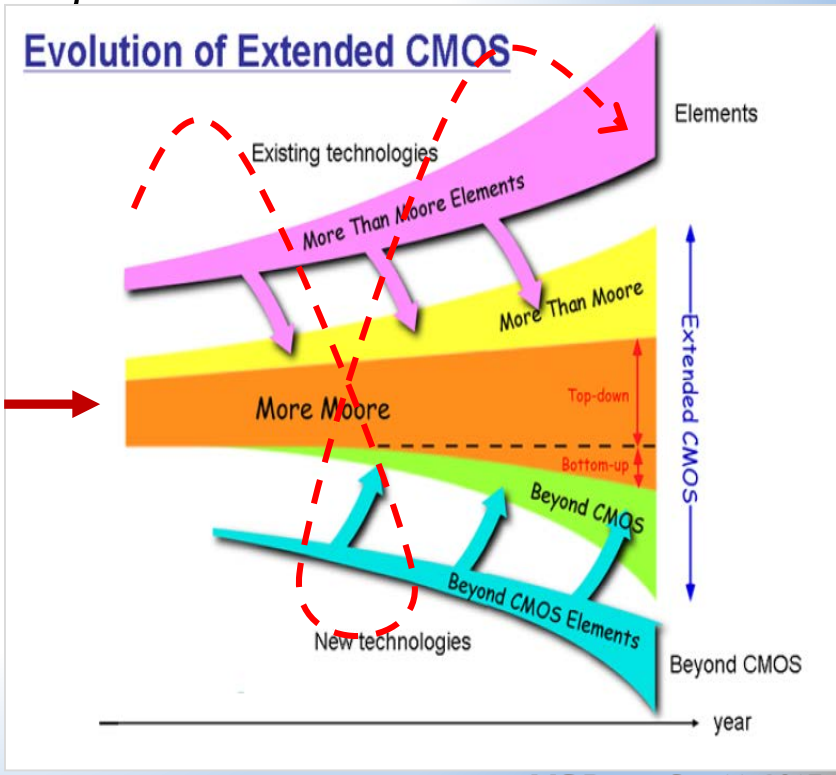
2. The convergence process

(Ref 6: CKTS, Springer, 2013)

Convergence process is the escalating and transformative interaction of seemingly different disciplines, technologies, application domains, and communities

(it is a dynamic process)

- to achieve their mutual compatibility, synergism and integration,
- and through this process to *create added-value* and *branch out* for shared goals *(driven by the convergence driver)*



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

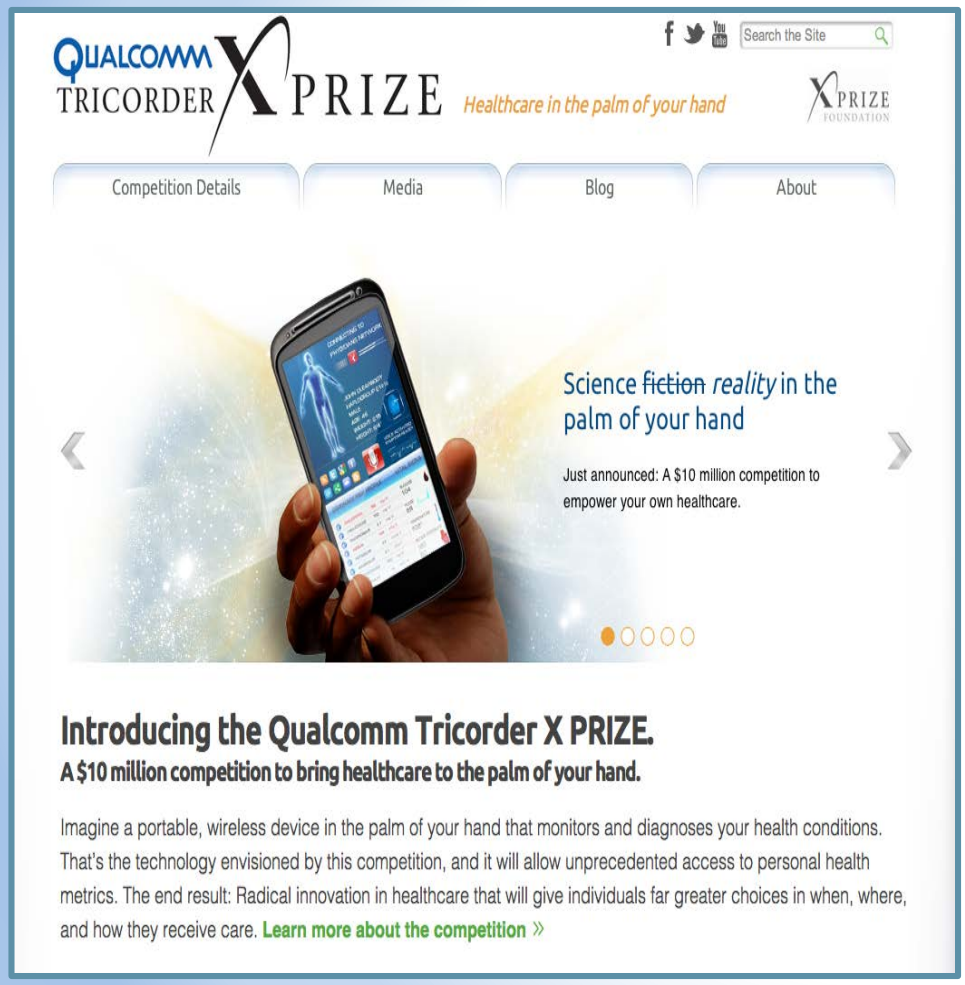
E. Confluence of resources leading to system changes (S curve)

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

PRINCIPLES FOR CONVERGENCE

Refs. 8 and 9

Example convergence-divergence opportunities: cellular phone



Example: http://www.qualcommtricorderxprize.org

Coincidental convergence:

- **Creative phase**: Confluence energy, environment, cognition, security, electronics, personalized learning, healthcare.

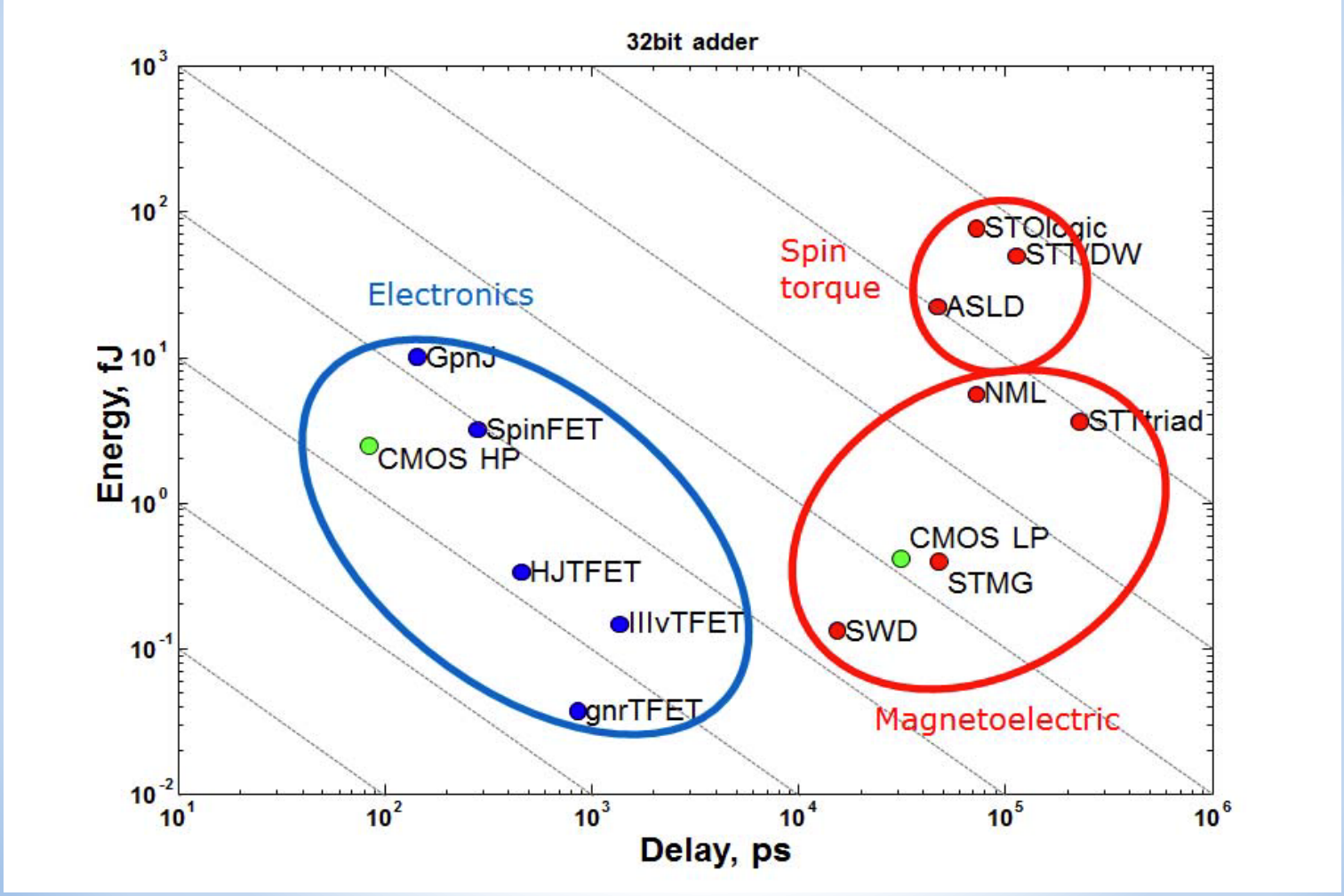
- **Integration phase**: Including high-frequency communications and switching protocols; data storage, touch screens, antennas, cognitive science and others

- **Innovation phase**: Smart phone and its platform, form groups

- **Outcomes, spin-off phase**: Social networks, controlling swarms, inexpensive miniaturized satellites, healthcare and many other examples

Example higher level multi domain languages:

Universal characteristics for performance benchmarking of semiconductors: *Energy – Delay*



Nanoelectronics Research Initiative, 2013; Nikonov and Young, Proc. IEDM, Dec. 2012

- Applications -

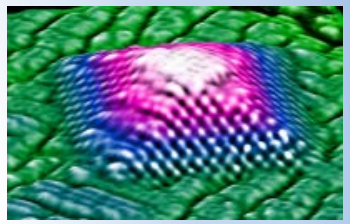
Three implemented stages
of Science/Technology/Innovation Convergence

Three stages of convergence
applied to general-purpose technologies

(Ref 6: CKTS, Springer, 2013)

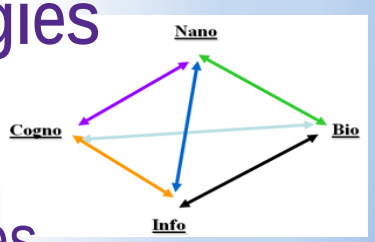
I. Nanoscale Science, Engineering and Technology
"Nanotechnology"

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

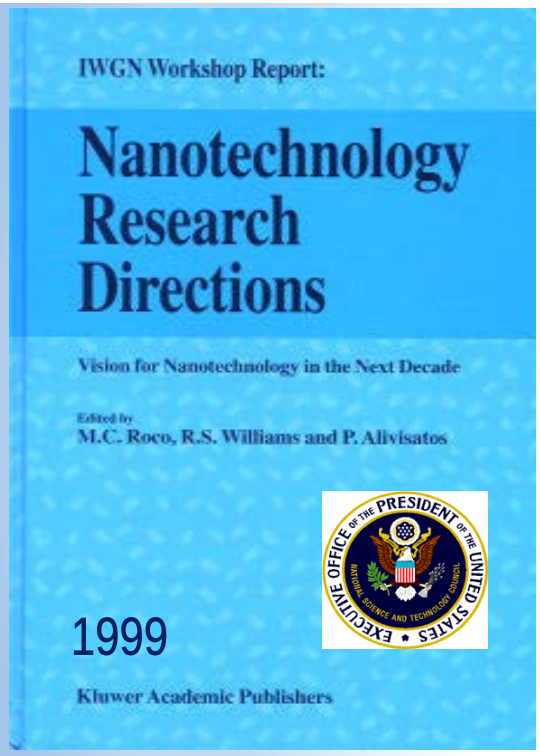


III. Convergence of Knowledge, Technology and Society
"CKTS"

Integrates the essential platforms of human activity using five convergence principles

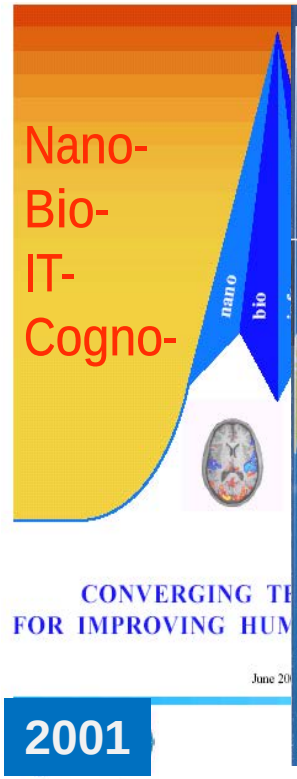
Nanotechnology: from scientific curiosity to immersion in NBIC & CKTS socioeconomic projects

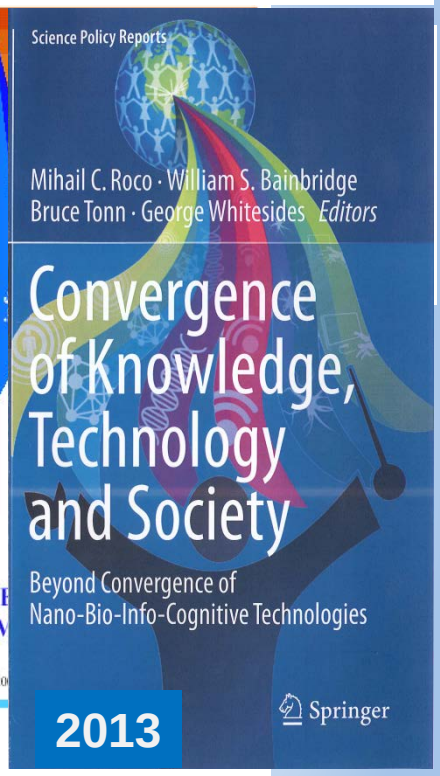
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1 & 2 (2011-2030)

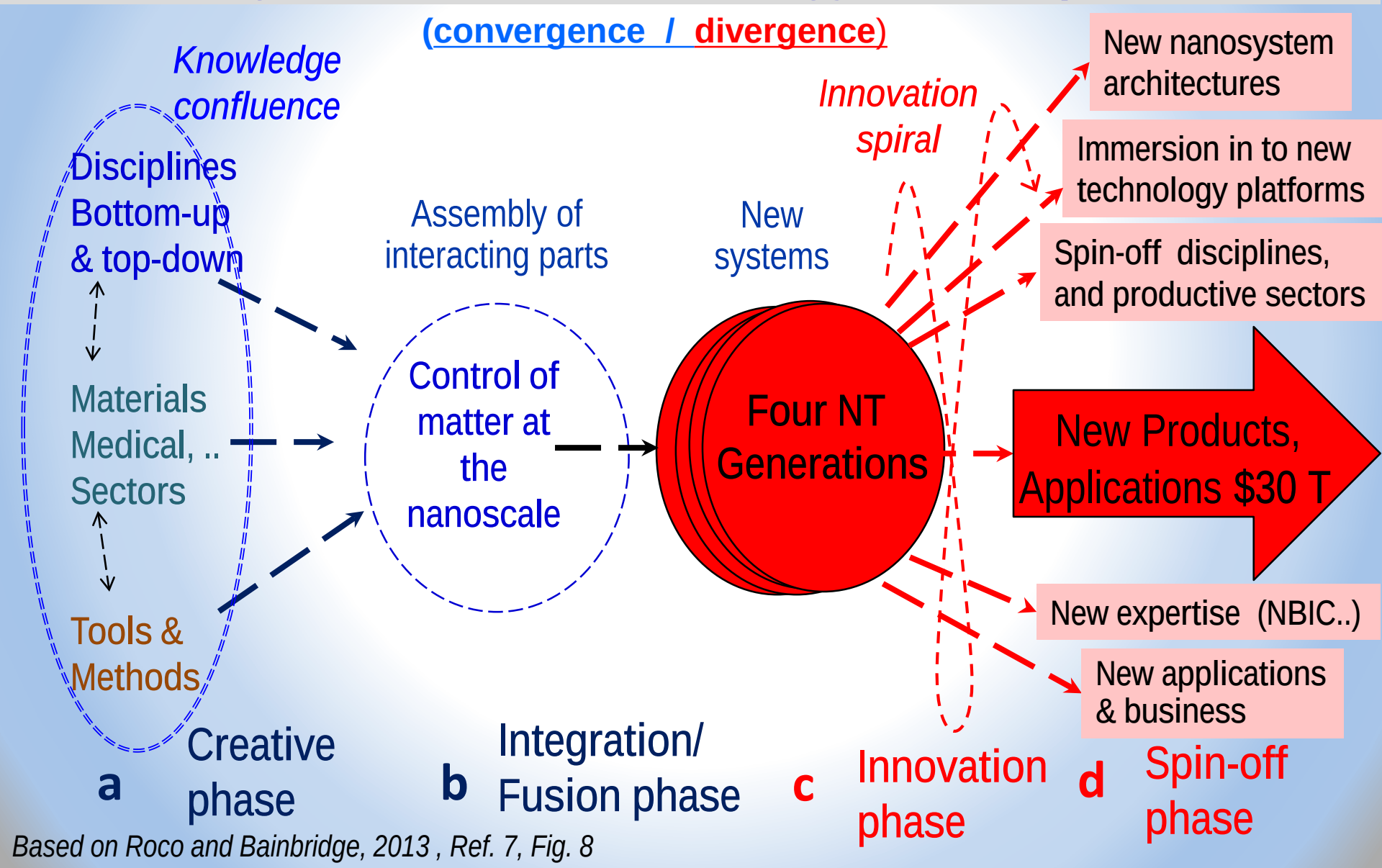




30 year vision to establish nanotechnology and convergence:
In 3 stages changing focus and priorities

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

I. 2000-2030 Convergence-Divergence cycle for global nanotechnology development



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

I. Nanotechnology programs: S&T divergence

OSTP

DOC/NIST

NASA

HHS/CDC/
NIOSH

DOS

DOTr

DOT

IC/DNI

DOJ

DOC/EDA

DOC/BIS

DHS

CPSC

ITC

DOEd

DOL

DOC/
USPTO

DOI/
USGS

NRC

EPA

USDA/FS

USDA/NIFA
USDA/ARS

HHS/FDA

DOD

NSF

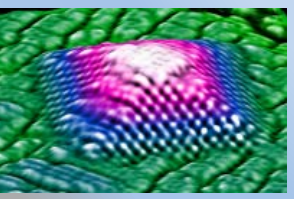
OMB

OSTP

HHS/NIH

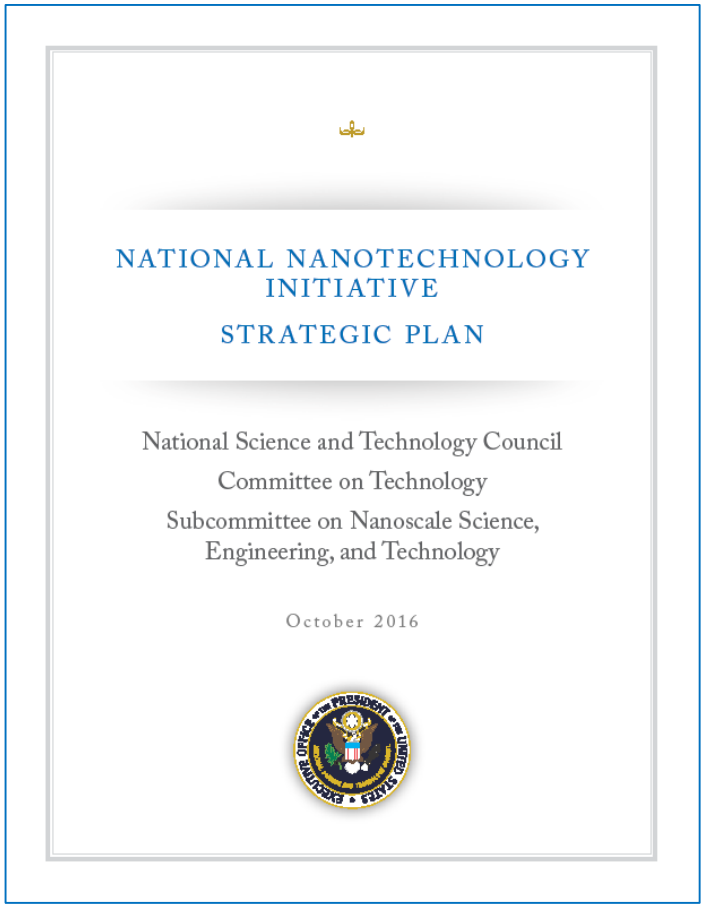
DOE

Control of matter at the nanoscale



U.S. National Nanotechnology Initiative, 2000-2030

I. National Nanotechnology Initiative in 2017-2018


NATIONAL NANOTECHNOLOGY INITIATIVE

STRATEGIC PLAN

National Science and Technology Council

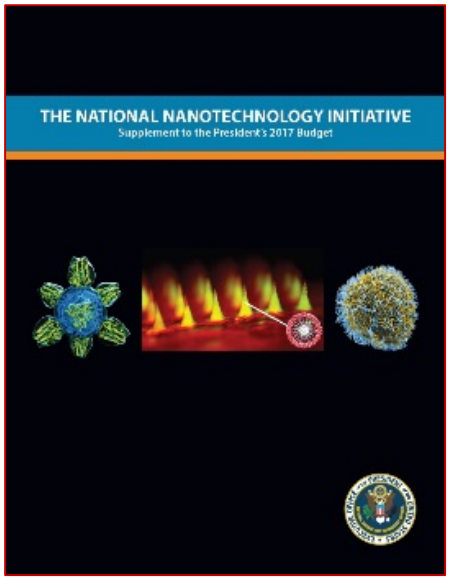
Committee on Technology

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 (& 2018) 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 (2016-)

- Applications -

Nanotechnology and IT Convergence

Converging foundational technologies (NBIC) leads *to*

II. U.S. emerging S&T initiatives

OSTP

Brain–like Computing; Smart systems

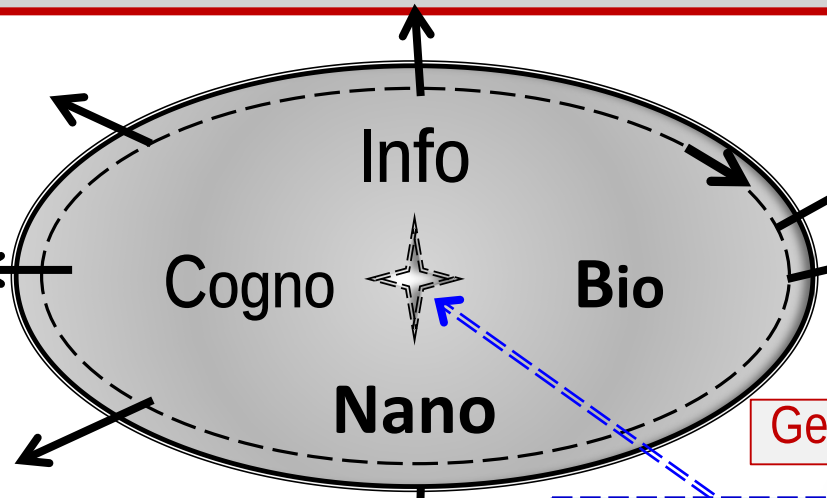
Big Data | National Strategic Computing Initiative

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

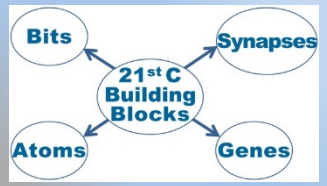
Precision Med

Genome(s) | Microbiome

Architecture, Life, Human-technology

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

Materials Genome | Photonics | NNI Grand Challenges

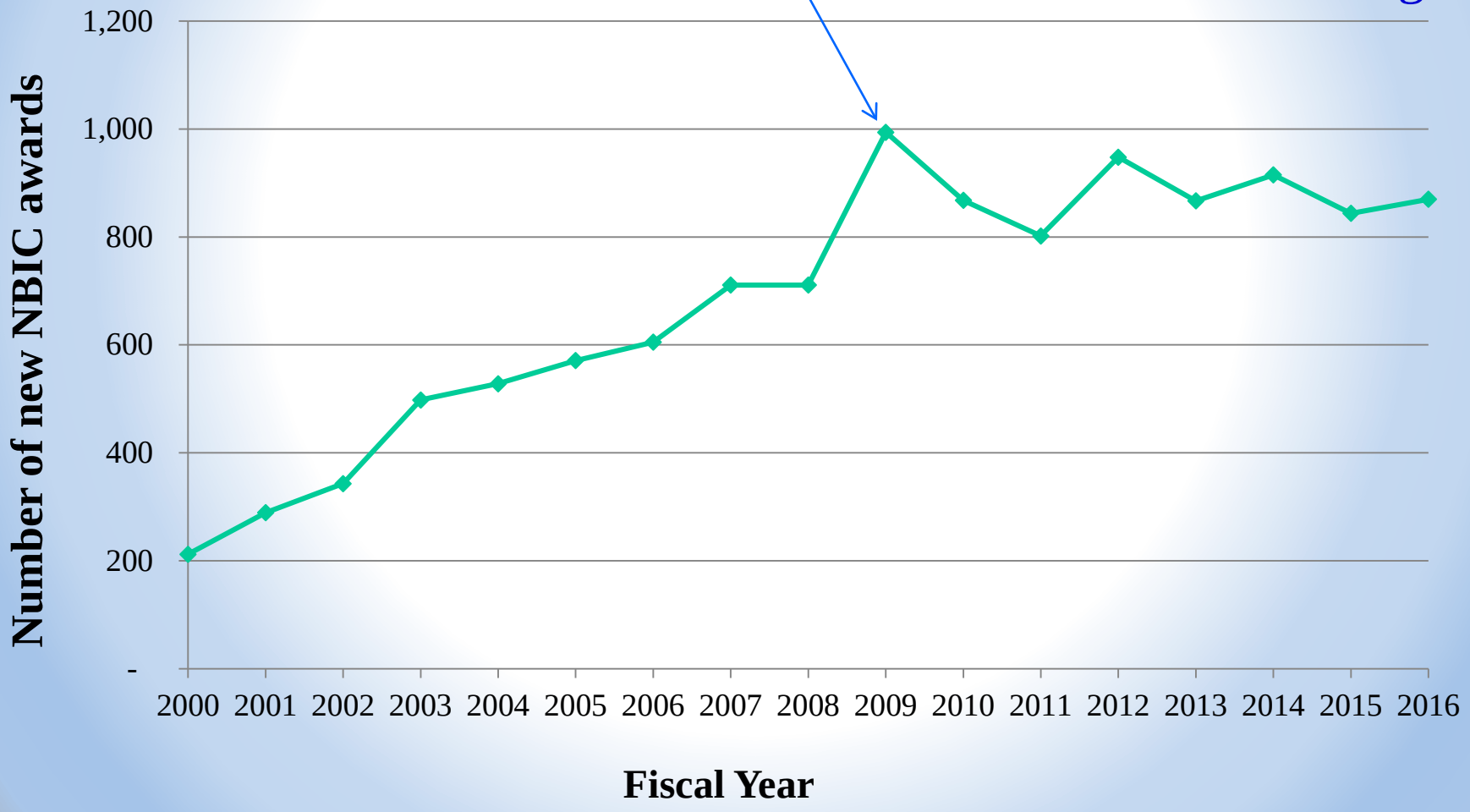


Ref 9: Roco, "NBIC", in Handbook of S&T Convergence, 2015

Number of NBIC Awards at NSF (2000-2016)

Search by combined keywords

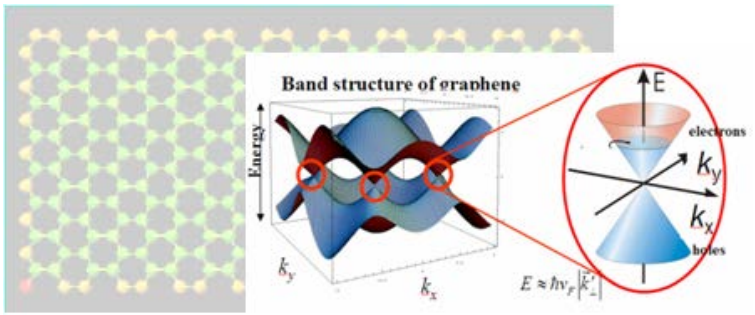
Since 2009, about 5% of total NSF new awards on NBIC;
of which about 1/10 of these focused on NT-IT convergence



NNI Signature Initiative:
Nanoelectronics for 2020 and Beyond

Agencies involved:
DOD, DOE, IC/DNI, NASA, NIST, NSF

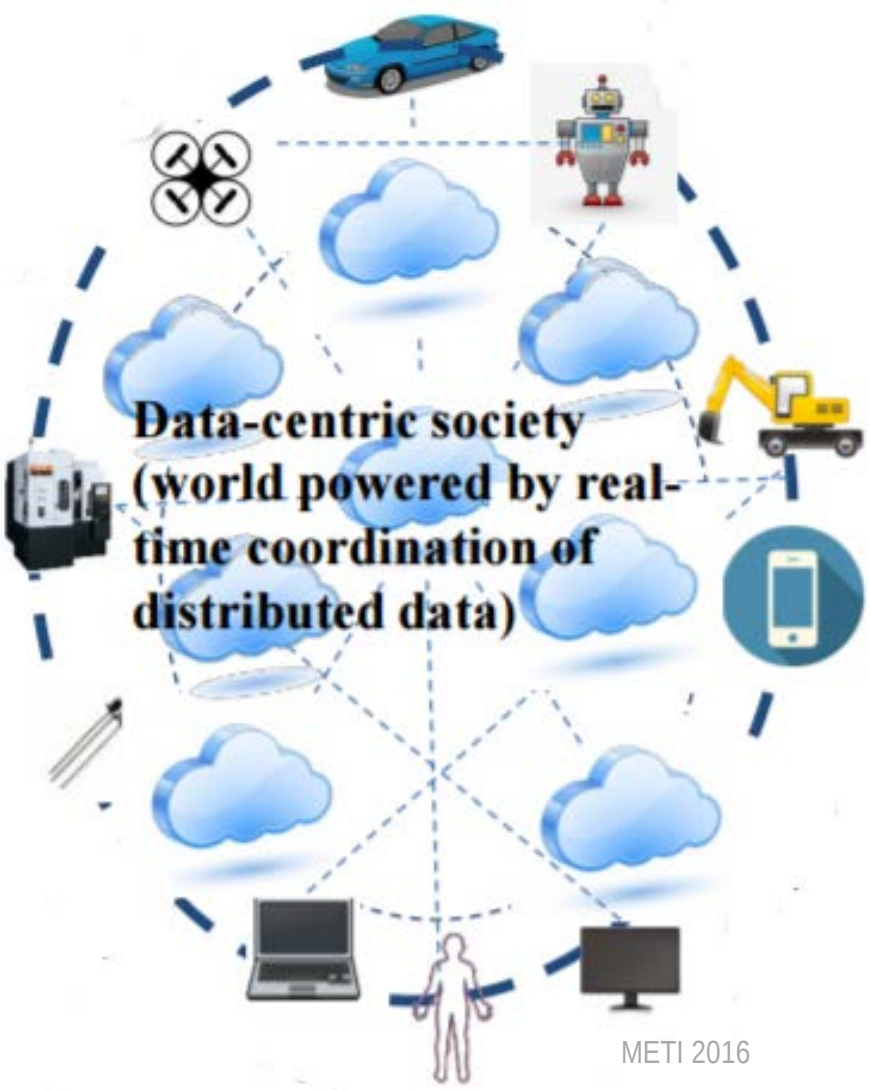
Goal: Accelerate the discovery and use of novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures to advance the field of nanoelectronics.



Thrust areas:

- Exploring new or alternative “state variables” for computing
- Merging nanophotonics with nanoelectronics
- Exploring carbon-based nanoelectronics
- Exploiting nanoscale processes and phenomena for quantum information science
- Expanding the national nanoelectronics research and manufacturing infrastructure network (university-based infrastructure)

IoT with Nanosensors: IoNT



Nanotechnology for Sensors

www.nano.gov/SensorsNSIPortal

Goals:

1 nm sensors selfpowered

Wireless connections

Distributed network

NSF program announcements

- **ACQUIRE:** Advancing Communication Quantum Information Research In Engineering

- **NewLAW:** New Light, EM (Electronic) and Acoustic Wave Propagation: Breaking Reciprocity and Time- Reversal Symmetry

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

- Invests in radical new approaches – from new devices architectures to hybrid digital-analog designs
- Partnership between NSF (ENG and CISE) and Semiconductor Research Corporation (SRC)

Examples: 2D Electrostrictive FETs for Ultra-Low Power Circuits and Architectures, A Fast 70 mV Transistor Technology for Ultra-Low-Energy Computing, Electronic-Photonic Integration Using the Transistor Laser for Energy-Efficient Computing, Energy Efficient Computing with Chip-Based Photonics, Energy Efficient Learning Machines, Self-Adaptive Reservoir Computing with Spiking Neurons: Learning Algorithms and Processor Architectures

Ex: Nanoelectronics Research Initiative, n-CORE

NIST
(co-funds NRI centers)

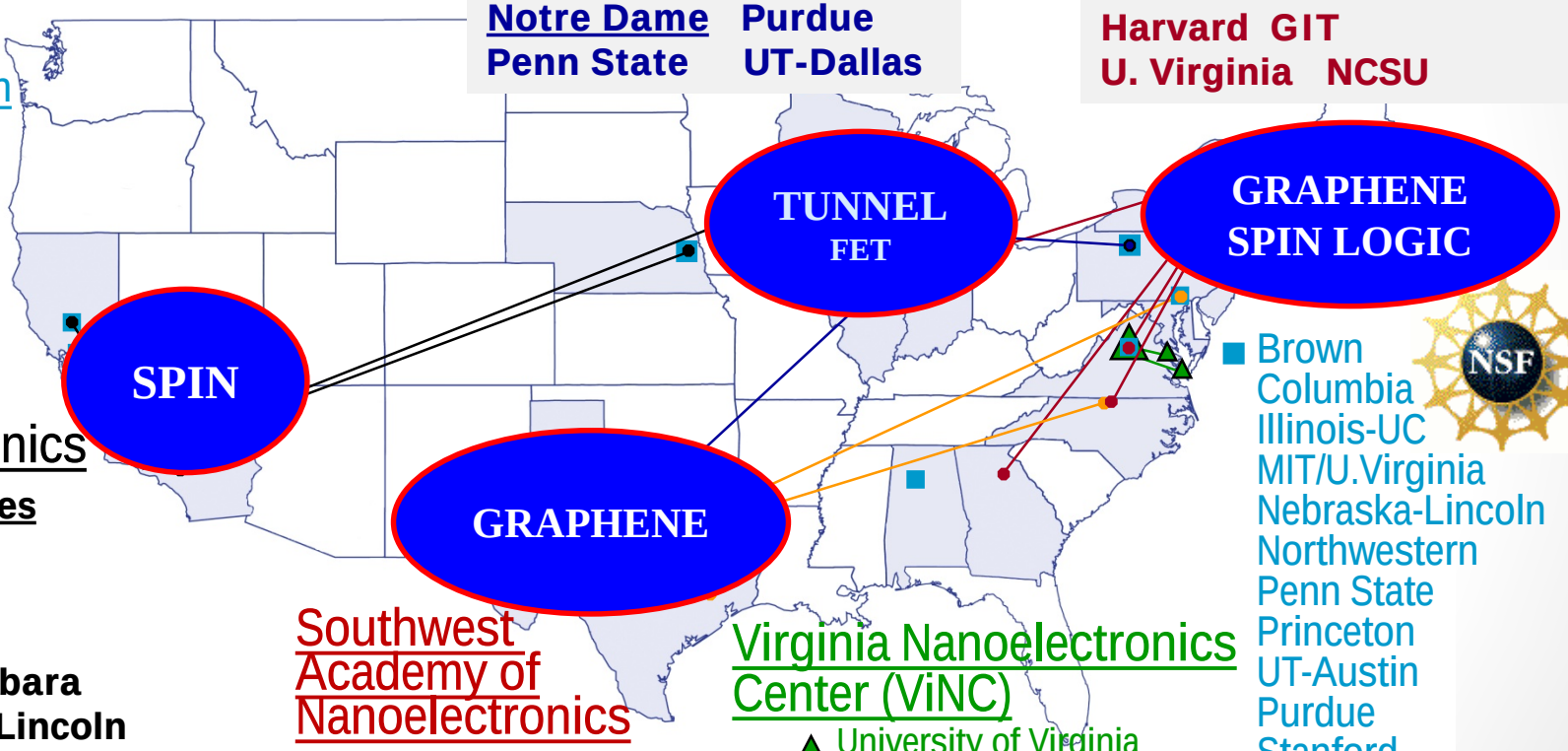
- Awards made In 2011- for collaborative group research (NNI Signature Initiative)

Midwest Institute for Nanoelectronics Discovery

Notre Dame **Purdue**
Penn State **UT-Dallas**

Institute for Nanoelectronics Discovery and Exploration

SUNY-Albany
Purdue MIT Columbia
Harvard GIT
U. Virginia NCSU



Western Institute of Nanoelectronics

UC Los Angeles
UC Berkeley
UC Irvine
UC Riverside
UC Santa Barbara
U. Nebraska-Lincoln
U. Wisconsin-Madison

Southwest Academy of Nanoelectronics

UT-Austin **Rice**
UT-Dallas **Texas A&M**
U. Maryland **NCSU**

Virginia Nanoelectronics Center (ViNC)

- University of Virginia
- Old Dominion University
- College of William & Mary

- Brown
- Columbia
- Illinois-UC
- MIT/U.Virginia
- Nebraska-Lincoln
- Northwestern
- Penn State
- Princeton
- UT-Austin
- Purdue
- Stanford
- U. Alabama
- UC Berkeley

2016: Partnerships NSF, NIST, SIA, SRC with > 30 Universities in 20 States

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):

Announcement: http://www.nano.gov/futurecomputing

ICA: Intelligent Cognitive Assistants,

(NSF, SRC & SIA, Oct. 2016)

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

"Brain like computing" (NNI Grand Challenge)

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

- 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."

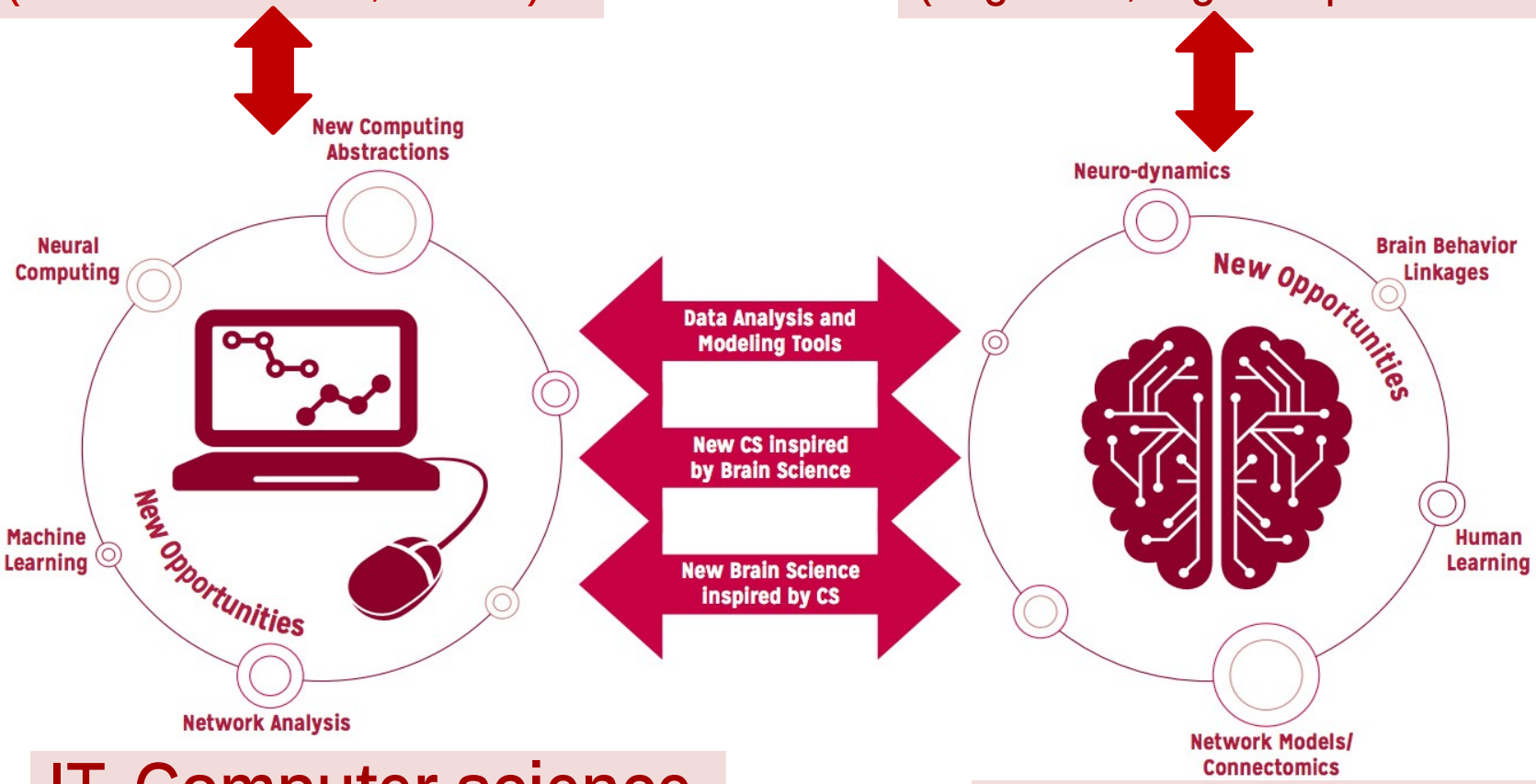
  Also: pattern recognition, human like simultaneous perception of information from various sources including the five senses,

Towards Brain – like Computing

Technology Convergence: Beyond "one-way" thinking

Nanotechnology
(create hardware, model)

Cognitive technologies
(cognition, logic requirements)



IT, Computer science
(create software)

Brain science
(core system, model)

Intelligent cognitive assistants (ICA)

2016 & 2017 workshops (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"
- Explore scenarios for developing the novel architectures, concepts and algorithms which will be required for "assistants" to energy-efficient perceive, compute, and interact, and in this way to provide actionable information and informed advice to their human users. Modular functions and architectures.
- Establish a long-term vision (10-20 years), from "knowledge and data" in 2015 to "intelligence and cognition" in 2030

NSF-SRC-IARPA solicitation NSF- 17-557 on

"Semiconductor Synthetic Biology for Information Processing and Storage Technologies (SemiSynBio)"

- The *exploratory research solicitation* is for $4M per year for three years:

  NSF- ENG (ECCS) $1M per year for three years

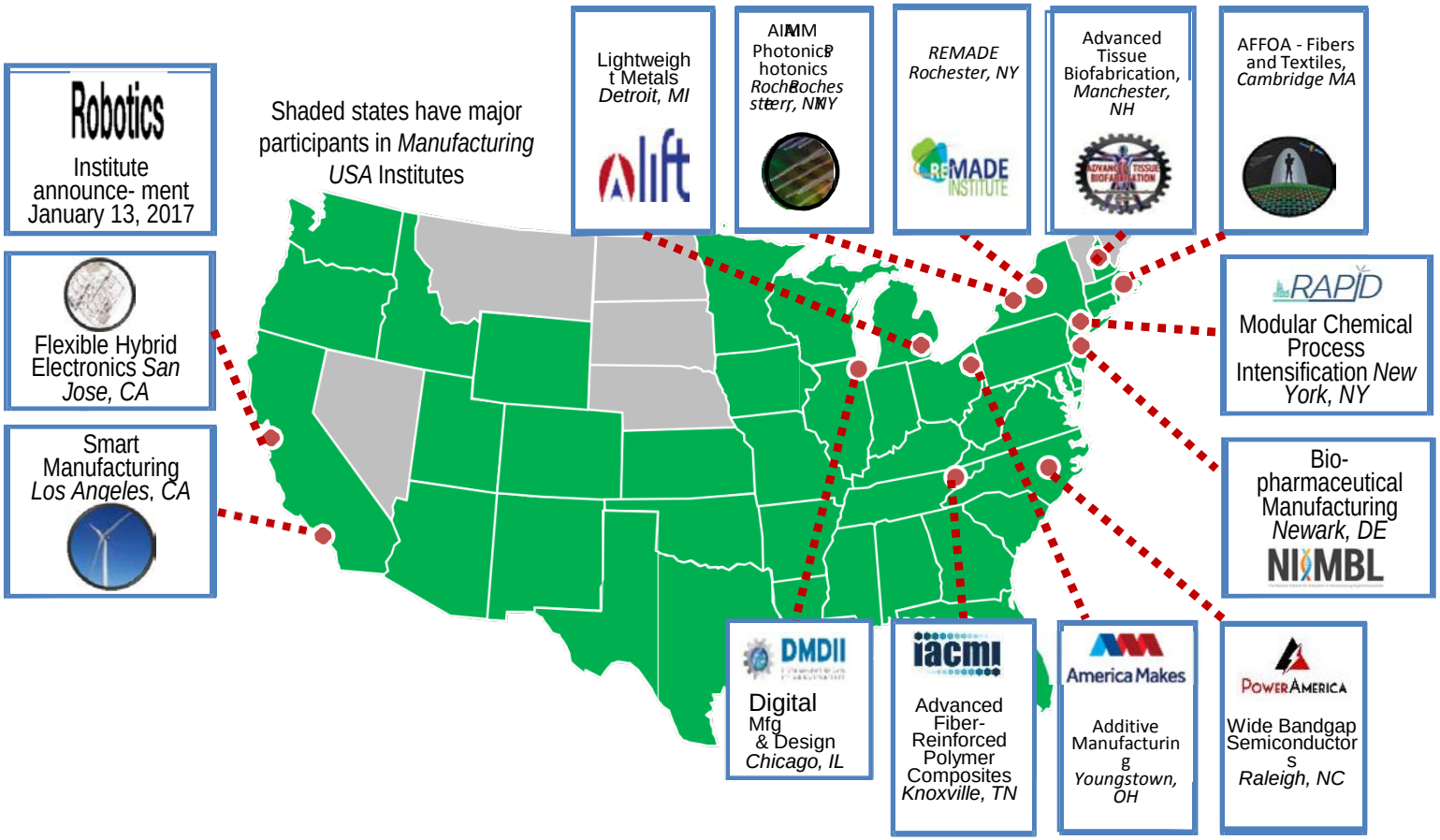
  NSF- CISE (CCF) $1M per year for three years

  NSF-BIO (MCB) $1M per year for three years

  SRC- $1M per year for three years
  IAPRA will fund proposals on individual basis

- Submission window is October 2, 2017 - October 30, 2017

Example: The National Network for Manufacturing Innovation (NNMI)



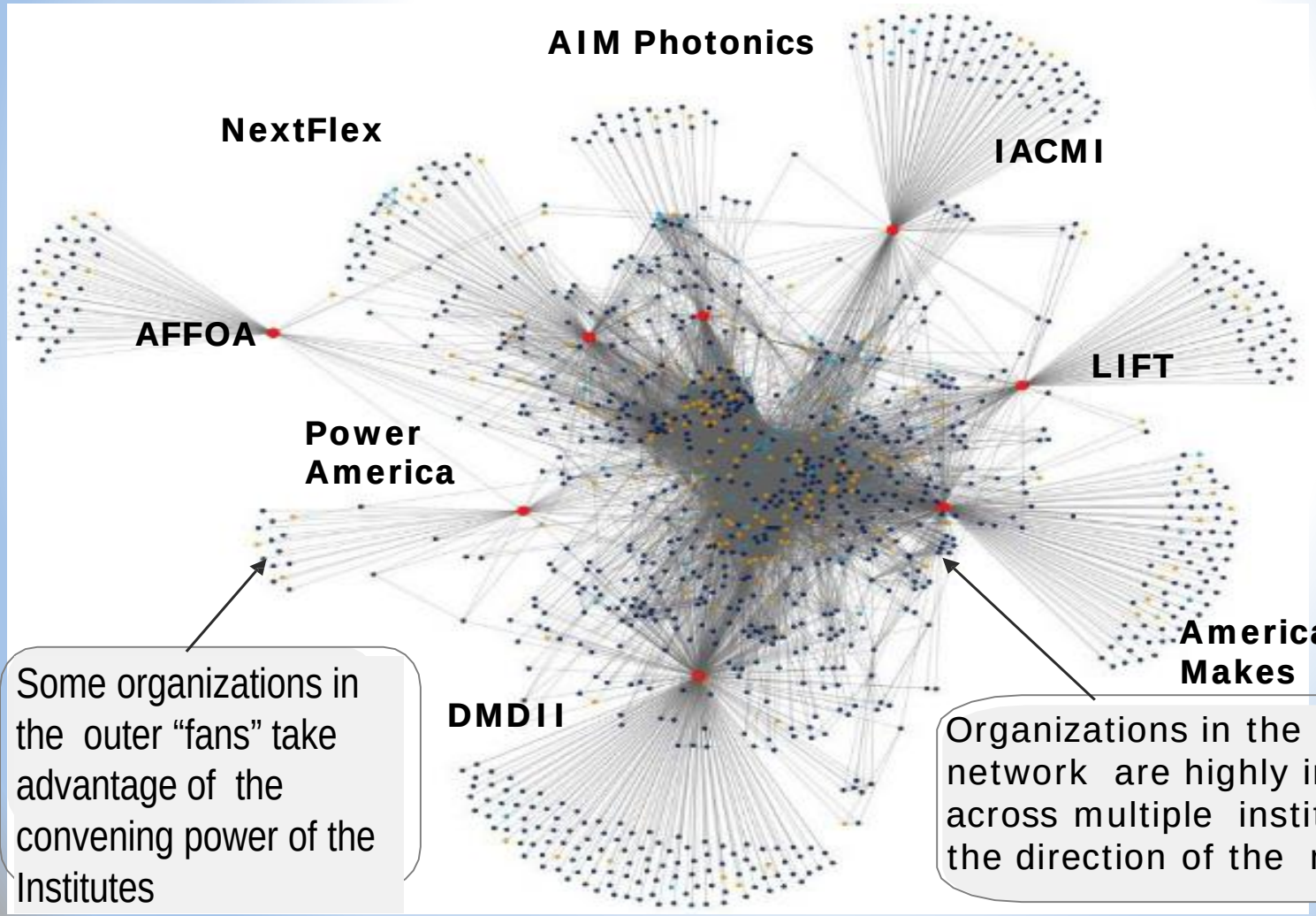
2017: A network of 14 translational manufacturing institutes

Example: Manufacturing USA Institutes

https://www.manufacturingusa.com/institutes

Deloitte assessment: The Power of Connections

https://www2.deloitte.com/us/en/pages/manufacturing/articles/manufacturing-usa-program-assessment.html



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

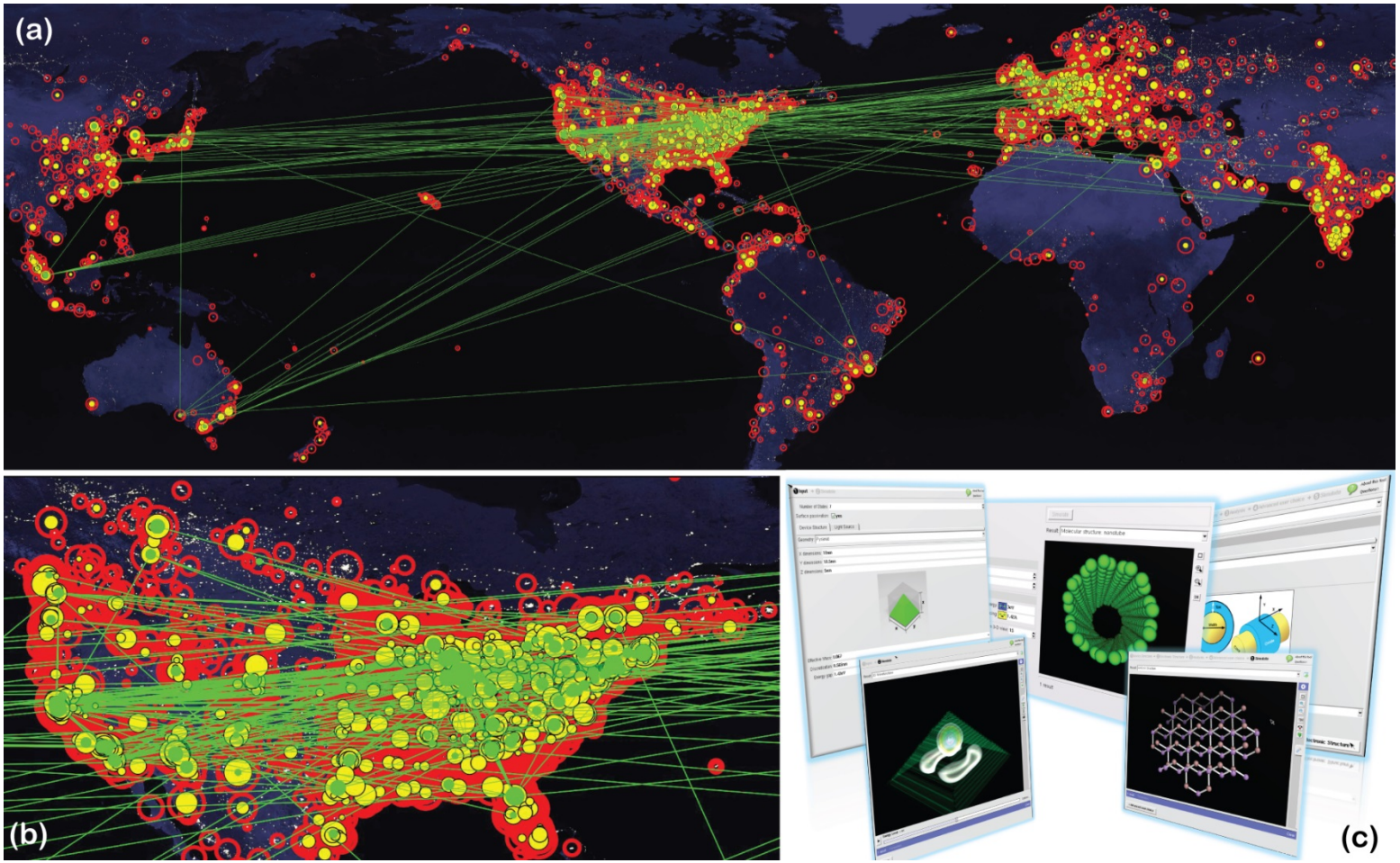
Some organizations in the outer "fans" take advantage of the convening power of the Institutes

Organizations in the center of the network are highly involved in projects across multiple institutes and help steer the direction of the network.

Example: U.S. Consortium for Advanced Manufacturing Foresights

- Result of the recommendations of the PCAST Advanced Manufacturing Partnership 2.0 Report
- Will “provide coordinated private-sector input on national advanced manufacturing technology R&D priorities.”
- Jointly NSF and NIST-funded (2016-)
- $1-2 million/year for 3 years, renewable

Example: Network for Computational Nanotechnology



nanoHUB usage in 2015: 172 countries

Over 3,00 authors collaborating

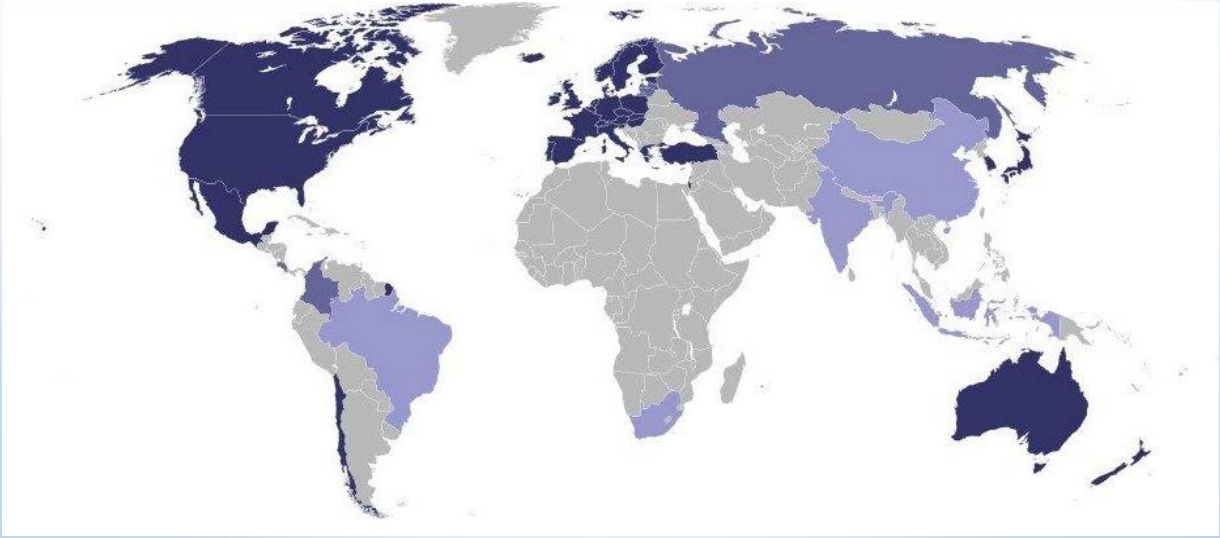
Over 13,000 users running interactive simulations

Over 1.4 million visitors using lectures and tutorials

OECD Working Party on
Bio-, Nano- and Converging Technologies (BNCT)

Examples of BNCT activities (2017-2018):

- Harnessing Converging Technologies for the Next Production Revolution
- Gene Editing in an International Context: Scientific, Economic and Social Issues across Sectors



2001-2017

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

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

FY 2017 Budget Request: **$415 M**

FYs 2016 actual ~ $510 M (including other core programs)

FYs 2000-2016: NSF total investment is ~ $35 per capita (US)

– Fundamental research

> 6,000 active projects in all NSF directorates

– Establishing the infrastructure

> 30 centers & networks, 2 general user facilities

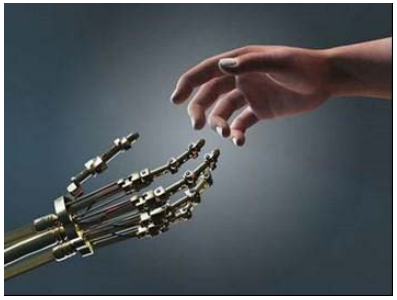
– Training and education

> 10,000 students and teachers/y; ~ $50M/y

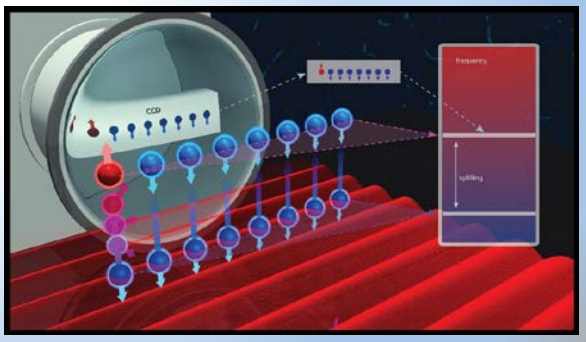
2016 NSF 10 Big Idea *(a. research)*

- **Understanding the Rules of Life: Predicting Phenotype**
- **Shaping the New Human-Technology Frontier**
- **Windows on the Universe: Era of Multi-messenger Astrophysics**






- **Navigating the New Arctic**
- **Data science**
- **The Quantum Leap**

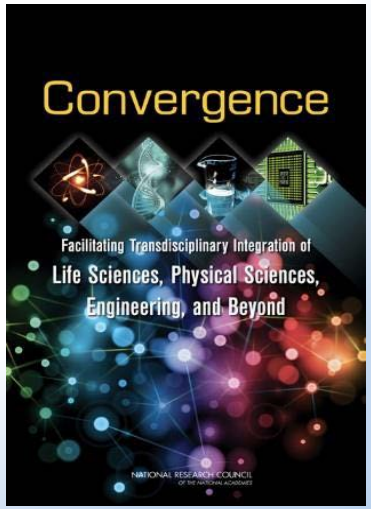
2016 NSF 10 Big Idea *(b. operation)*

- **INCLUDES: Enhancing Science & Engineering through Diversity**

- **Mid-scale Research Infrastructure**

- **NSF 2050: The Integrative Foundational Fund**

- **Growing Convergent Research at NSF**



Related publications

(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: "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. *"Science and technology convergence, with emphasis for nanotechnology-inspired convergence" (Bainbridge & Roco, JNR, 2016)*
10. *HSTC: "Handbook of Science and Technology Convergence" (Bainbridge & Roco, 2016)*

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- Exchange most recent scientific results and developments in each country in the selected NanoForum topics this year
- Explore trends and new research opportunities
- Develop partnerships between researchers from the two countries