Convergence of Nanoscale Science and Engineering

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

15th US-KOREA NanoForum, Seoul, July 12, 2018

Convergence is a core opportunity for progress

Contents

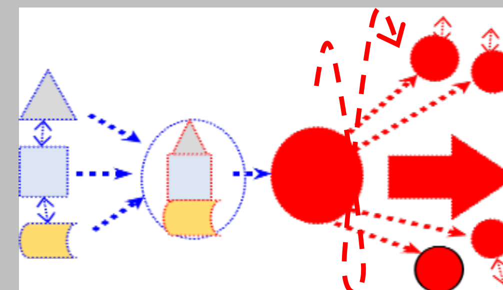
- <u>Three stages of science and technology convergence</u>
  - *Nanotechnology - global S&T challenge since 2000*
  - *Foundational emerging technologies (NBICA)*
  - *Global society oriented initiatives*
- <u>Several trends for the next decade (USA)</u>

Evolution in nature, science, technology, society is

- ***Turbulent***
- ***Coherent***
- ***Emergent***

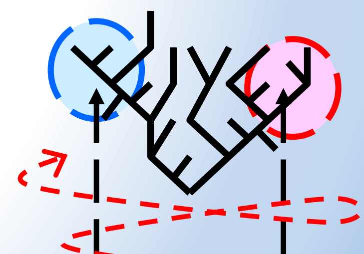
Research trends

(Ref. 1-5) Coherence cycle



Education trends

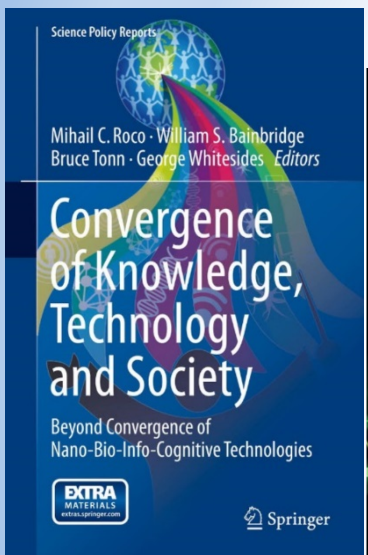
(Ref. 1-5) Ex: Trading zones



Examples of ecosystems
too complex for simple methods

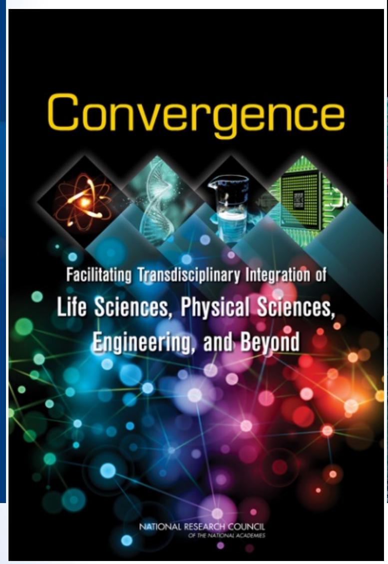
Convergence is a general strategy to holistically understand and transform a system for reaching a common goal *(Roco 2002)*

Recent Convergence Reports



International benchmarking

2013

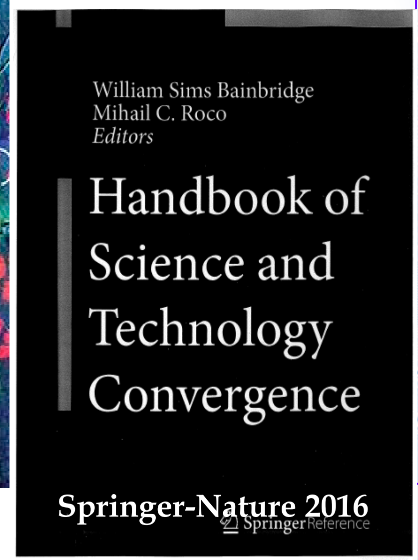


Life, physical and engng. sciences convergence

2014

Convergence of health

2016



Springer-Nature 2016

Convergence principles and methods

2016

Convergence engineering centers

2017

1. Defining S&T convergence

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

Convergence is:

- the deep integration of knowledge, tools, domains, and modes of thinking, driven by unifying concepts and common goal
- to form new frameworks, paradigms or ecosystems
- from where emerge novel pathways, opportunities & frontiers for problem solving and progress

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

(Ref 7-10)

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

A. Holistic - The interdependence in nature and society

B. Dynamic pattern - Processes of convergence and divergence

C. Unifying - System-logic deduction in decisions

D. Cross-domain - Higher-level languages

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

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

PRINCIPLES FOR CONVERGENCE

Ref. 8

Ref 7: Science and technology convergence, J Nanopart Res (2016) 18:211

- General purpose applications -

Three hierarchical stages of S, T & I *Convergence*

I Nanotechnology

II Foundational NBICA

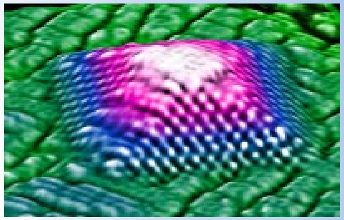
III Society ecosystem

Three stages of convergence

(Ref 6: CKTS, Springer, 2013)

I. Nanoscale Science, Engineering and Technology

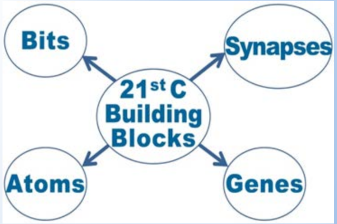
"Nanotechnology"



Integrates disciplines and knowledge of matter from the nanoscale

II. Nano-Bio-Info-Cognitive-AI Converging Technologies

"NBICA"



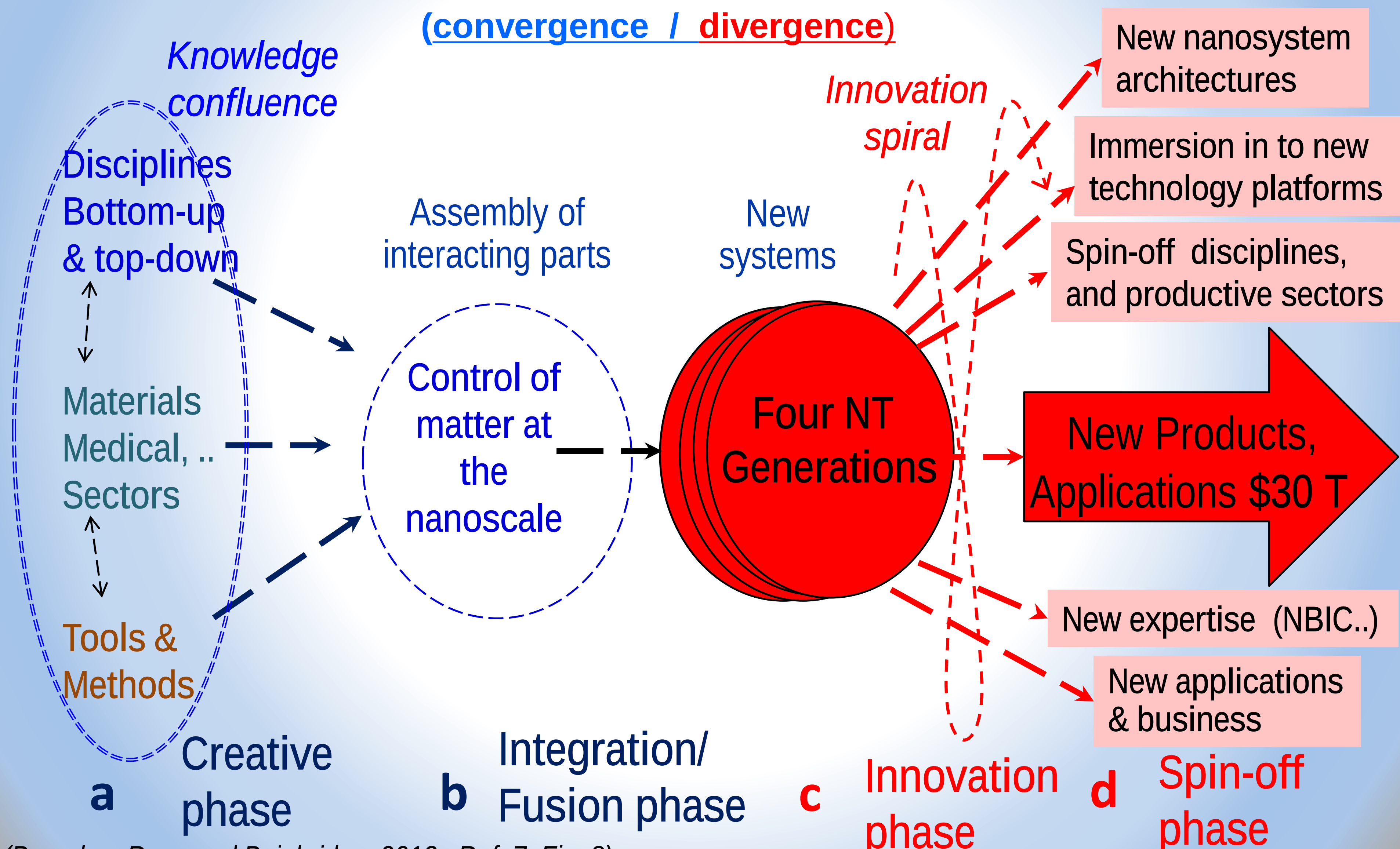
Integrates foundational and emerging technologies from key basic elements using similar system architectures and dynamic networking

III. Convergence of Knowledge, Technology and Sc

"CKTS"

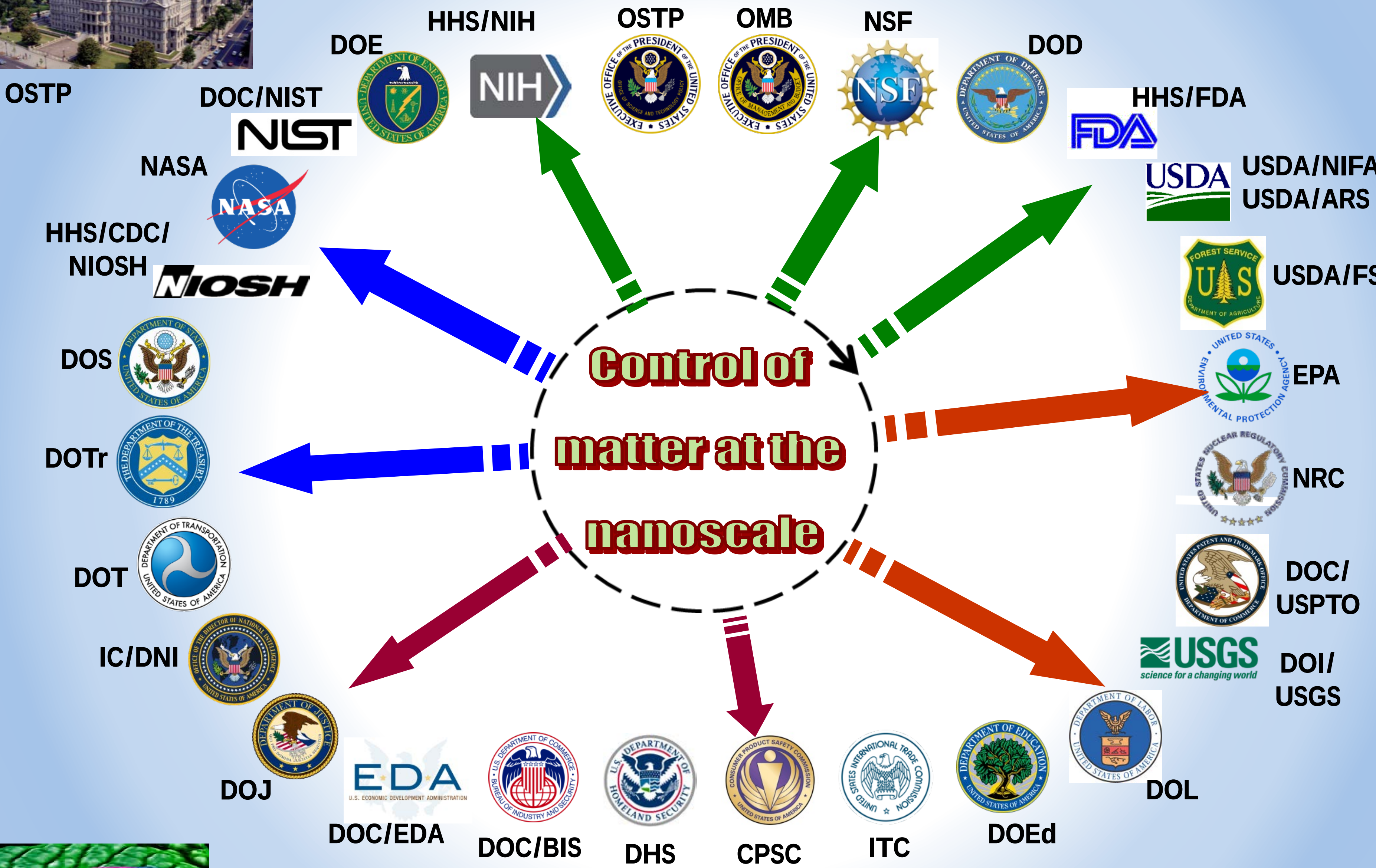
Integrates the essential platforms of human activity using six convergence principles

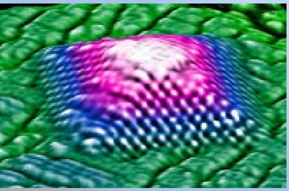
I. 2000-2030 Convergence-Divergence cycle for global nanotechnology development



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

I. Nanotechnology programs: S&T divergence

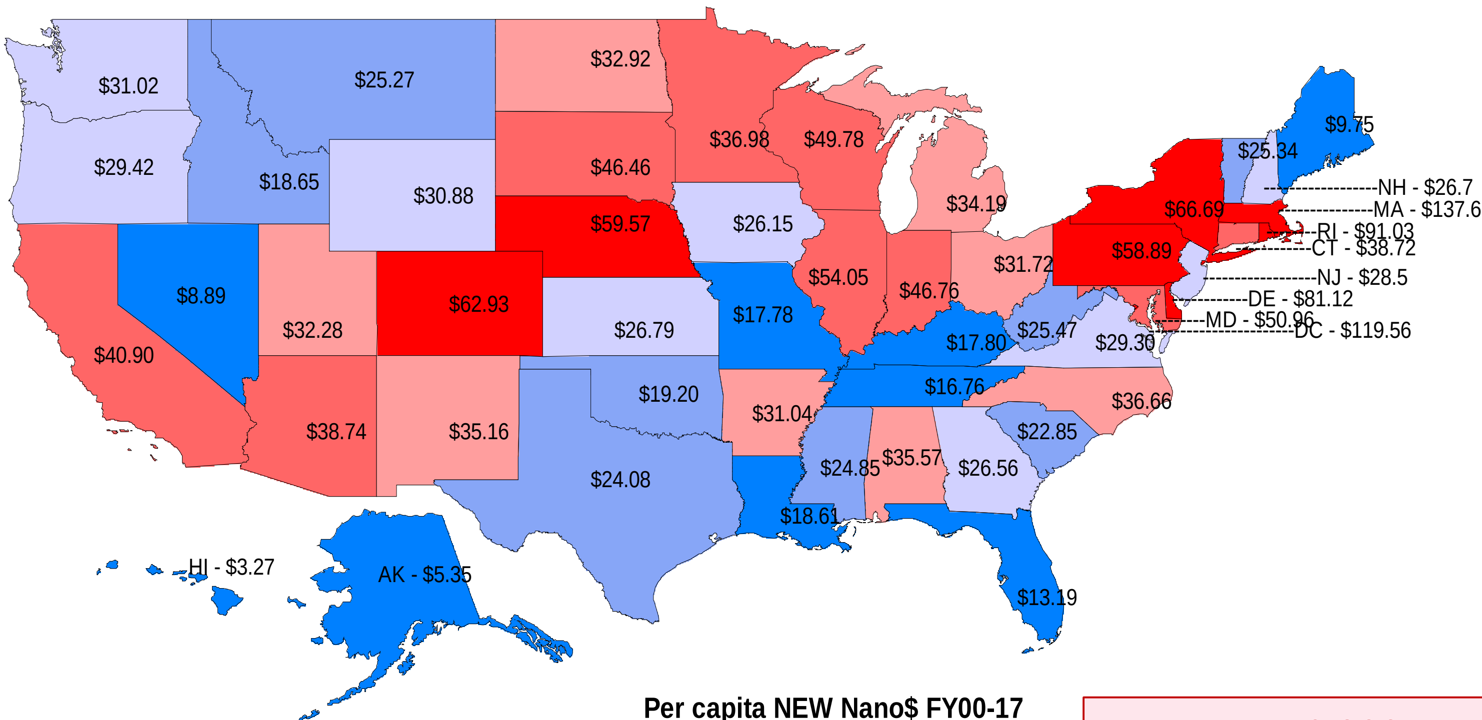




U.S. National Nanotechnology Initiative, 2000-2030

NSF's NS&E amount new awards per capita

FYs 2000 - 2017: U.S. average amount ~ $38 /capita



Per capita NEW Nano$ FY00-17

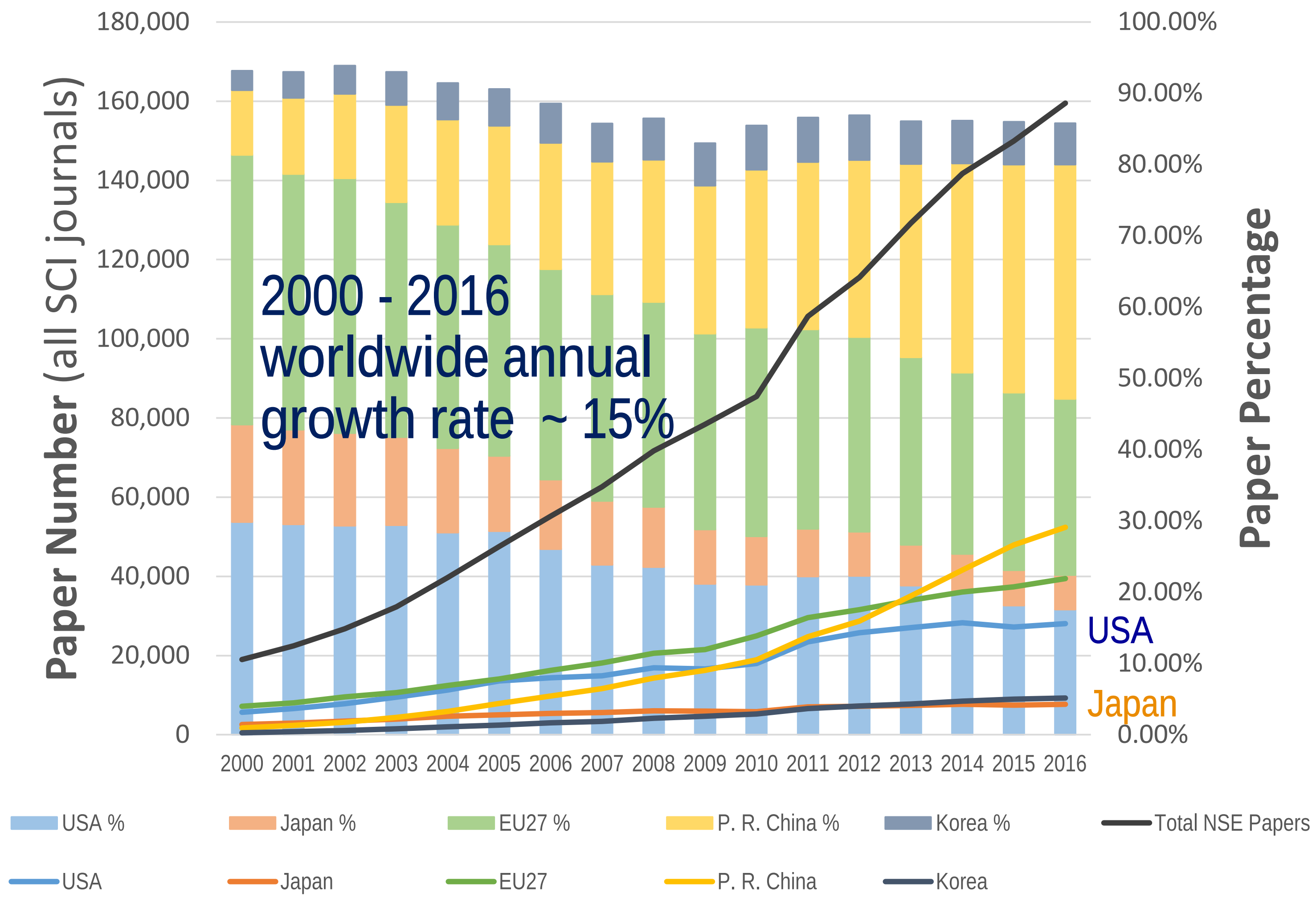
<= 18.61	18.61 - 25.47
25.47 - 31.02	31.02 - 36.66
36.66 - 54.05	54.05 - 137.7

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

#1 MA $138 / capita (2000-2017)

AK 5.34; AL 35.57; AR 31.04; AZ 38.74; CA 40.90; CO 62.93; CT 38.71; DC 119.55; DE 81.12; FL 13.19; GA 26.56; HI 3.27; IA 26.15; ID 18.65; IL 54.05; IN 46.76; KS 26.79; KY 17.80; LA 18.61; MA 137.65; MD 50.96; ME 9.75; MI 34.19; MN 36.98; MO 17.78; MS 24.85; MT 25.27; NC 36.66; ND 32.92; NE 59.57; NH 26.69; NJ 28.49; NM 35.16; NV 8.89; NY 66.69; OH 31.72; OK 19.20; OR 29.42; PA 58.89; PR 19.85; RI 91.03; SC 22.85; SD 46.46; TN 16.76; TX 24.08; UT 32.28; VA 29.30; VT 25.34; WA 31.02; WI 49.78; WV 25.47; WY 30.88

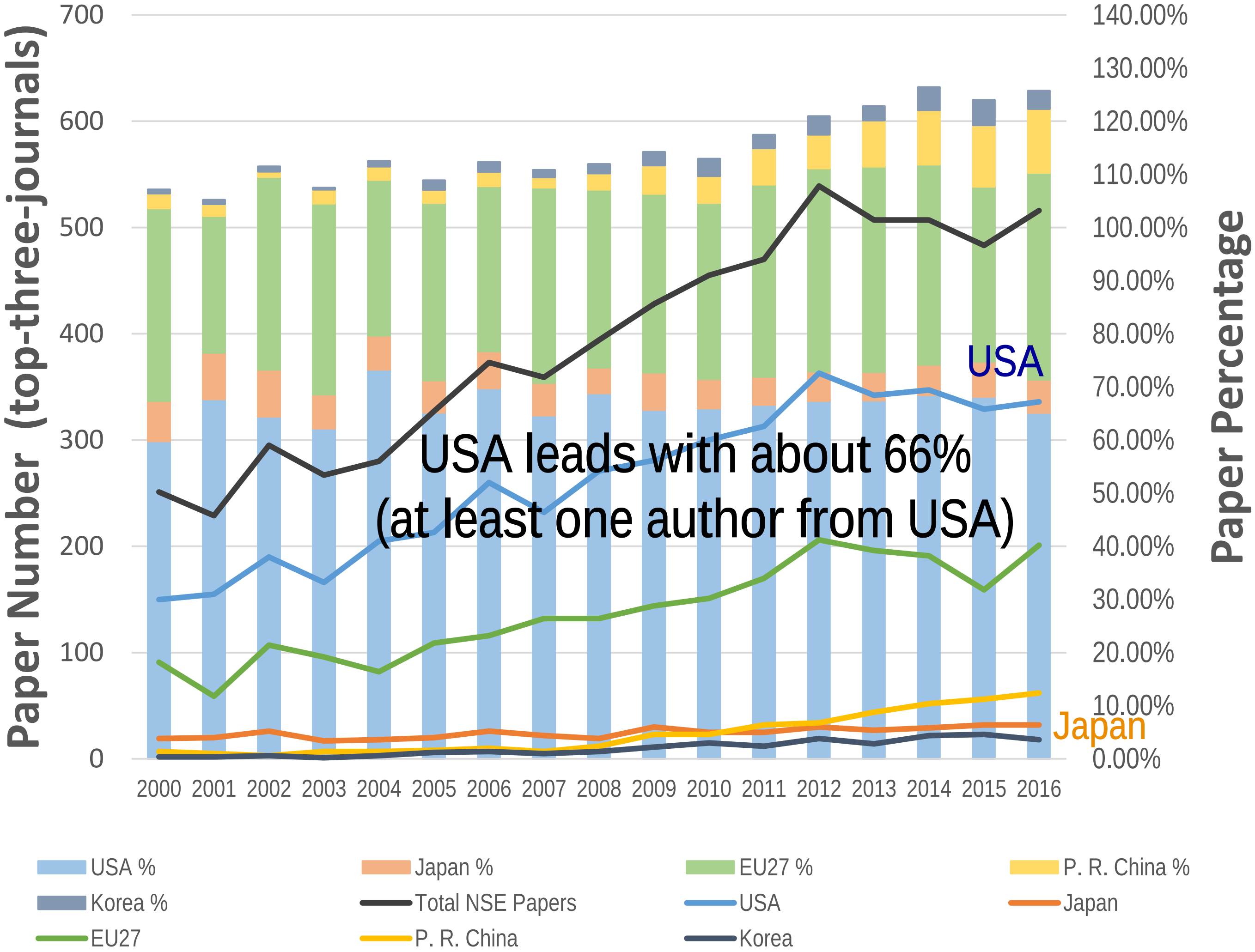
Nanotechnology papers in all SCI extended journals in the Words of Science, in 2000-2016, by five regions



"Title-abstract" search by keywords (International perspective on nanotechnology papers, patents and NSF awards (2000-2016), J. Nanoparticle Research, Nov 28017)

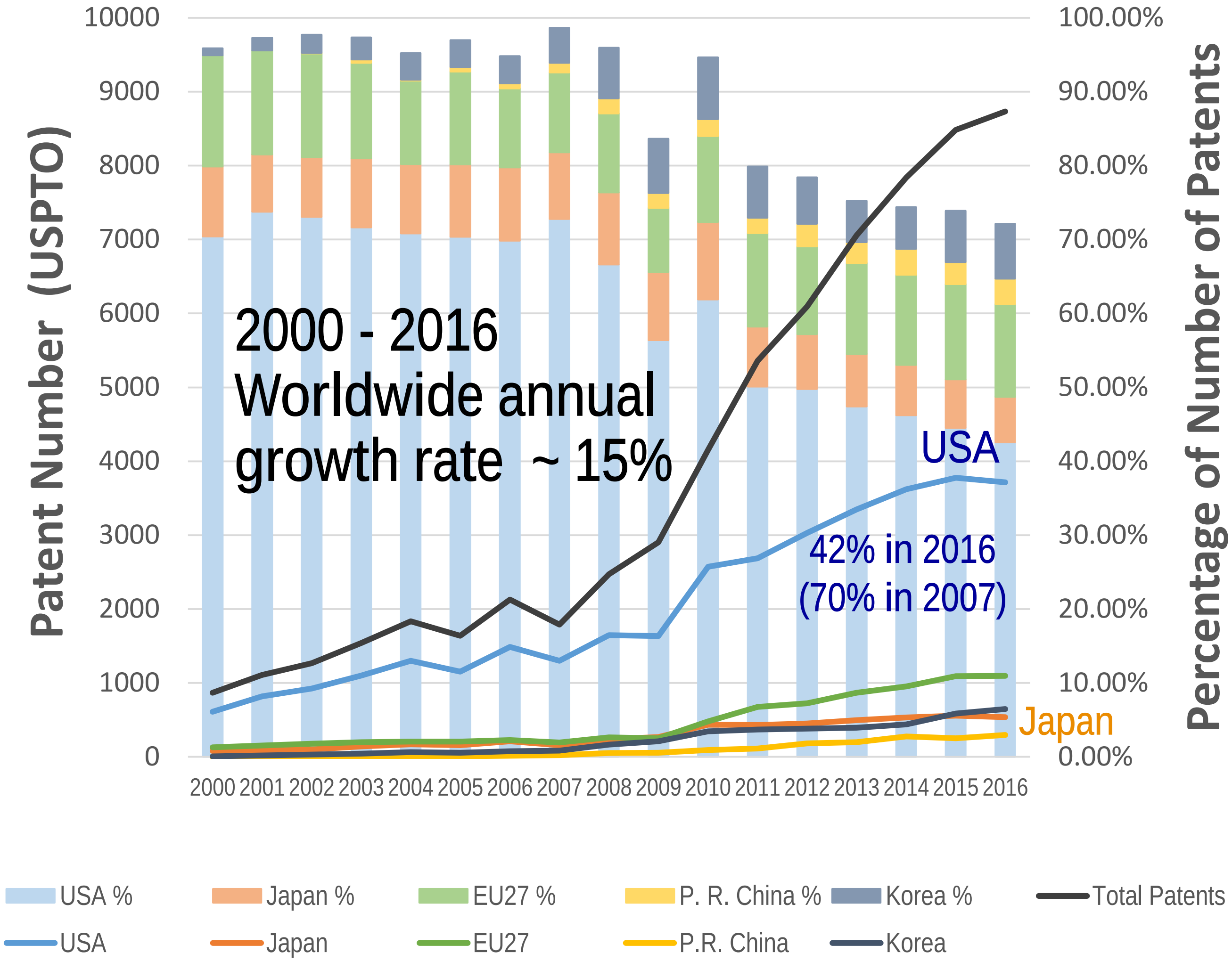
MC Roco, July 12 2018

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



"Title-abstract" search by keywords (International perspective on nanotechnology papers, patents and NSF awards (2000-2016), J. Nanoparticle Research, Nov 28017)

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



"Title-abstract-claims" search by keywords(International perspective on nanotechnology papers, patents and NSF awards (2000-2016), J. Nanoparticle Research, Nov 28017)

MC Roco, Feb 16 2018

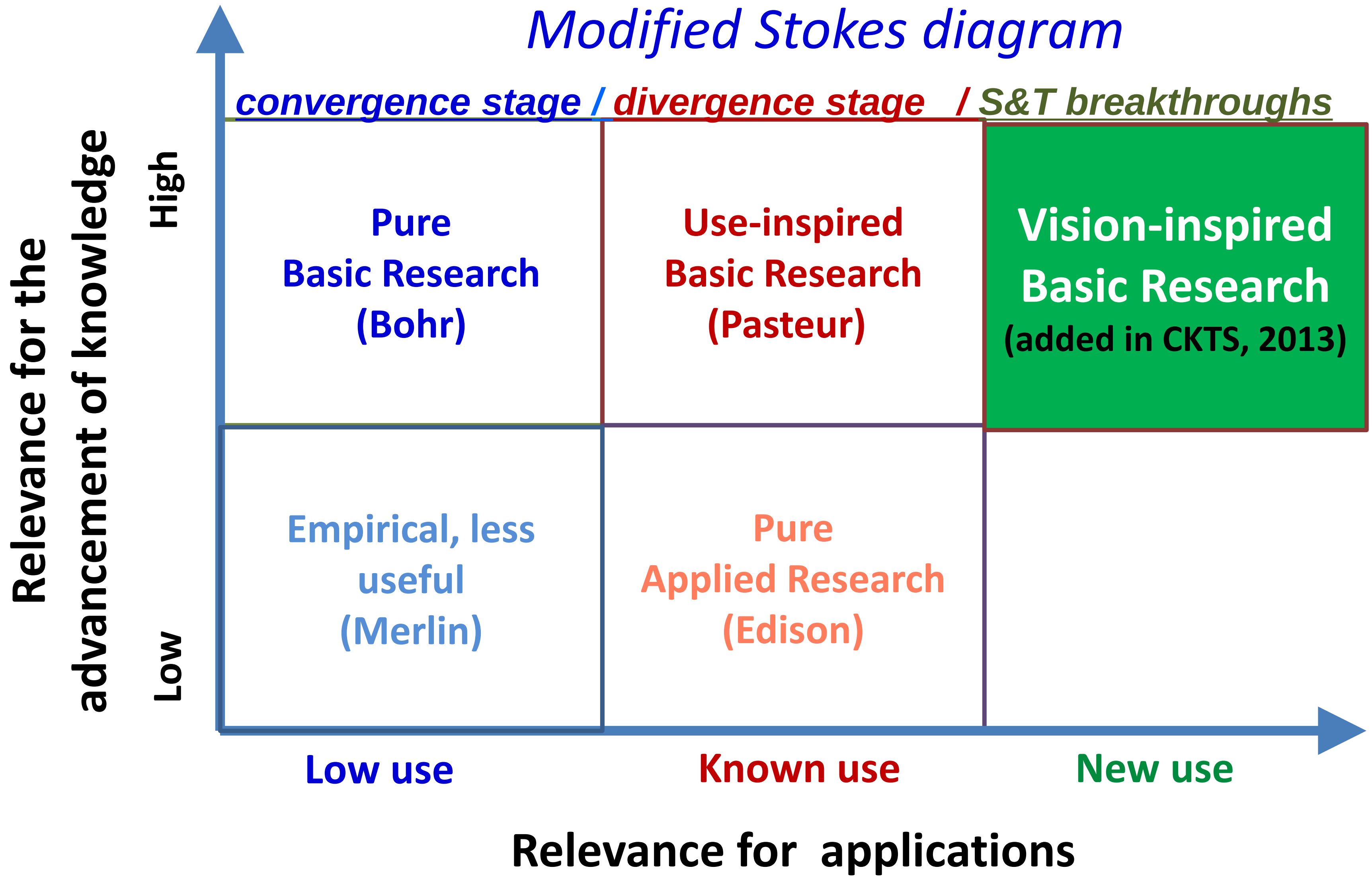
Papers and patent publications per million capita in the five regions

(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**	**23.1**	**4.2**	**18.8**	**53.3**	**42,822**

MC Roco, July 12 2018

F. Vision inspired discovery and inventions are essential for the future of innovation



Ref 5: "Convergence of Knowledge, Technology and Society: Beyond NBIC" (Springer,2013)

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

GENERATIONS OF NANOPRODUCTS

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

2030

DIVERGENCE

CONVERGENCE

2000

New socio-economic capabilities

nano3 Technology divergence

2020-2030

To general purpose technology

nano2 System integration

2010-2020

Create library of nanocomponents

nano1 Component basics

2000-2010

6. Nanosystem Conv. Networks

5. NBIC Technology Platforms

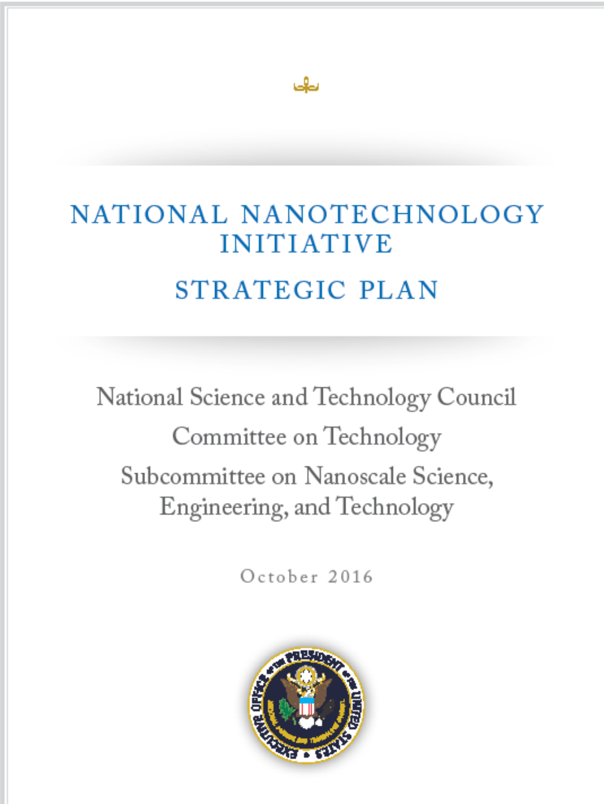
4. Molecular Nanosystems

3. Systems of Nanosystems

2. Active Nanostructures

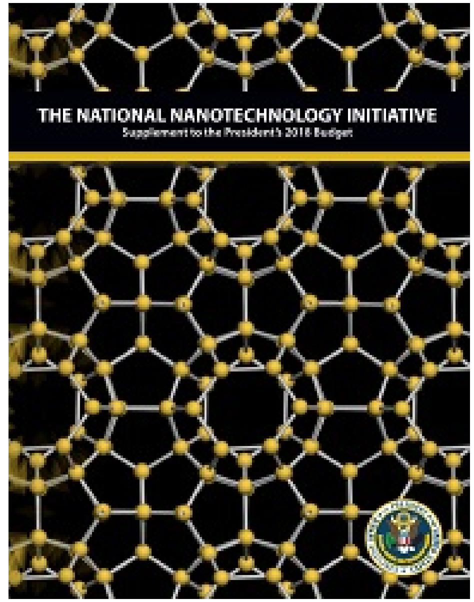
1. Passive Nanostructures

I. National Nanotechnology Initiative in 2018-2019



2016-2020 NNI Strategic Plan approved by WH and submitted to Congress

(available on www.nano.gov)



2019 NNI Supplement to the President's Budget (including NSF, NIH, DOE, ...)

PCAST report on NNI (view to 2030)

NAS/NRC report on NNI (next in 2020)

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

Signature Initiatives (2016-2021)

I. National Nanotechnology Initiative, 2018-2019

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 : 5 year goals for filtration, transportation, and sensors

Nanotechnology Knowledge Infrastructure

www.nano.gov/NKIPortal

Nanotechnology for Sensors

www.nano.gov/SensorsNSIPortal

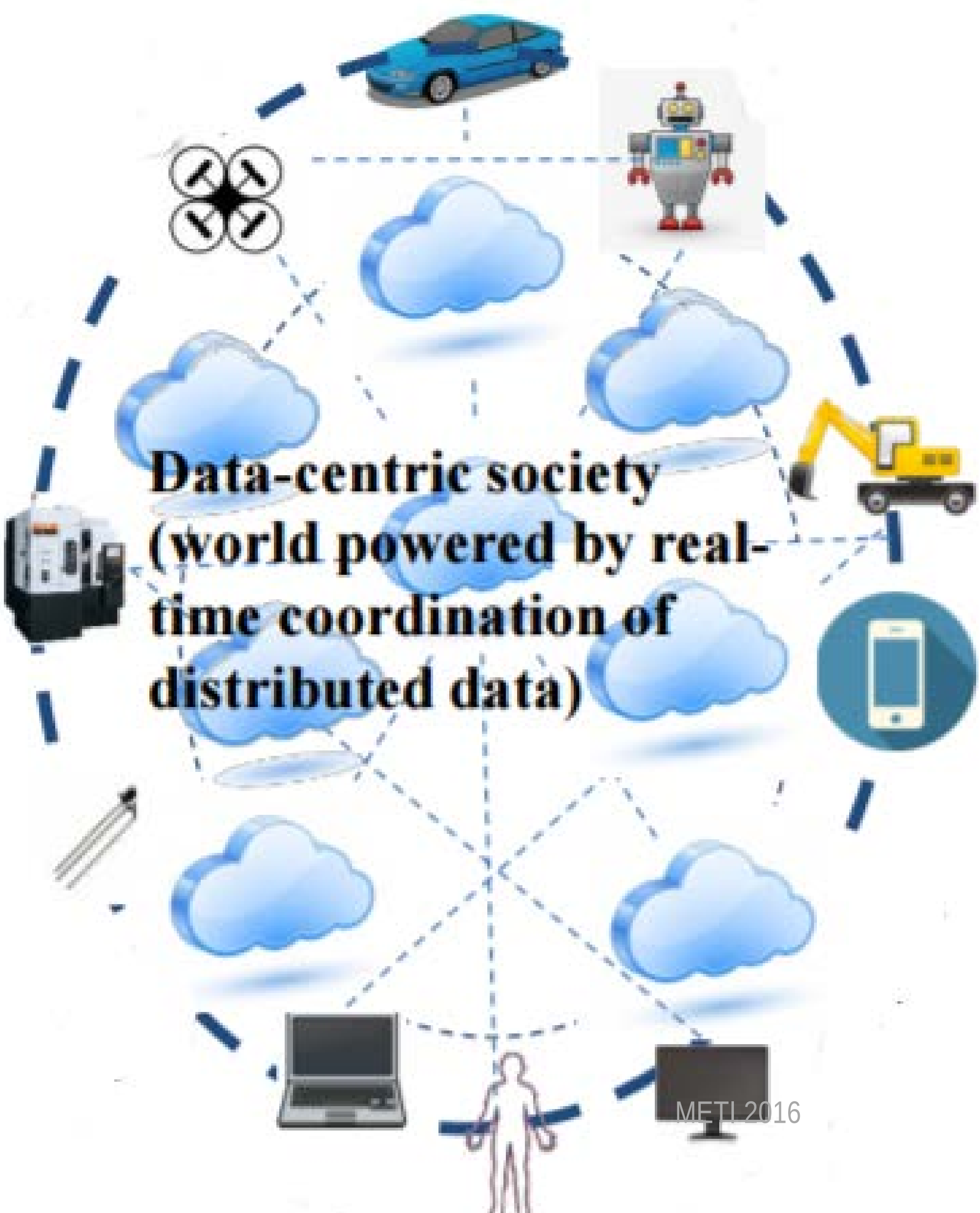
NNI Signature Initiative:

Nanoelectronics for 2020 and Beyond

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:

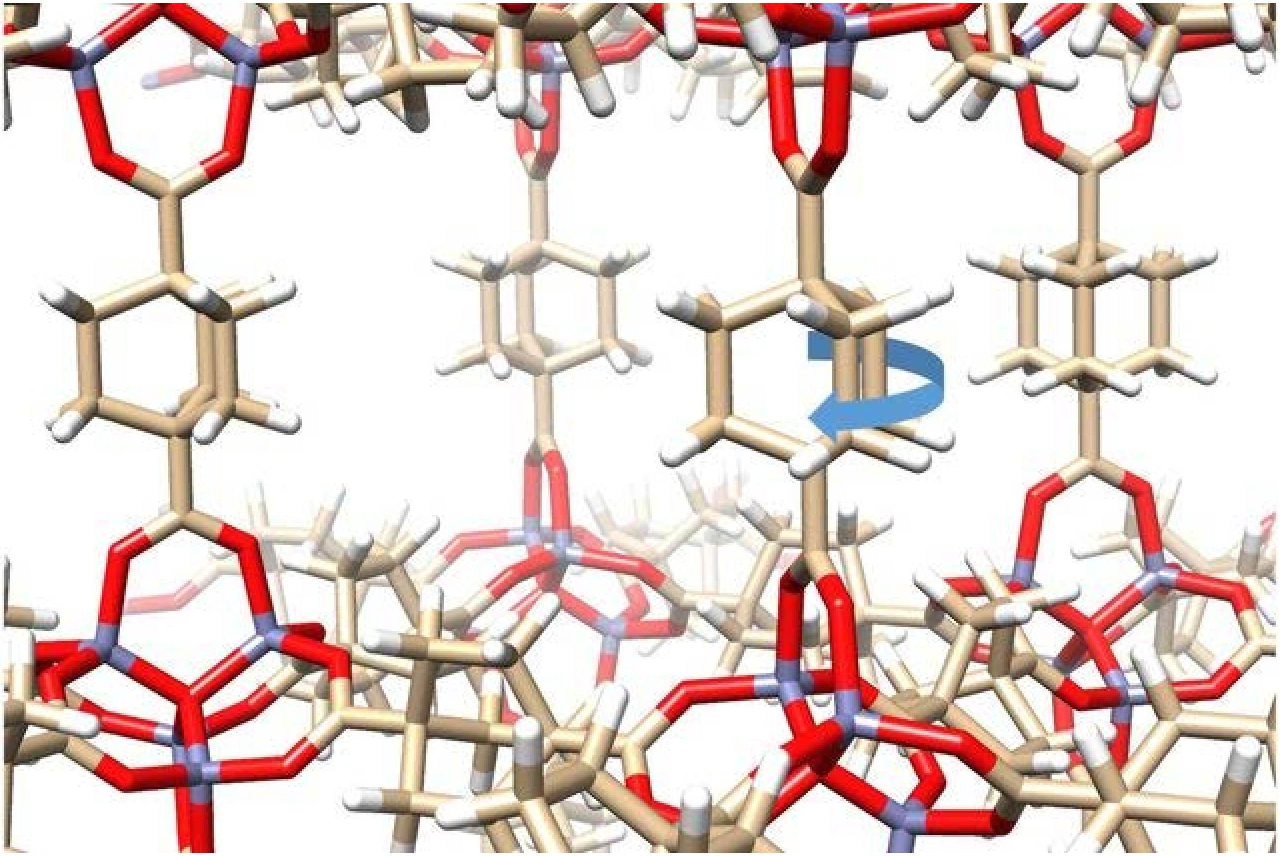
1 nm sensors selfpowered

Wireless networked connections

Distributed network

Example NSF programs: core on advanced materials

UCLA - *Gyroscope' molecules form crystal that has a solid exterior but contains moving parts.*

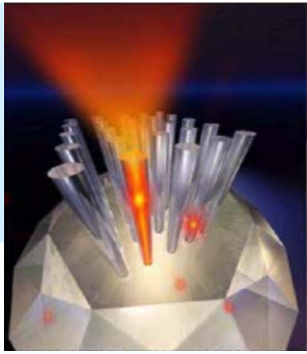


Miguel García-Garibay et al, UCLA, 2018, Credit: Kendall Houk Laboratory/UCLA

Examples of NSF programs (2018-2019)

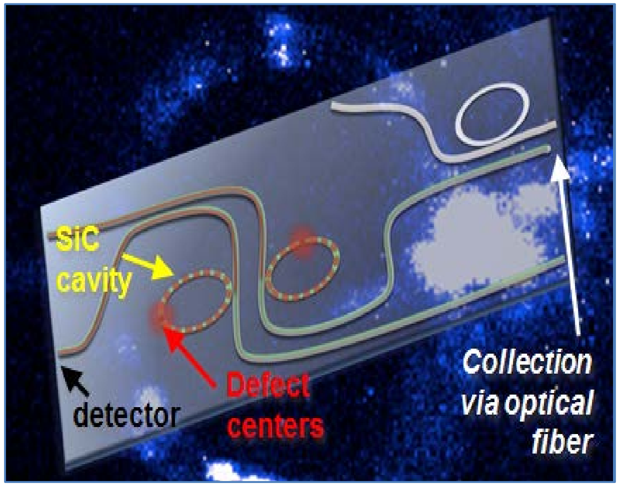
- ACQUIRE: Advancing Communication Quantum Information Research In Engineering
- SemiSynBio: Semiconductor Synthetic Biology for Information Processing and Storage Technologies
- NewLAW: New Light, EM (Electronic) and Acoustic Wave Propagation: Breaking Reciprocity and Time-Reversal Symmetry

FY 2018: Advancing Quantum Information Research in Engineering (NSF/AQUIRE)



Single photon device (Harvard U.)

Goal: room temperature, chip-level transducers, repeaters, systems and architectures for a secure, scalable quantum communication network.



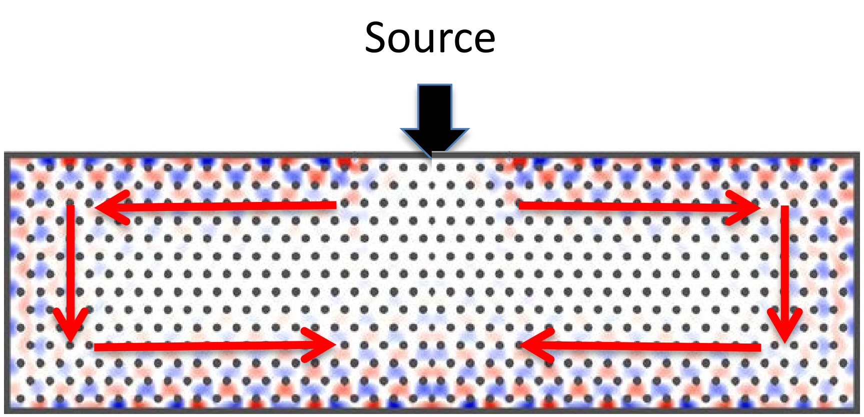
On-chip SiC-based Quantum Node (NSF award)

- Room temperature single photon sources, detectors, memories, repeaters and other low-energy photonic components
- Scalable on-chip integration of quantum photonics with silicon electronics

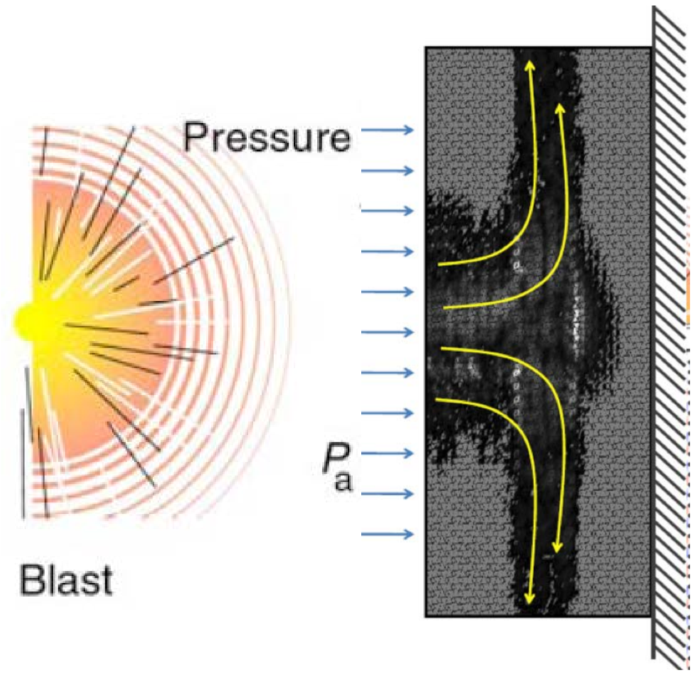
New Light & Acoustic Wave Propagation (NewLAW)

Breaking Reciprocity and Time-Reversal Symmetry in Acoustics/Mechanics, Nature Photon. 8, 821 (2014)

- Topological insulator concepts can be transformative for acoustic/vibrational/mechanical waves
- Nanostructures might find uses in acoustic technologies, such as soundproofing and sonar stealth systems, energy absorbing materials



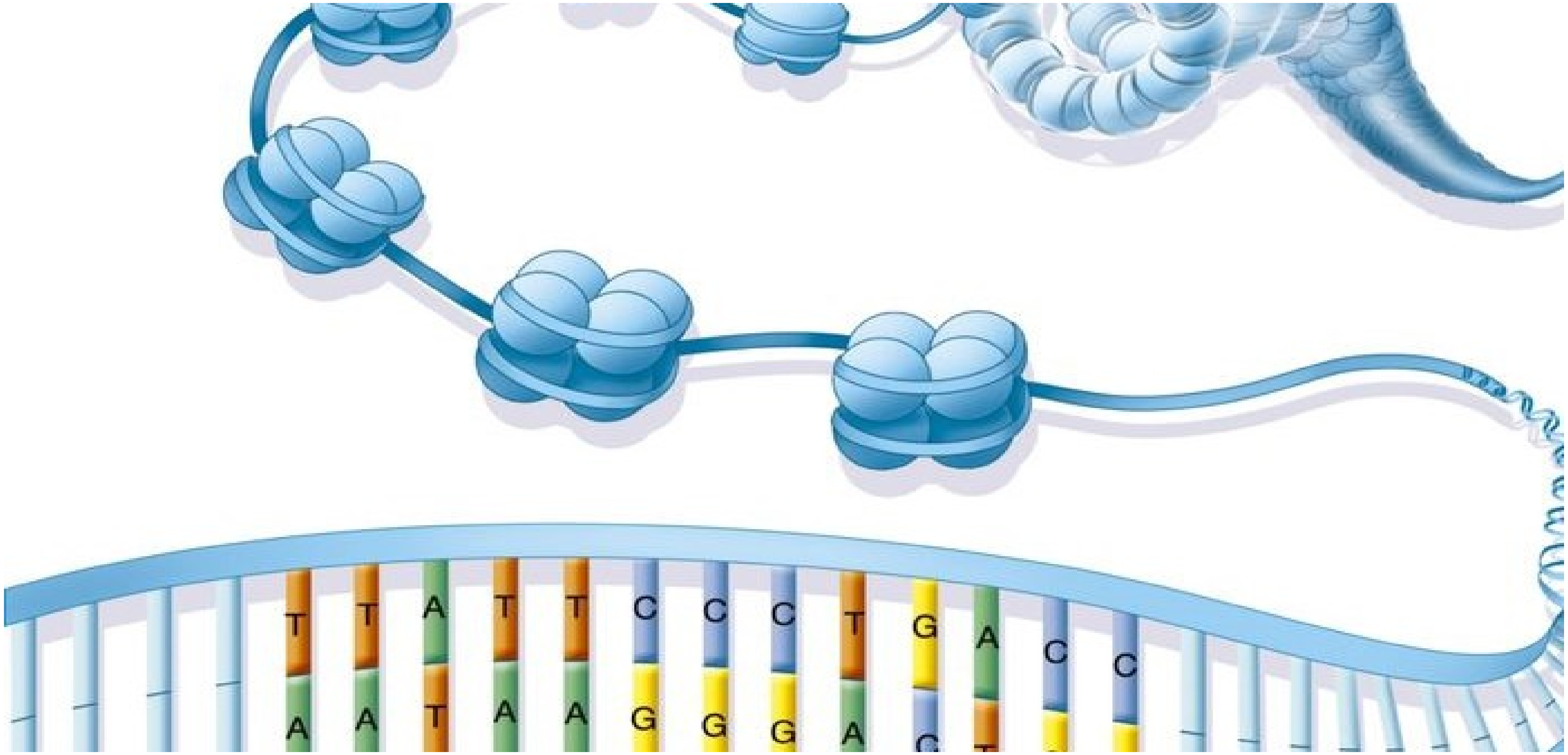
Yang et *al.*, Topological Acoustics, PRL 114, 114301 (2015)



Chromatin and epigenetic engineering

(ENG/EFRI, 2018-2019 competitions)

Goal: To describe and control chromatin and its nano-environment, thereby modulating cellular characteristics



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

- 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 & Architectures,
- Energy Efficient Computing with Chip-Based Photonics,
- Energy Efficient Learning Machines,
- Self-Adaptive Reservoir Computing with Spiking Neurons: Learning Algorithms and Processor Architectures

Two-dimensional (2-D) materials collaborative US-S. Korea projects in 2017-2018

1. Few-layer and Thin-film Black Phosphorus for Photonic Applications
   Fengnian Xia(Yale U.) and Young Hee Lee (SKKU)
2. Monolayer Heterostructures for Biosensors with Optical Readout
   Alan T Johnson (U. of PA) and Yung Woo Park (Seoul National University)
3. Phosphorene, an Unexplored 2D High-mobility Semiconductor
   Peide Ye (Purdue U.) and Won-Kook Choi (KIST), Young Hee Lee (SKKU)
4. Scalable Growth and Fabrication of Anti-Ambipolar Heterojunction Devices
   Lincoln Lauhon (Northwestern U.) and Seongil Im (Yonsei U.)
5. Crystalline Atomically Thin Layers for Photonic Applications
   Humberto Terrones (RPI) and Hyeongtag Jeon (Hanyang U.), Suklyon Hong (Sejong U.)
6. Black Phosphorus Electronics
   Jim Hwang (Leigh) – Devices (RF), Kaustav Banerjee (UCSB) – Devices & Circuits (Digital), Won Kook Choi (KIST) – Synthesis & Devices, Young Hee Lee (SKKU) – Synthesis,

Two-dimensional (2-D) materials collaborative US-S. Korea projects in 2017

6. Black Phosphorus Electronics

   Jim Hwang (Leigh) – Devices (RF)

   Kaustav Banerjee (UCSB) – Devices and Circuits (Digital)

   Won Kook Choi (KIST) – Synthesis and Devices, Young Hee Lee (SKKU) – Synthesis

7. Nucleation and Growth of 2-D Layers – Modeling and Experiments

   – Physical and Chemical Interfaces, Epitaxy, Graphoepitaxy

   Lincoln Lauhon (Northwestern) – Synthesis, Materials Characterization

   Suklyun Hong (Sejong) – Modeling

8. Strain Engineering of 2-D Crystals and Heterostructures

   Philip Feng (Case Western) – Devices, Systems

   Young Hee Lee (SKKU) – Synthesis, Suklyun Hong (Sejong) – Theory and Modeling

9. 2-D SPASER (Surface Plasmon Amplification of Stimulated Emission of Radiation)

   Volker Sorger (GWU) – Devices, Tony Low (Minnesota) – Theory,

   C.J. Lee (Korea Univ) – Synthesis

Two-dimensional (2-D) materials collaborative US-S. Korea projects in 2017

10. CVD/ALD of Sn(S, Se)2 for 2-D Electronics and Photovoltaics

    Joan Redwing (PennState) – CVD and Materials Characterization

    Hyeongtag Jeon (Hanyang Univ) – ALD, Zi-Kui Liu (PennState) – Theory

11. 2-D Materials Design (Materials Genome)

    Kaustav Banerjee (UCSB) – Devices, Suklyon Hong (Sejong) – Theory

    Humberto Terrones (RPI) – Theory, Yu Huang (UCLA) – Synthesis

12. Theory and Experiments on Optoelectronics Properties of TMDCs

    Humberto Terrones (RPI) – Theory

    Joan Redwing (PennState) – CVD, Suklyon Hong (Sejong) – Theory

13. Spectroscopy of Defects and Carrier Transport in 2-D Materials

    Lincoln Lauhon (Northwestern U.) – Synthesis, Materials Characterization, Humberto Terrones (RPI) – Theory, Seongil Im (Yonsei) – Devices and Defects Spectroscopy, Margaret Kim (Univ of Alabama) – THz Spectroscopy, Berardi Sensale-Rodriguez (Utah) – Spectroscopy and Devices, Jae Hoon Kim (Yonsei) – THz Spectroscopy

NanoMech Racing Total Care

AtomLube
100 Racing Grease (Wheel Bearing)

NGLIDE
Racing Engine Oil Treatment

AtomOil
Ultra Synthetic 75W-140 Racing Gear Oil

TuffTek
Cutting Tools (Advanced Machining of Aluminum Wheels, Axle, and Engine Block)

GUARDX
A2001 Insulating Enamel (Electrical system)

GUARDX
Abrasion Resistant Coating (Exterior Protection)

AtomLube
Multi-purpose Grease (Chassis Lubrication and Assembly)

AtomLube
Dielectric Grease Spray (Electrical System)

AtomLube
Dielectric Grease (Electrical System)

AtomLube
Ultra Coupling Grease (Tripod Joint)

AtomLube
32 Racing Grease (Wheel Bearing)

www.indycar.com

AtomOil™ GUARDX AtomLube TuffTek®

Continuing To Protect the Nanotechnology Workforce: NIOSH Nanotechnology Research Plan for 2018-2025

- 10 critical research areas for nanotech research and communication:

  1. Toxicity & internal dose; 2. Measurement methods; 3. Exposure assessment; 4. Epidemiology & surveillance; 5. Risk assessment; 6. Engineering controls & personal protective equipment (PPE); 7. Fire & explosion safety; 8.Recommendations & guidance; 9. Global collaborations; and 10. Applications & informatics.

- The draft plan (Docket #CDC-2018-0038)

  is at: <https://www.regulations.gov>

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

NBIC 2001: NSF Workshop "Converging Technologies for Improving Human Performance: Nano-Bio-Information-Cognitive"

NBICA 2015: added general purpose "*Artificial intelligence*" as a foundational emerging field affecting human performance

Synergistic combination of 5 foundational emerging fields from their basic elements (atoms, bits, genes, neurons, logic step) up and using similar system architecture concepts, for common core goals such as learning, productivity & aging

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

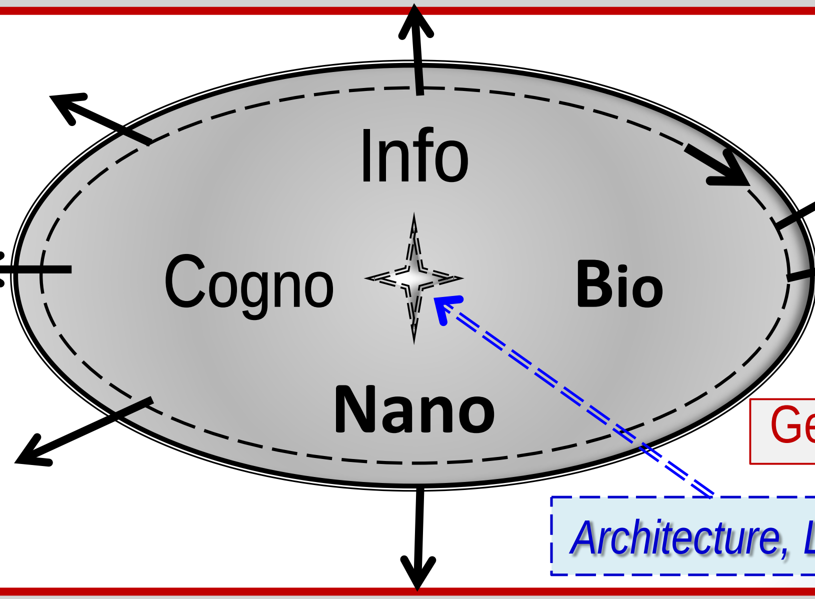
OSTP

Big Data | National Strategic Computing Initiative

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

Brain–like Computing; Smart systems

- Artificial Intelligence
- BRAIN Initiative (whitehouse.gov/share/brain-initiative)
- National Robotics Initiative

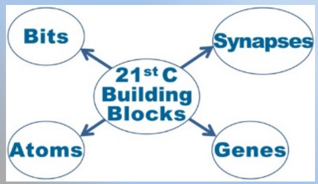


- Biology centered
- Biomedical / Health focus
- Precision Med
- Genome(s) | Microbiome

Architecture, Life, Human-technology

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

Materials Genome | Photonics | NNI Grand Challenges

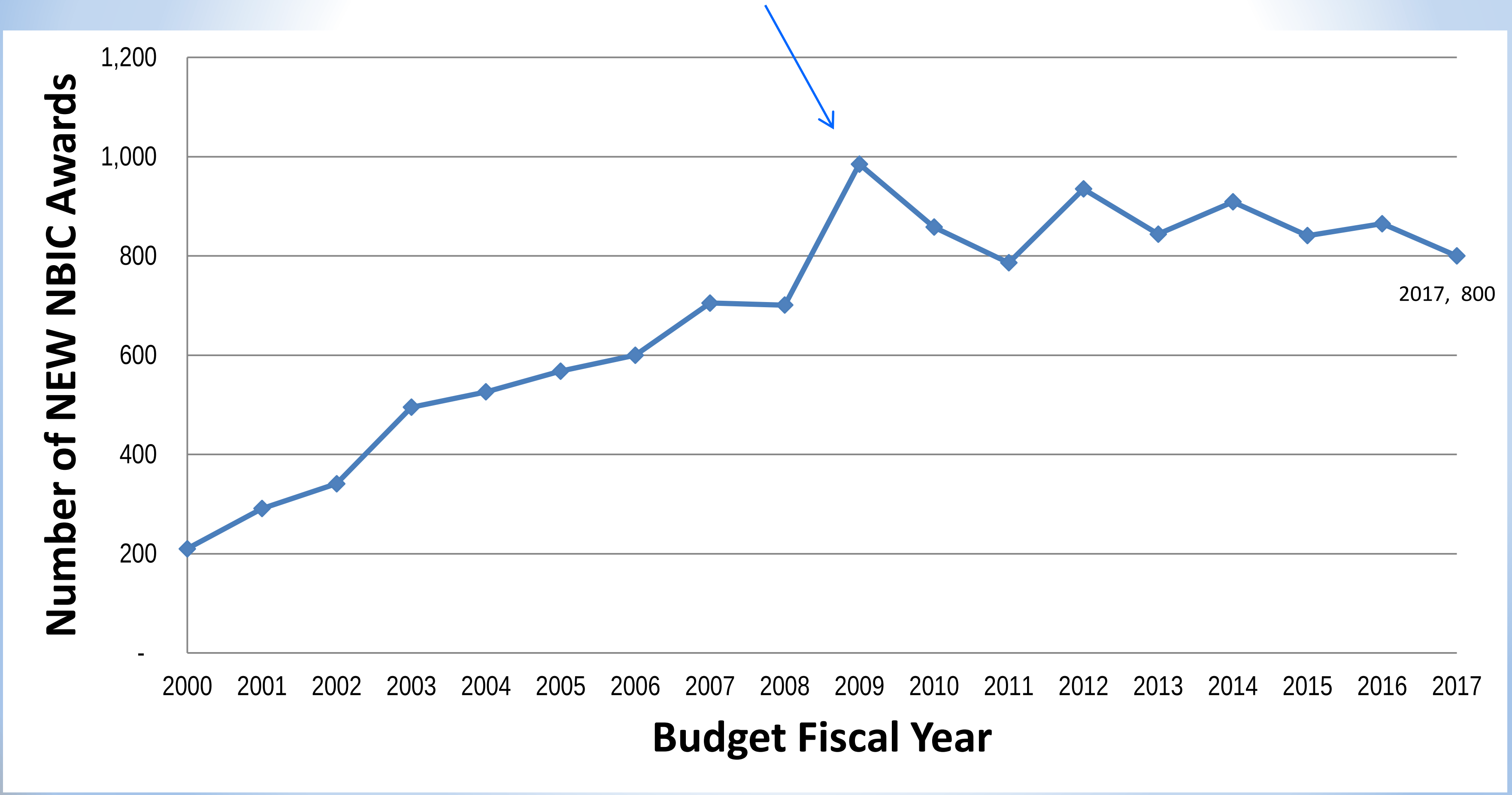


Ref 9: Roco, "NBIC", in Handbook of S&T Convergence, 2015

II. Number of NBIC Awards at NSF (2000-2017)

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



MC Roco, July 12 2018

Ex. II Smart Systems programs with nanotechnology components

- National Robotics Initiative (NRI)

- Cyber-Physical-Social Systems (CPS)

  Integration of intelligent decision-making algorithms and hardware into physical systems

- Human-Centered smart service systems

- Smart and Connected Communities

Ex II: "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

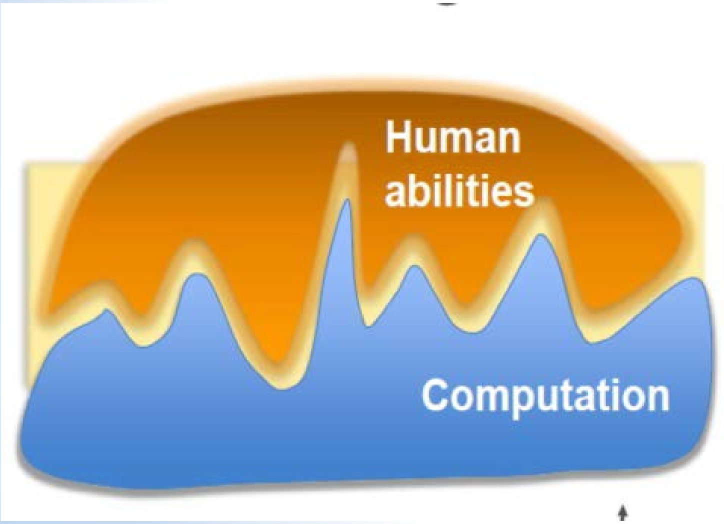
- Purpose: "Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain."

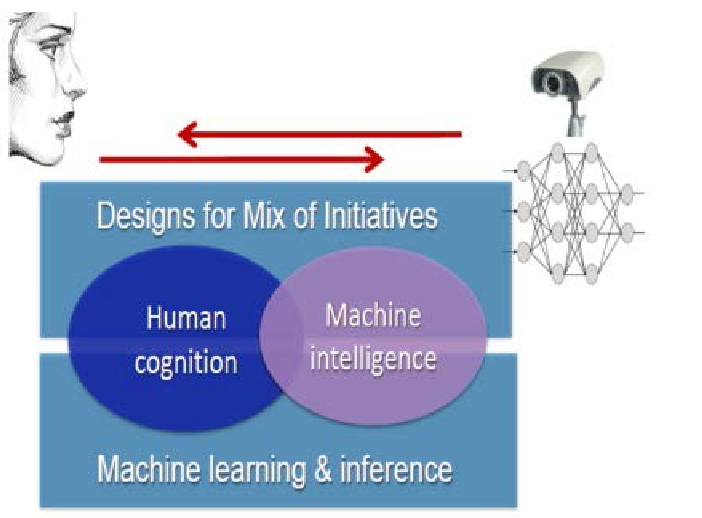
  Also: pattern recognition, human like simultaneous perception of information from various sources including the five senses,

Ex II: Intelligent cognitive assistants

2016 workshop (sponsored by NSF, SIA, SRC)

Systems harnessing new machine intelligence and problem-solving capabilities to work collaboratively and enhance human cognitive and physical abilities - by assisting in working, learning, interacting with new cyber-physical systems, transport, healthcare, and other daily activities.





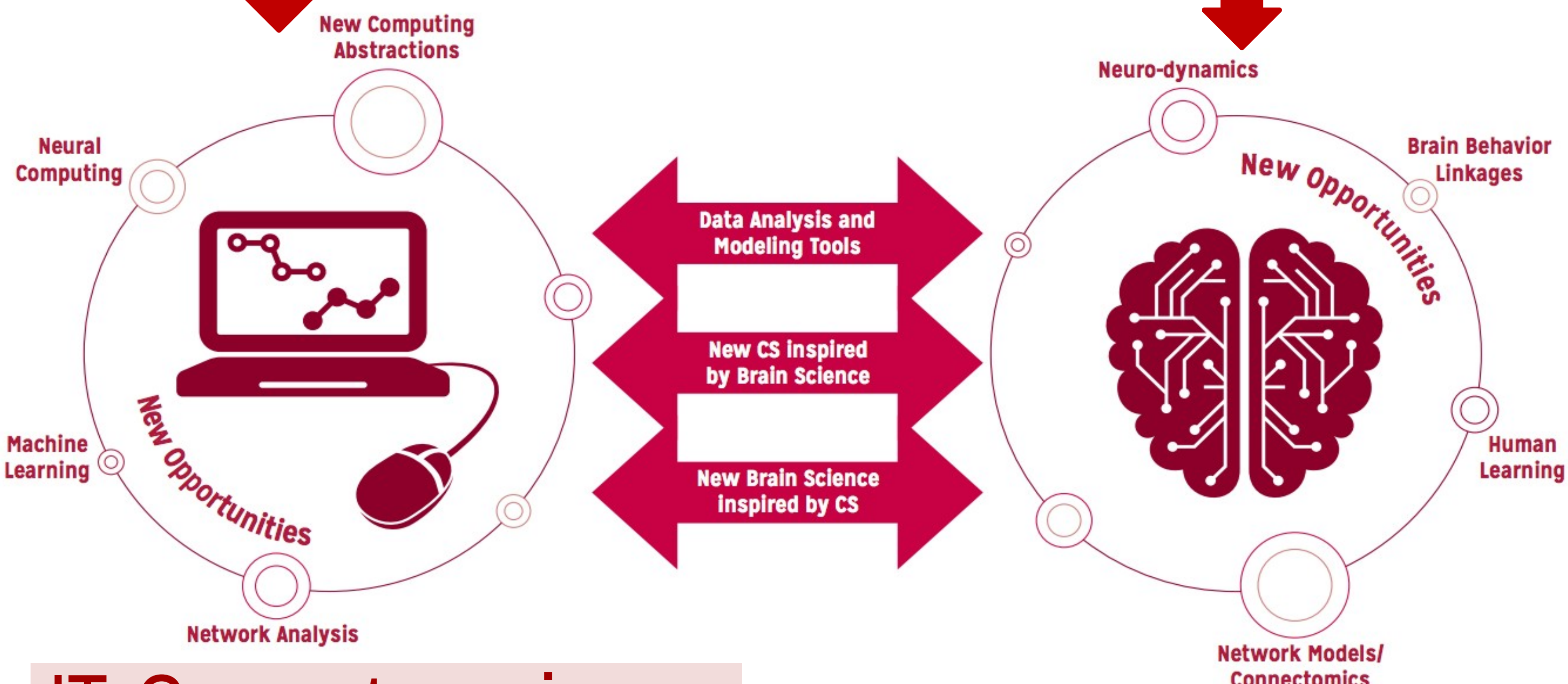
Ref: Intelligent Cognitive Assistants (ICA) report, 2016; and ICA2-2017
The report is available on: www.nsf.gov/nano (4th item) and www.semiconductors.org/issues/research/research/

Ex II: Towards Brain – like Computing

Technology Convergence: Beyond "one-way" thinking

Nanotechnology
(create hardware, model)

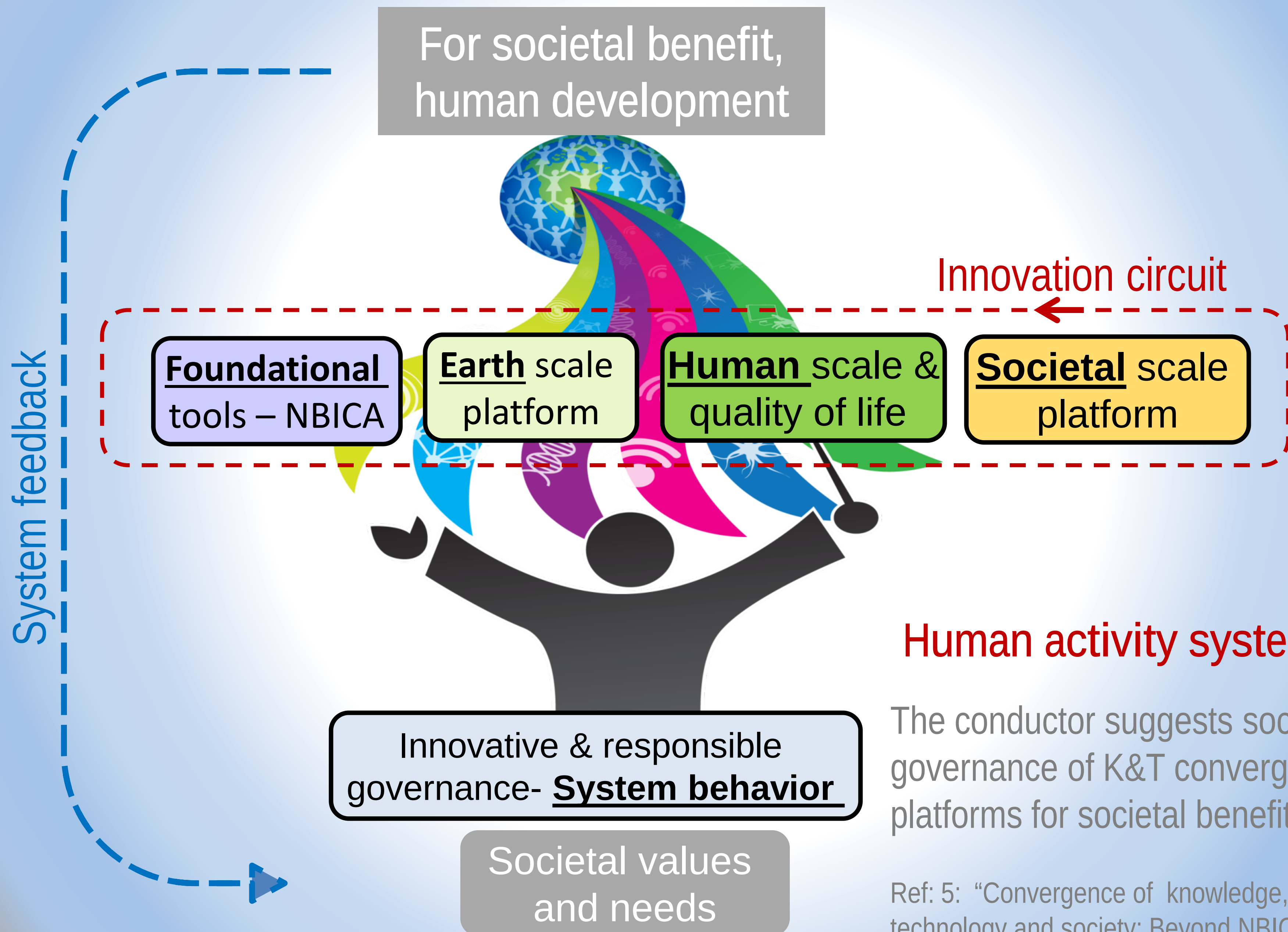
Cognitive technologies
(cognition, logic requirements)



IT, Computer science
(create software)

Brain science
(core system, model)

III. Convergence of Knowledge, Technology and Society



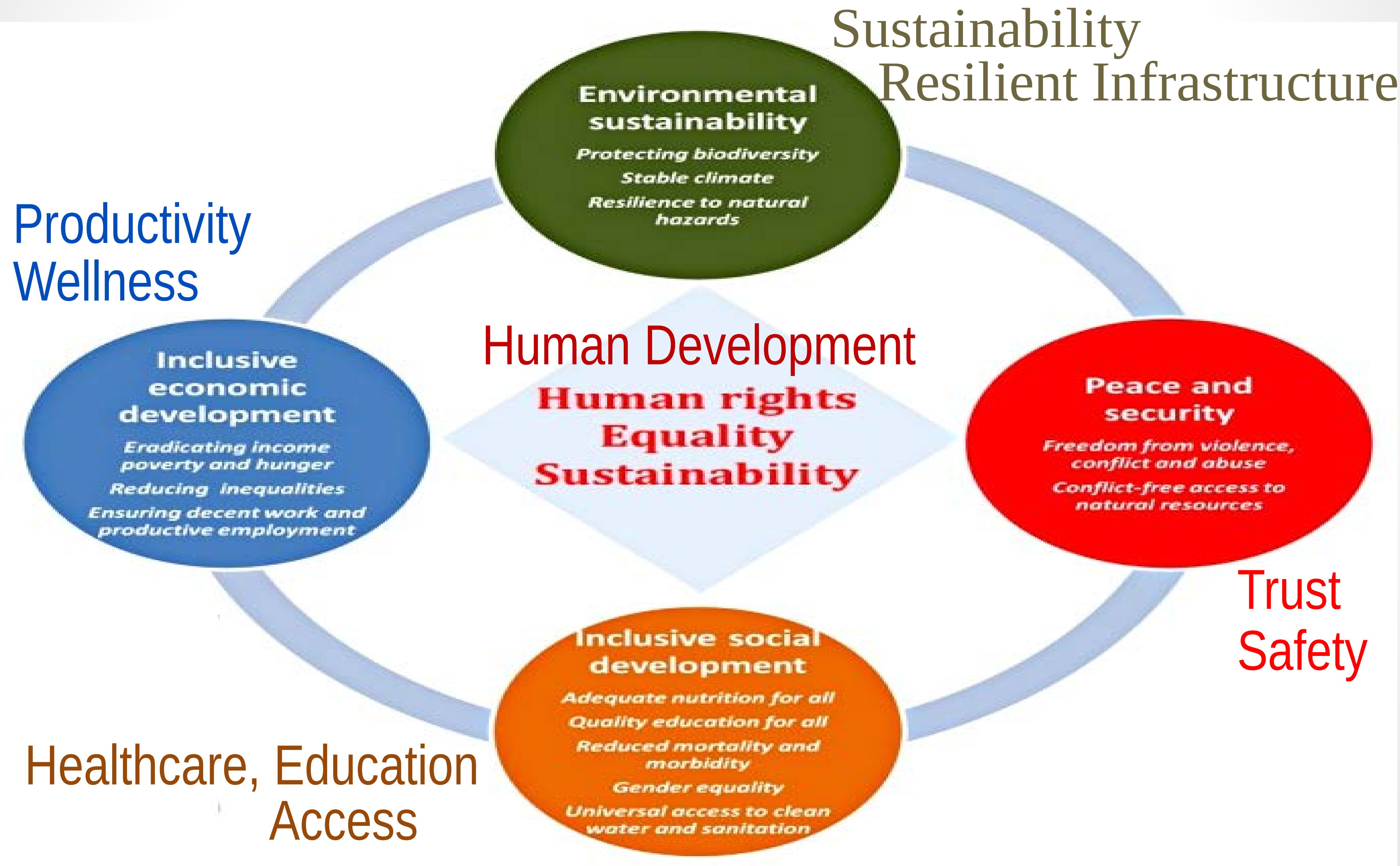
Human activity system

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

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

III. An integrated vision for the future society

(including UN Millennium Development Goals; advanced by S&T)



(Ref 5: Convergence of Knowledge, Technology and Society, 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

Global Change Research Program

(Global Change.gov) (with coord office)

Asteroid GC (NASA..)

Space Station (NASA..)

Smart and Connected Communities

I-Corps

Innovation

Aging Population

STEAM Education Initiative (NSF, DoEd)

Societal

Earth ***Human***

NBIC+

Productivity, Sustainability, Equality, Safe

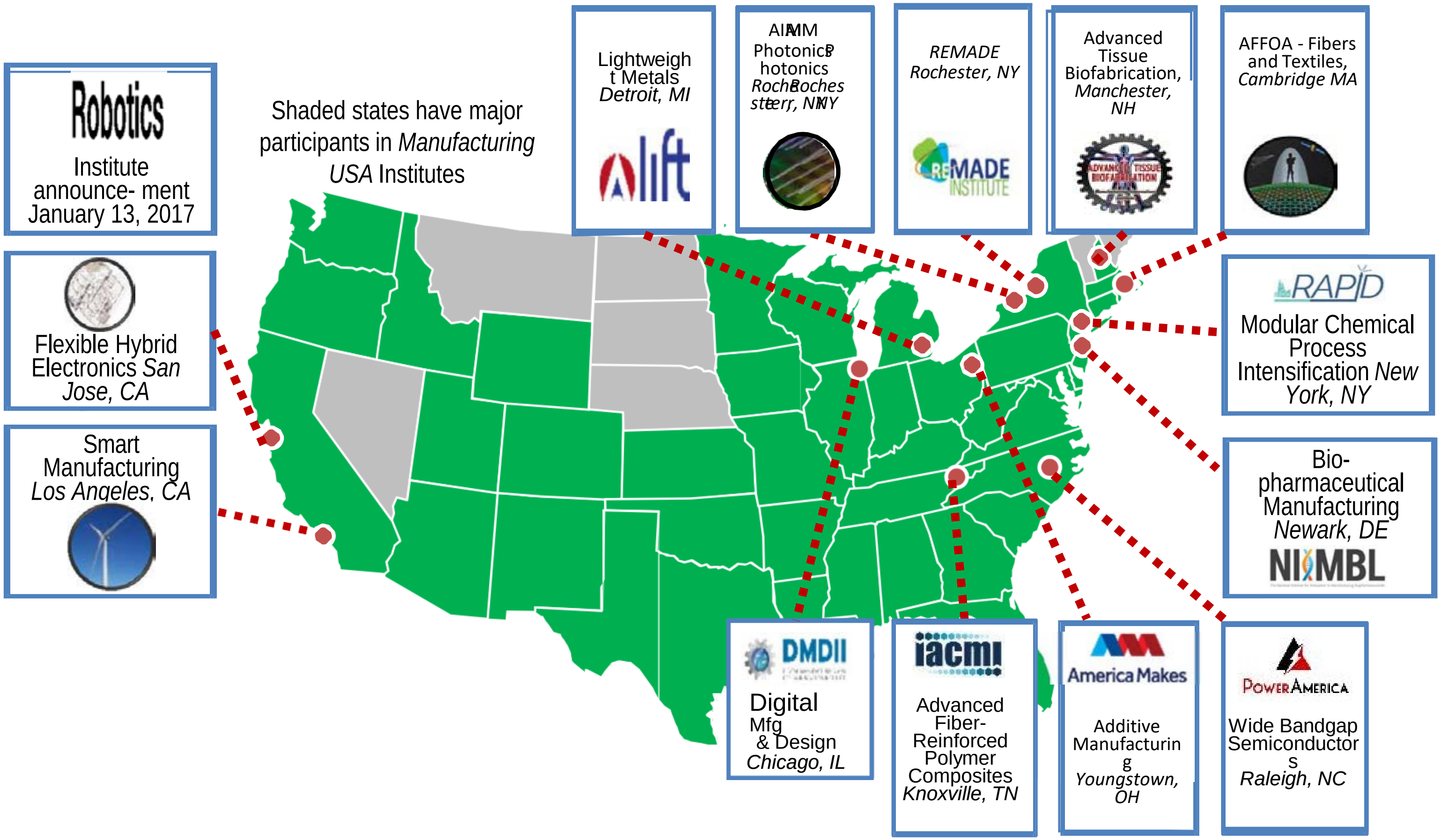
Advanced manufacturing:

National Network for Manufacturing Innovation (NNMI)

(http://www.manufacturing.gov/nnmi) (with program office)

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

Example: The National Network for Manufacturing Innovation (NNMI)



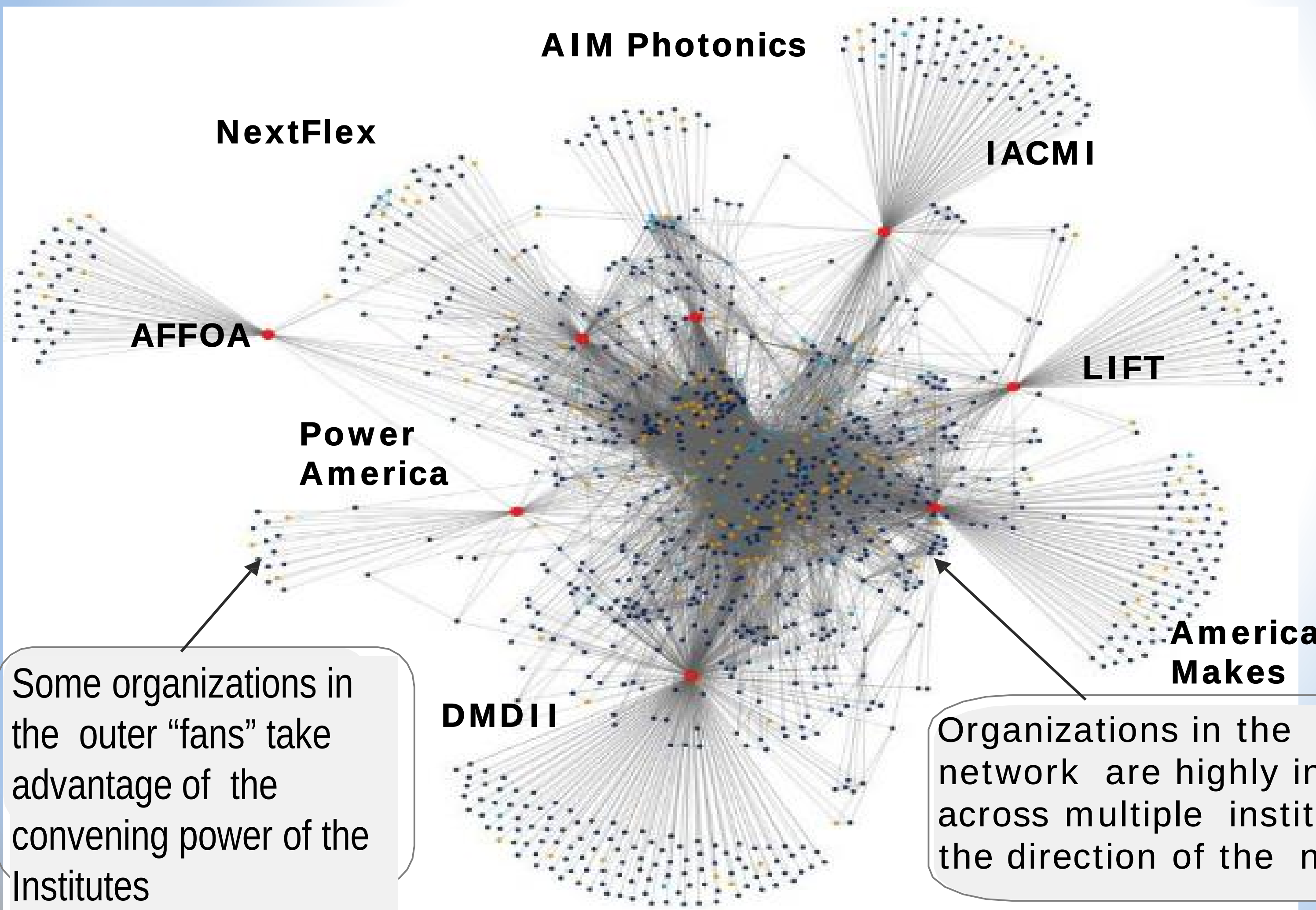
2017: A network of 14 translational manufacturing institutes

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

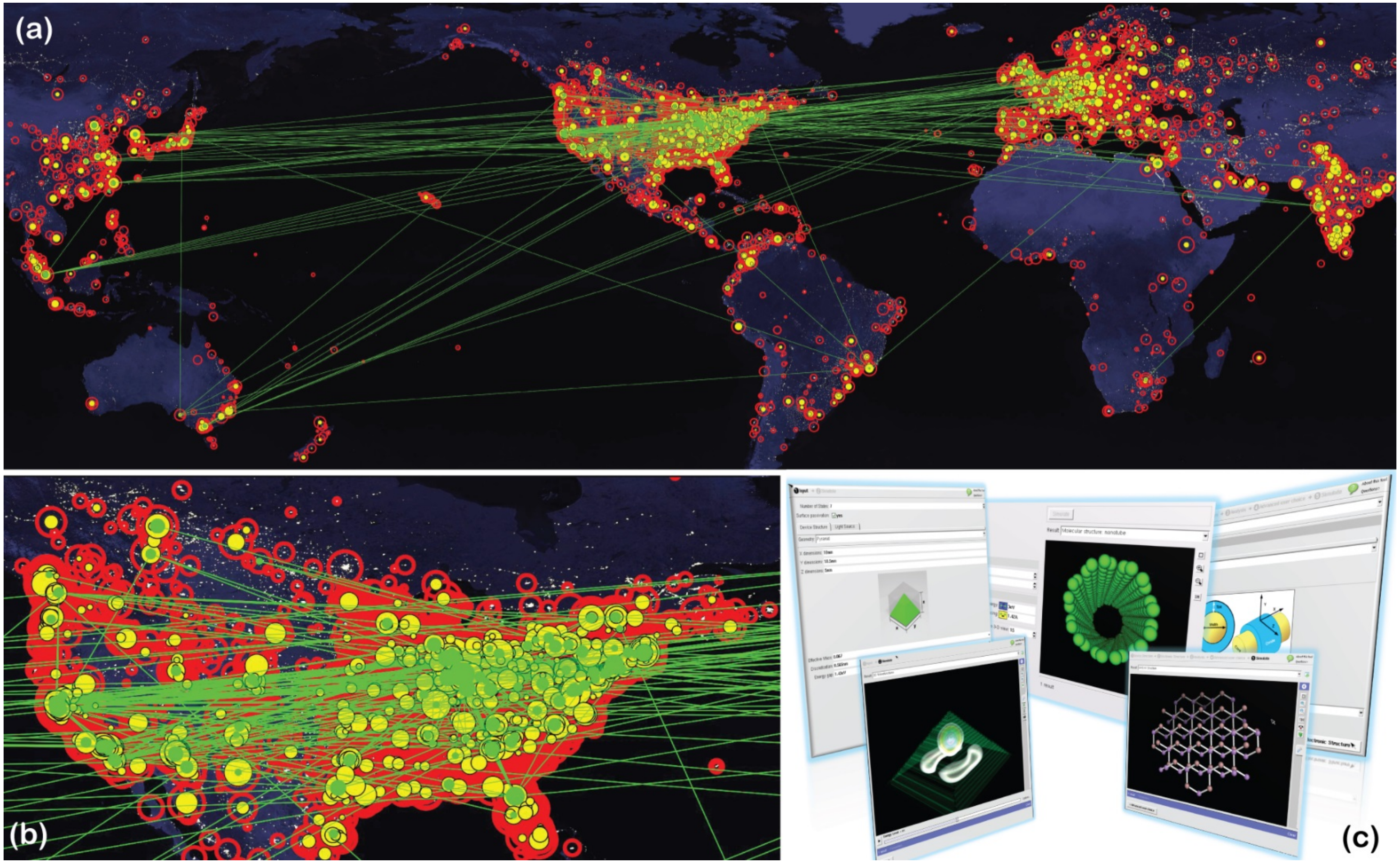


Some organizations in the outer "fans" take advantage of the convening power of the Institutes

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

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

Example: Network for Computational Nanotechnology



nanoHUB usage in 2015: 172 countries

Over 3,00 authors collaborating

Over 13,000 users running interactive simulations

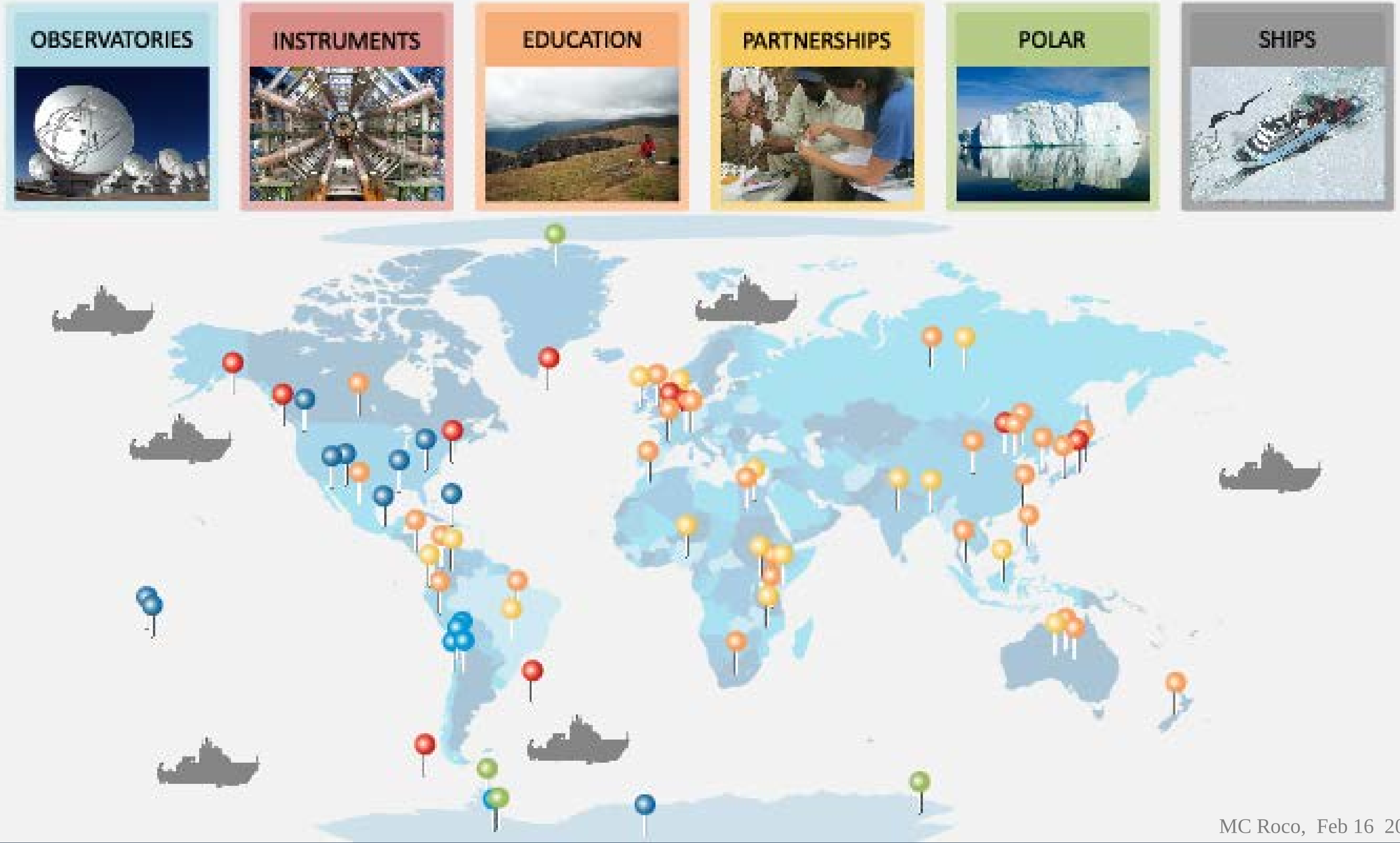
Over 1.4 million visitors using lectures and tutorials

Ex III: Innovations for Food, Energy, and Water Systems

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

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

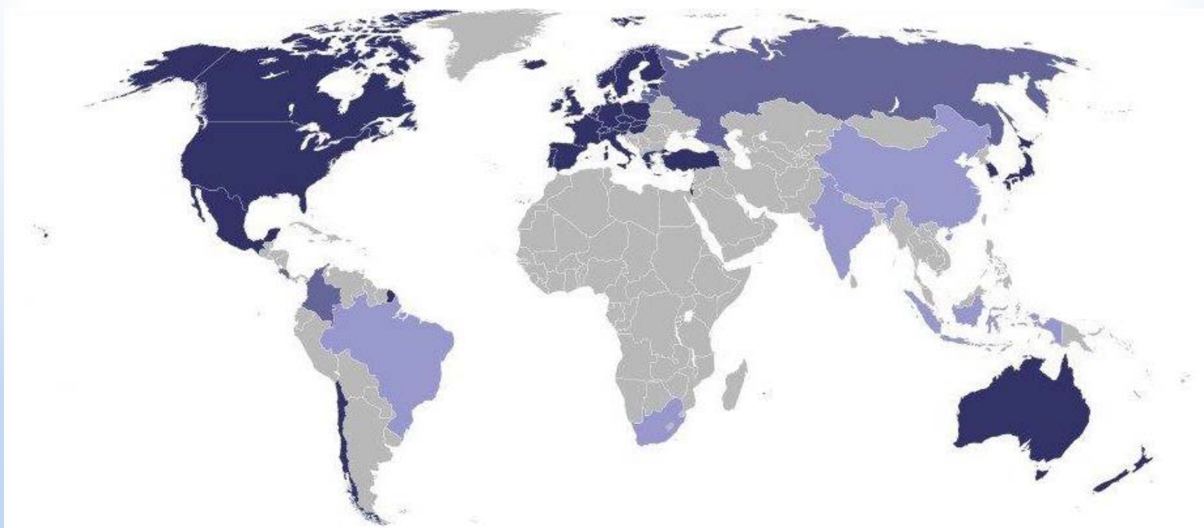
NSF's Global Presence
(sustainability well represented in large projects)



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



Defining convergence for research and education at NSF

NSF by the Numbers

93%
funds research, education and related activities

$7.5B
FY 2017 Enacted

50,000
proposals evaluated

2,000
NSF-funded institutions

11,000
awards funded

359,000
people NSF supported

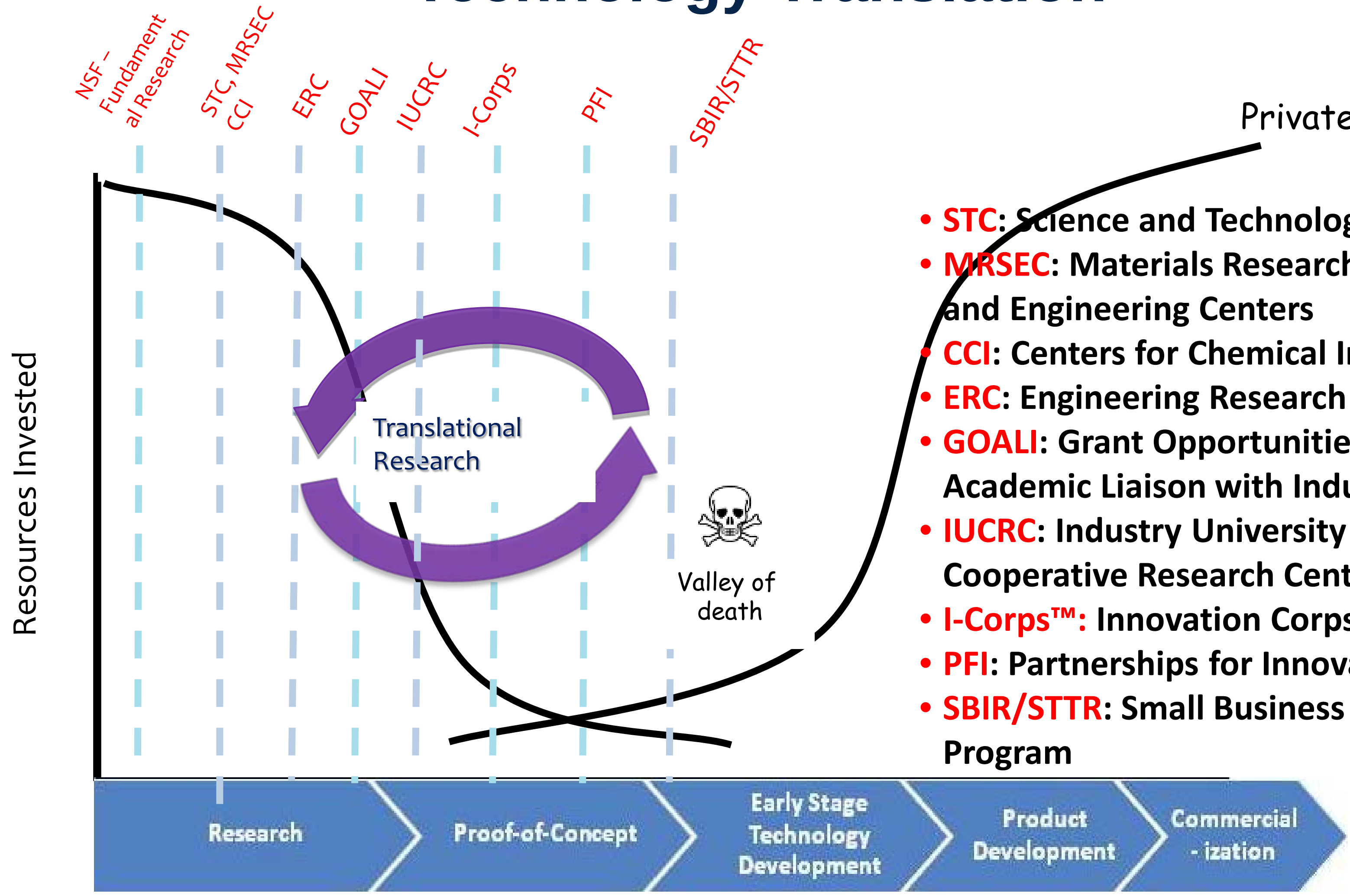
$1.2B
STEM education

$100M
to seed public/private partnerships

231
NSF-funded Nobel Prize winners

Numbers shown are based on FY 2017 activities.

Technology Translation



- **STC**: Science and Technology Centers
- **MRSEC**: Materials Research Science and Engineering Centers
- **CCI**: Centers for Chemical Innovation
- **ERC**: Engineering Research Centers
- **GOALI**: Grant Opportunities for Academic Liaison with Industry
- **IUCRC**: Industry University Cooperative Research Centers
- **I-Corps™**: Innovation Corps
- **PFI**: Partnerships for Innovation
- **SBIR/STTR**: Small Business Research Program

2001-
2017

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

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

FY 2018 Budget planned: **$421 M**

FYs 2017 actual ~ $465 M (including other core programs)

*FYs 2000-2017: NSF total investment is ~ **$38 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

RESEARCH IDEAS

Harnessing Data for 21st Century Science and Engineering

Work @ the Human-Technology Frontier: Shaping the Future

Navigating the New Arctic

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

The Quantum Leap: Leading the Next Quantum Revolution

Understanding the Rules of Life: Predicting Phenotype

PROCESS IDEAS

Mid-scale Research Infrastructure

NSF 2026

Growing Convergent Research at NSF

NSF INCLUDES: Enhancing STEM through Diversity and Inclusion

NSF Ten Big Ideas for Future NSF Investments

- Topical application areas-

Several opportunities of implementation of convergence

- Production processes
- Biomedicine, science and engineering
- Individualized learning

- Research and Education
- Intelligent cognitive assistants
- Citizen science

- Governance (local, national, global)
- Sustainability/global change (at NSF)
- Smart communities

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

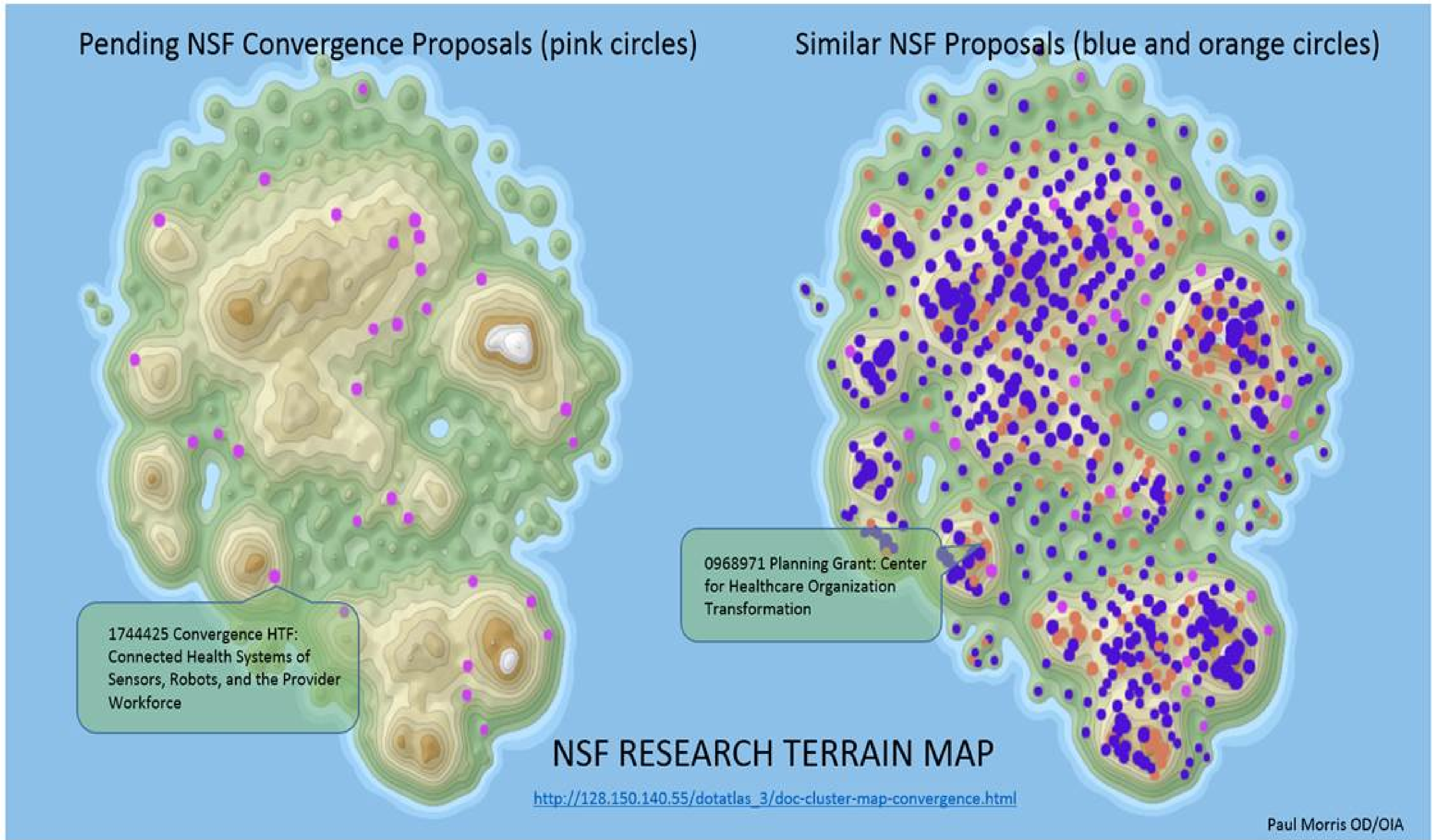
Convergence is the deep integration of knowledge, techniques, and expertise to form new and expanded frameworks for addressing scientific and societal challenges and opportunities, with two primary characteristics:

1. *Deep integration across disciplines*, *from which n*ew 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.

Ex: Upstream: **Germination**; Downstream: **Innovation Corps**

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

Convergence award topics "in the valleys" between traditional topics



Examples for: Convergence methods in education

- **Trading zones** among various areas of relevance

- **Confluence of topics**: bringing together
  - *Feasibility topics* (science and engineering),
  - *Desirabillity topics* (art and humanistics) with
  - *Viability topics* (economics and management)

- **Using higher level languages** (such as art, music, mathematics and other abstractization tools, virtual reality connecting fields, value and intellectual driven fields, challenge inspiring connections, ..)

Example in Education:

National Convergence Technology Center

illustrated for Collin County Community College, CA

www.connectedtech.org

The National Convergence Technology Center (CTC) leads the Convergence College Network (CCN), a group of 50+ community colleges and universities from across the country that shares resources and best practices at both regularly scheduled meetings and special one-off webinars.

Several future trends

- Hierarchical, modular, NBICA manufacturing
- Sustainability nanotechnology: recyclability, W, En, F
- Gene editing in medicine, agriculture, energy
- Brain–to-brain and -machine communication
- Quantum entanglement, communication and computing
- NT for smart systems: general purpose AI and IA, Intelligent Cognitive Assistants, in production, cyber-physical-human systems, transport, healthcare.

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)*

This NanoForum

- 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