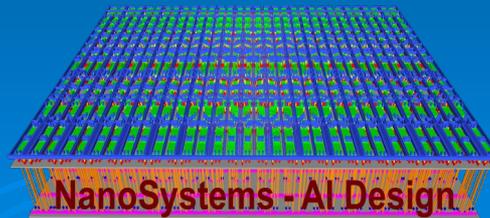




Nanoscale Science and Engineering at NSF

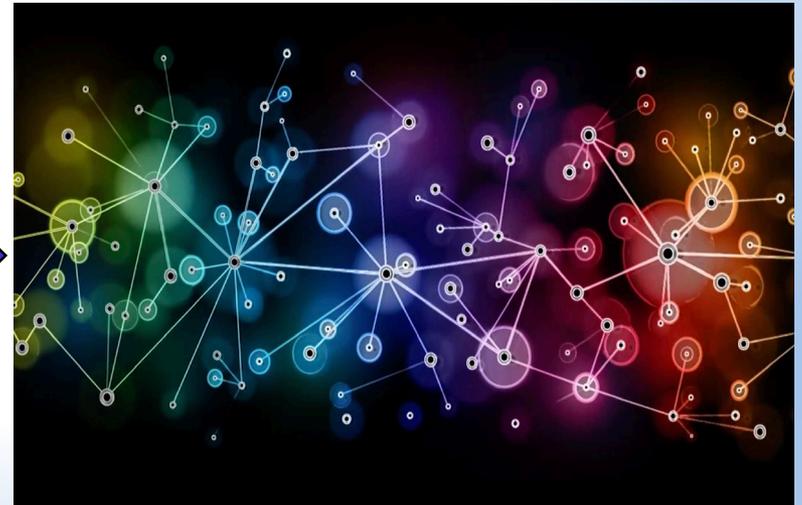
Mike Roco
NSF and NNI



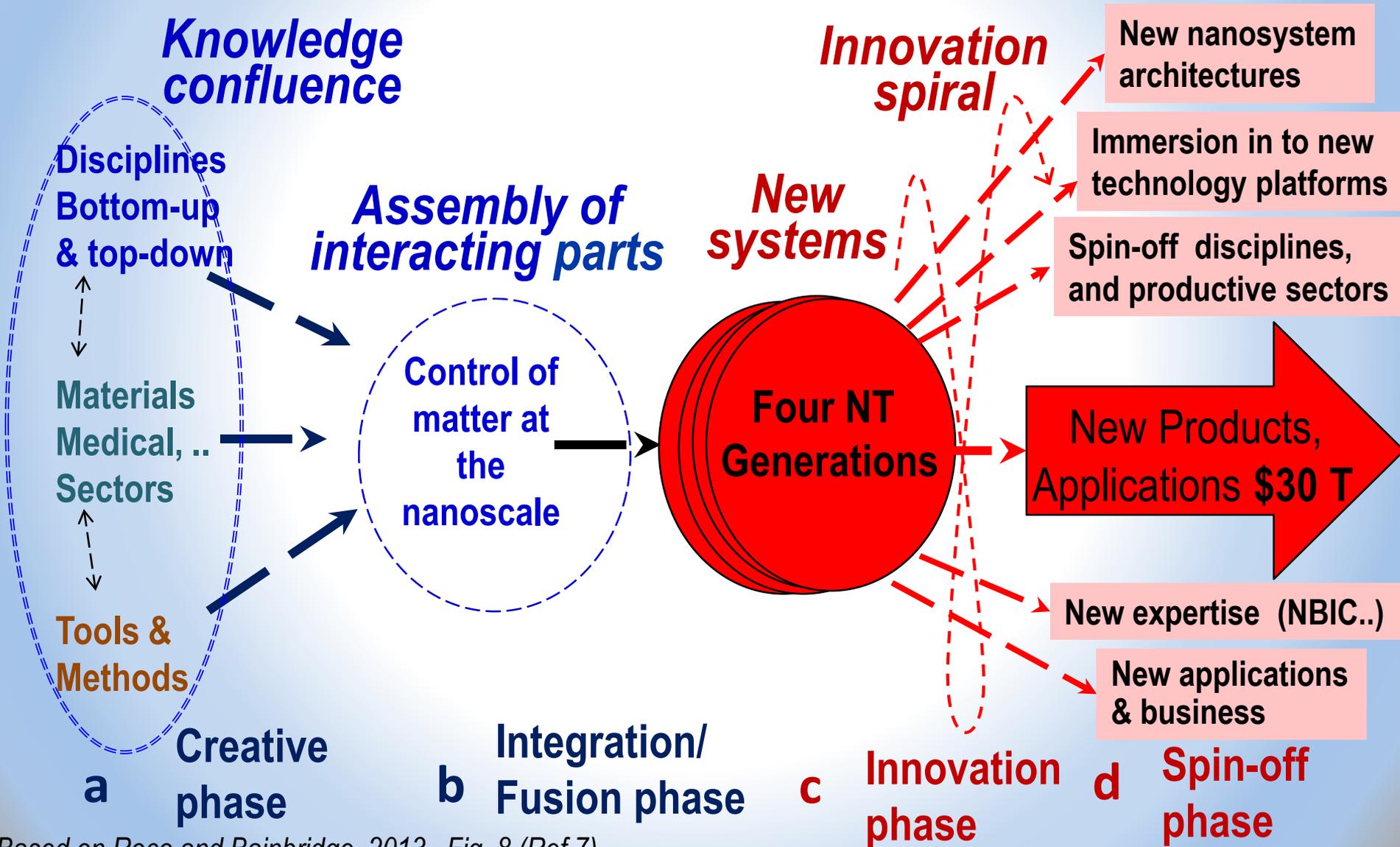
Credit: S. Mitra, Stanford U., 2019

19-th NSF Nanoscale Science and Engineering Grantees Conference
Alexandria, December 9-10, 2019

Vision-inspired view of nanotechnology development 2000 - 2030

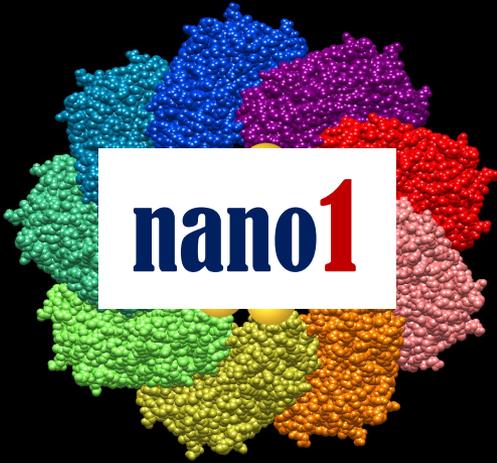


2000-2030 **Convergence-Divergence** cycle for global nanotechnology development

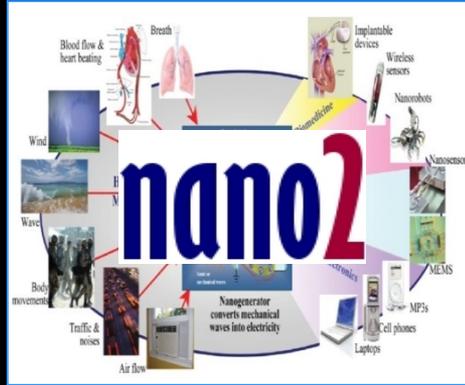


Based on Roco and Bainbridge, 2013, Fig. 8 (Ref 7)

2000



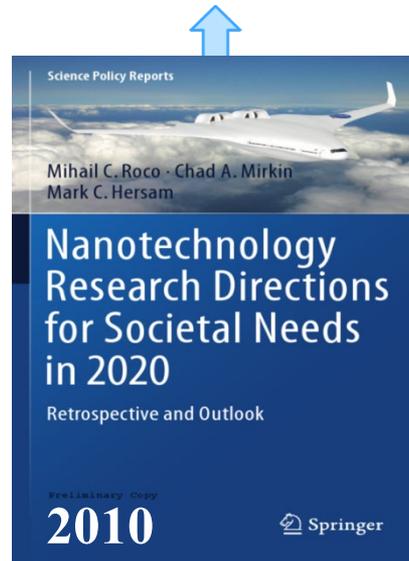
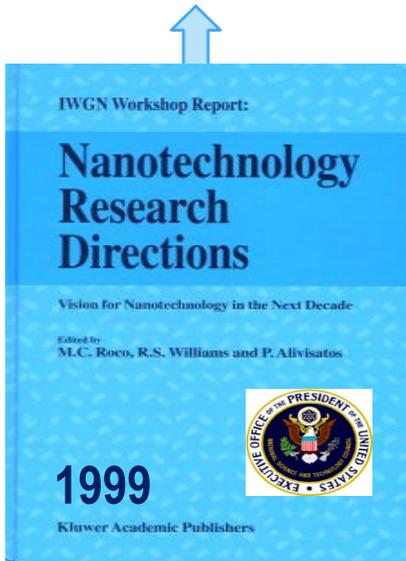
2010



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)

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

Based on NANO 2020, Fig. 5 (Ref. 4)

2030

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

DIVERGENCE

CONVERGENCE

2000

GENERATIONS OF NANOPRODUCTS

6. *Nanosystem
Conv. Networks*

5. *NBIC Technology
Platforms*

4. *Molecular
Nanosystems*

3. *Systems of
Nanosystems*

2. *Active
Nanostructures*

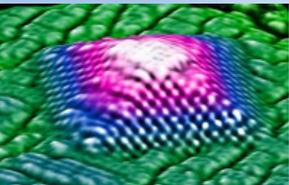
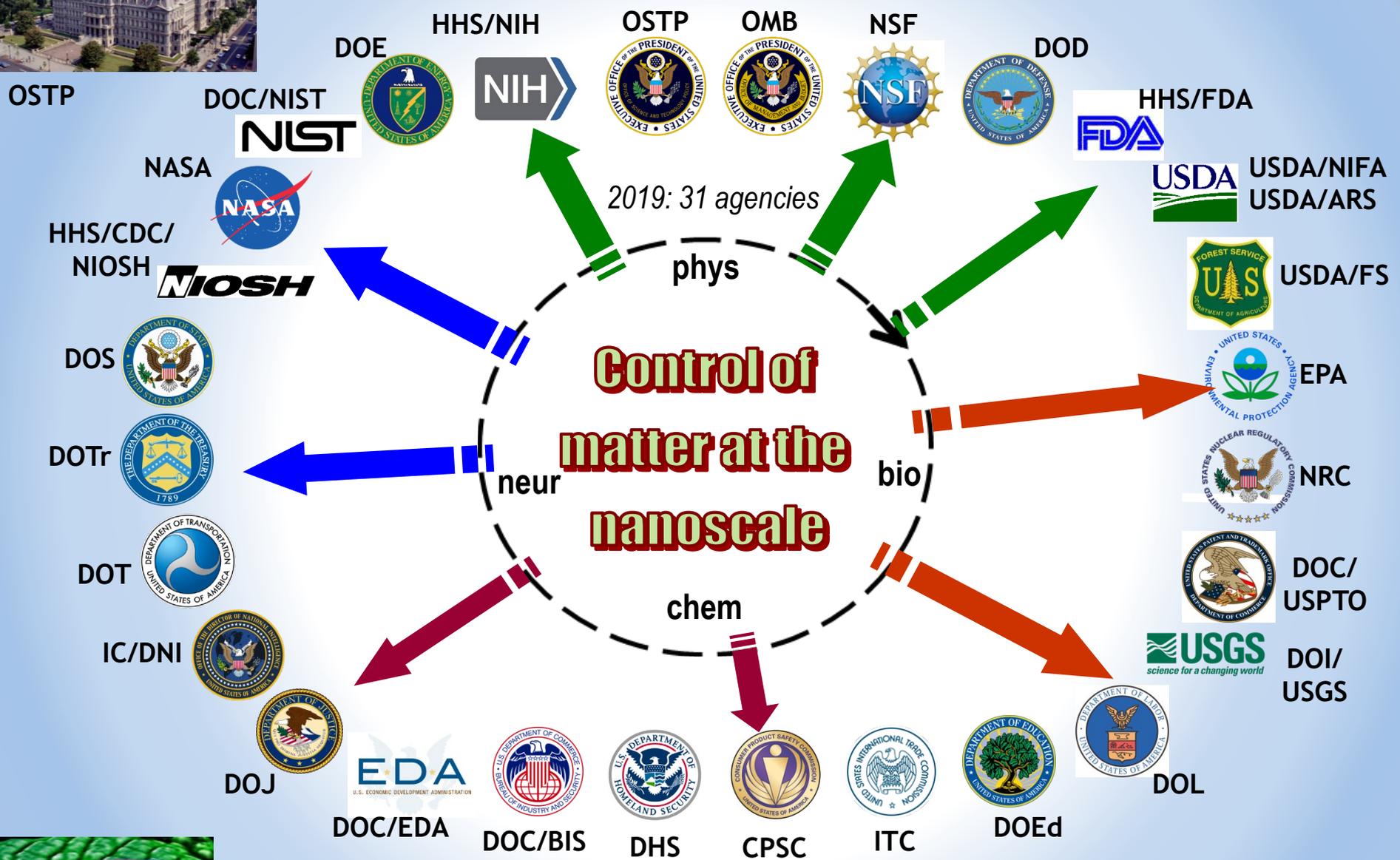
1. *Passive
Nanostructures*

nano2 Twelve global nano trends to 2020

10 year perspective, www.wtec.org/nano2/ (Ref. 4 and its summary paper)

- 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**

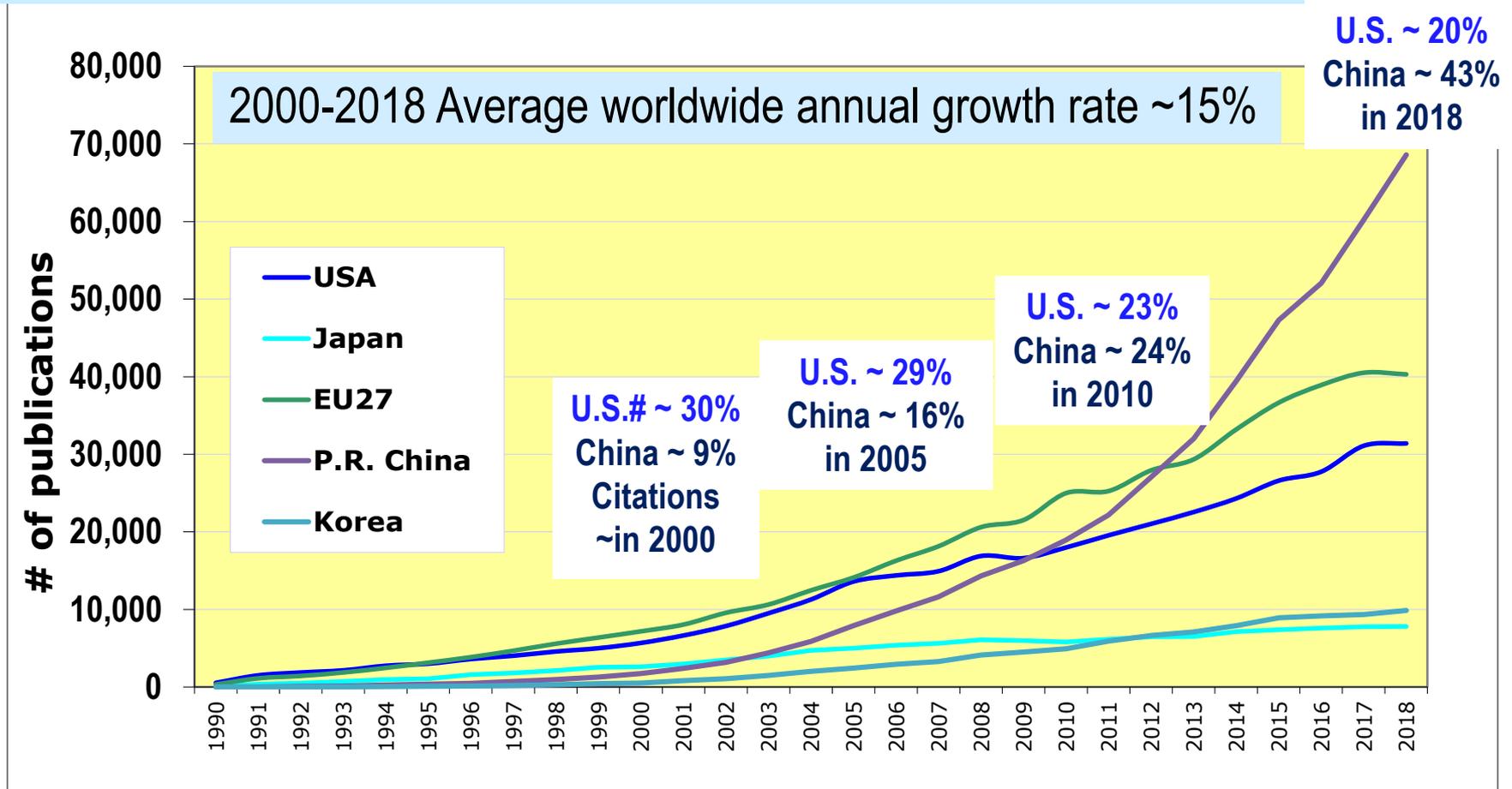
I. Nanotechnology programs: S&T divergence



U.S. National Nanotechnology Initiative, 2000-2030
Other 80 countries have created nanoscale R&D programs

Nanotechnology publications in the WoS: 1990 - 2018

*“Title-abstract” search for nanotechnology by keywords for five regions
(update of NANO 2020, Fig 1 [3])*



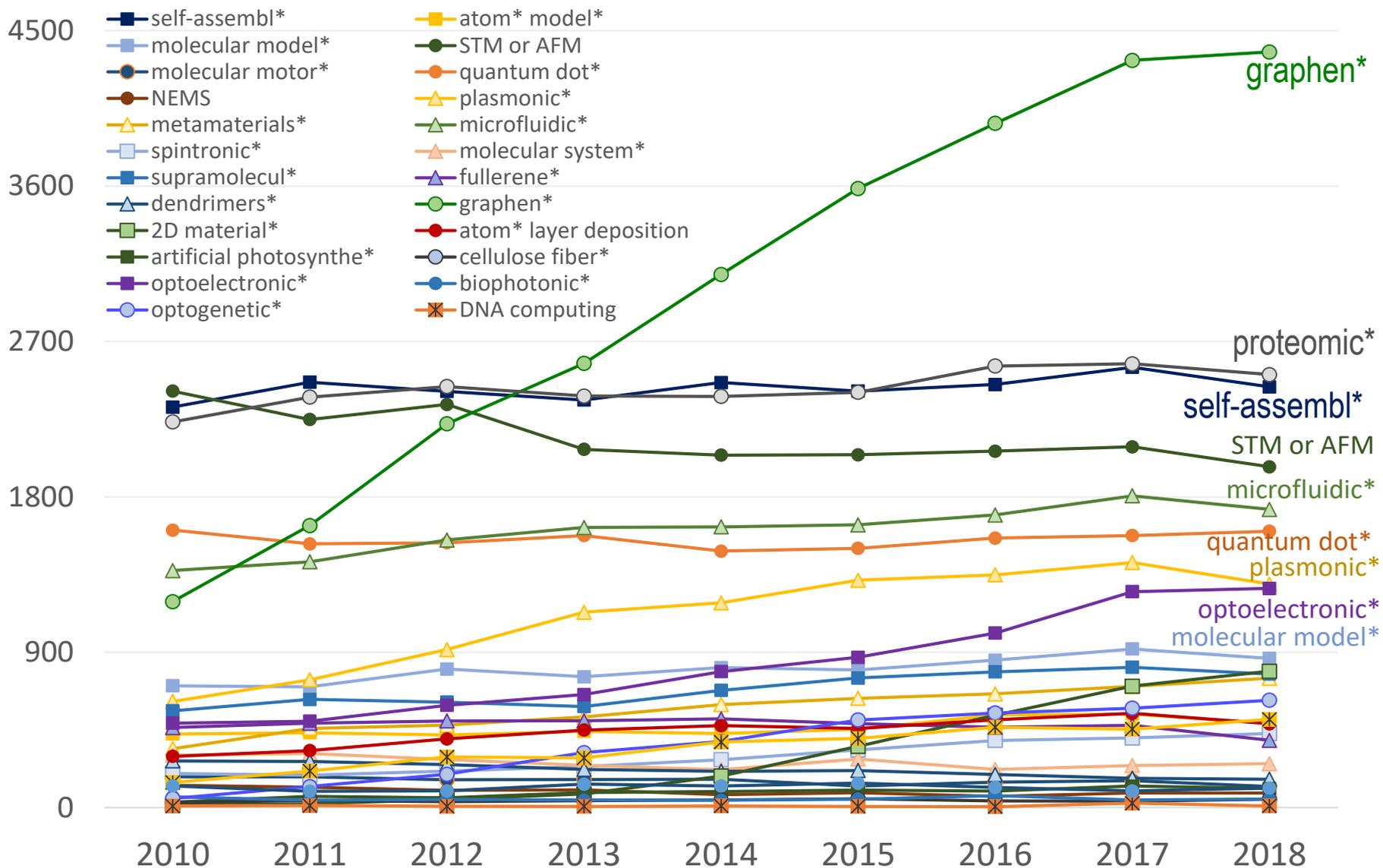
Rapid, uneven growth per countries

MC Roco, Dec 9 2019

U.S. contribution from ~29% in 2005 to ~20% in 2018 (about -0.7% per year)

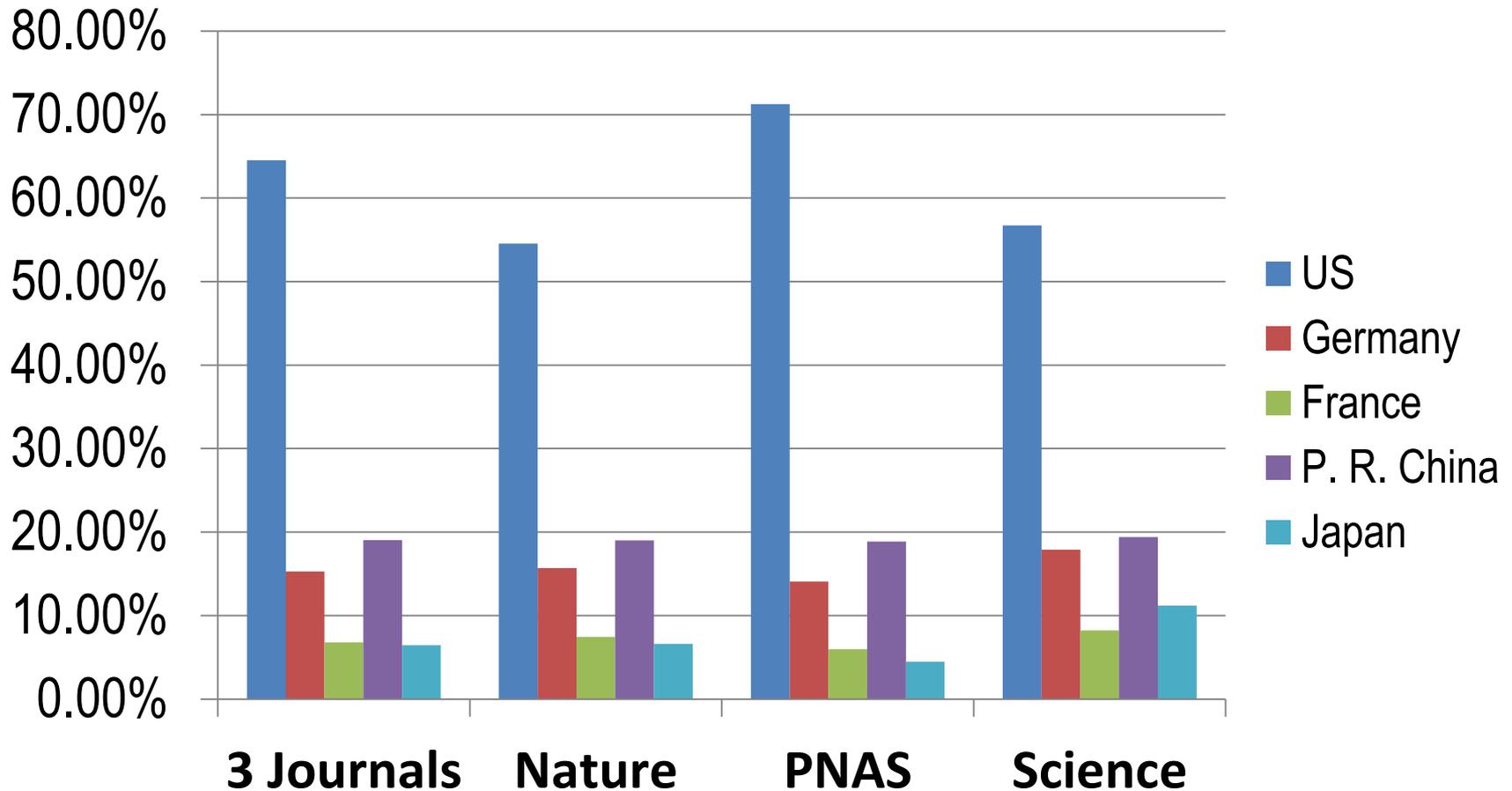
Nanotechnology publications in United States 2010 - 2018

"Title-abstract" search in WoS by individual keywords: nano + 27 (method Nano2020, Ref 3)*



Five countries' contributions to Top 3 journals in 2018

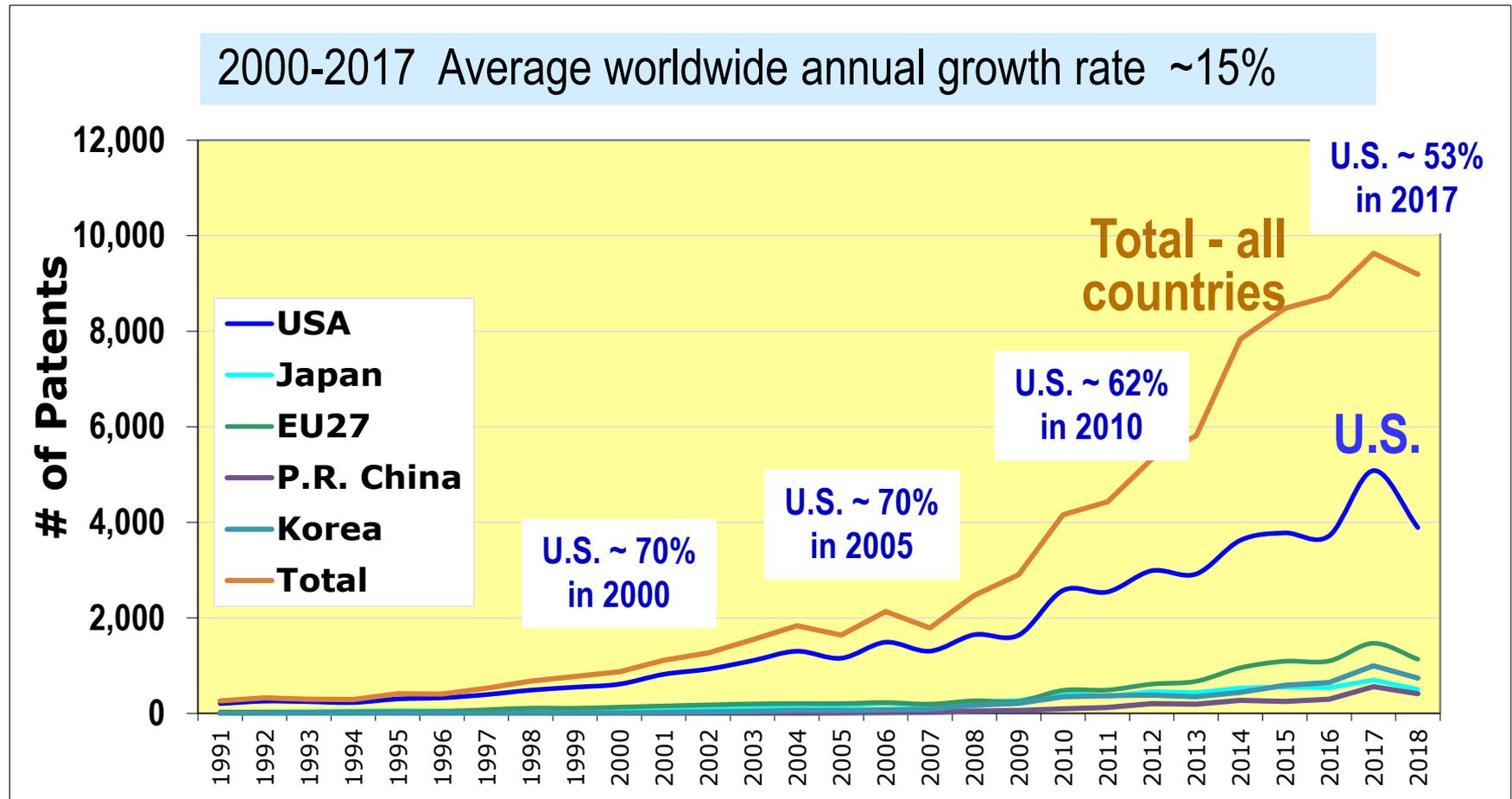
(about the average for last 5 years)



* Each article is assigned to multiple countries if its authors have different nationalities. Therefore, the sum of percentages from five countries exceeds 100%; ** Combined Keywords

Nanotechnology patents at USPTO: 1991-2018

"Title-abstract" search of nanotechnology by keywords (updt. Chen & Roco [7]); (data May 2019)

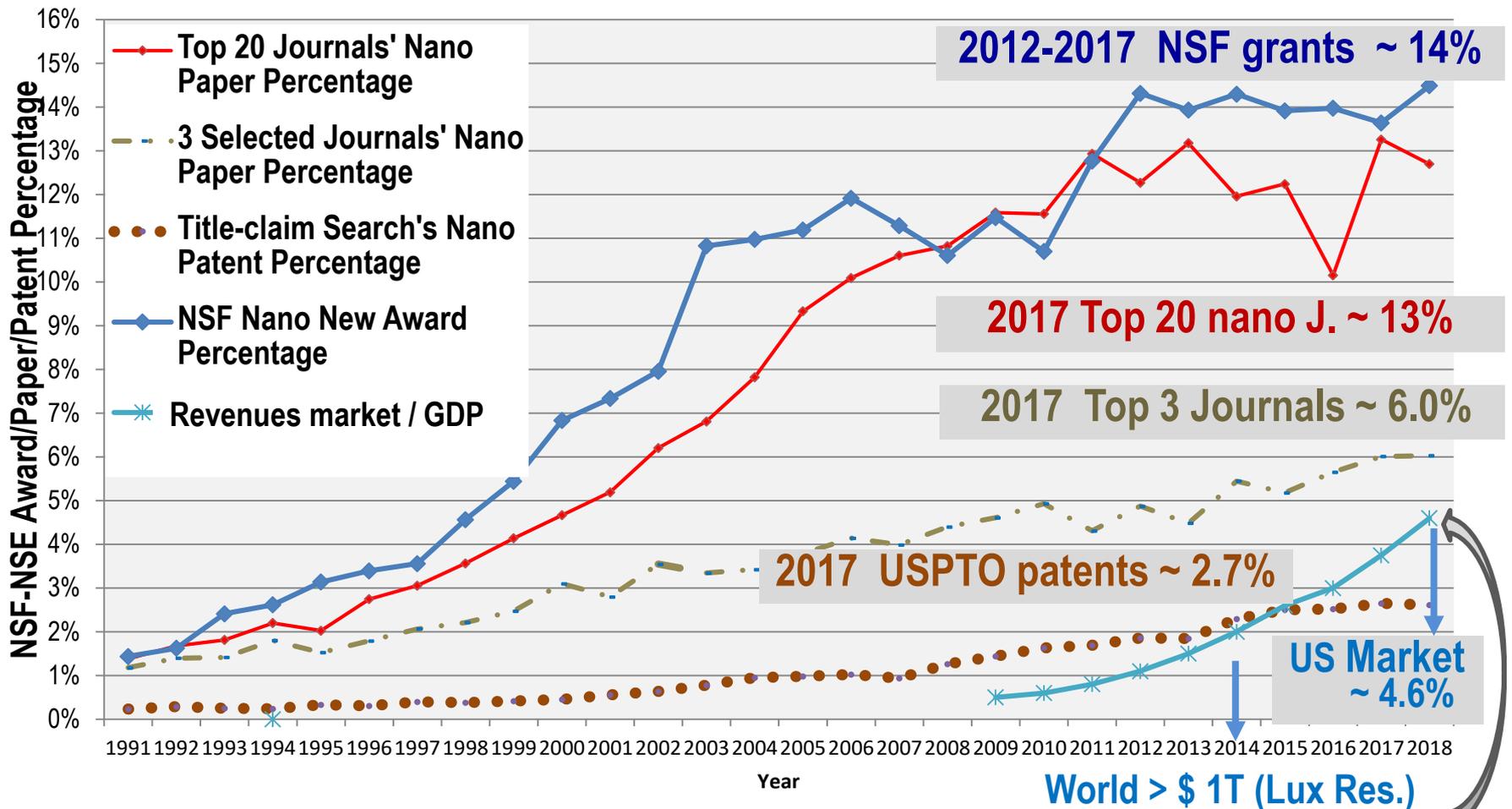


U.S. patent authors maintain the lead at USPTO in 2018

U.S. patent authors from ~70% in 2005 to ~53% in 2017 (about -1.4% per year)

Percentage rate of penetration of nanotechnology in NSF awards, WoS papers and USPTO patents (1991-2018)

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

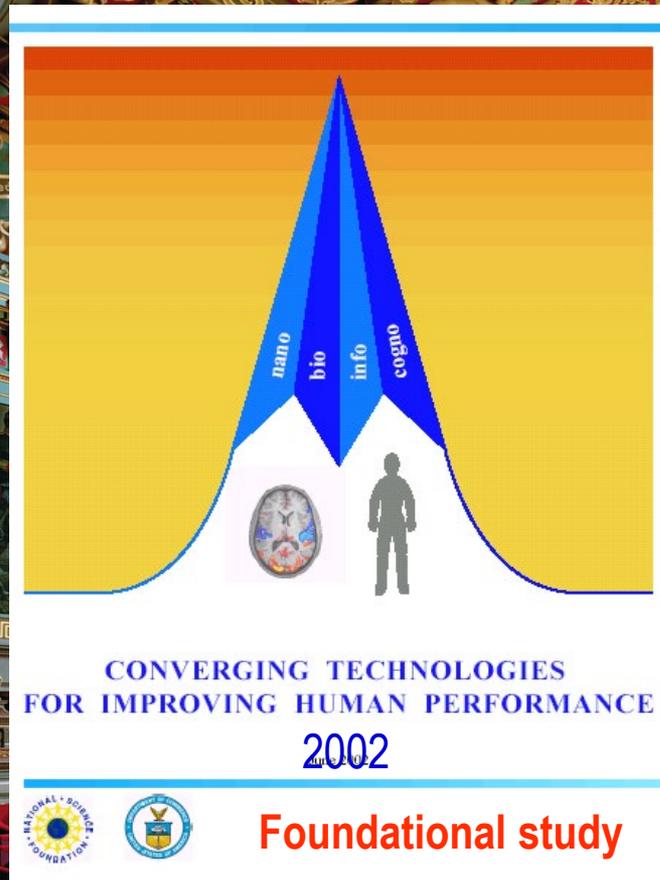


Est. US Market / US GDP: 2014 ~ 2%; 2018 ~ 4.6%; 2020 ~ 6% (if 25% market growth rate)

CONVERGENCE OF KNOWLEDGE, TECHNOLOGY, AND SOCIETY:

Beyond Convergence of Nano-Bio-Info-Cognitive Technologies

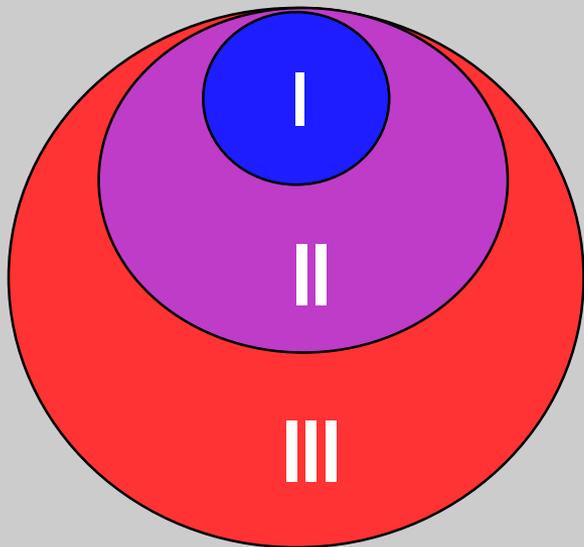
www.wtec.org/NBIC2-Report; M. Roco et al.



INTERNATIONAL BENCHMARKING and APPLICATIONS

Springer 2013

Three hierarchical stages of *STI convergence*



- I Nanotechnology (**NT**) ; **IT** ; **AI**
- II Foundational fields (**NBICA**)
- III Global society oriented initiatives (**CKTS**)

Nanotechnology development

also is guided by the convergence principles

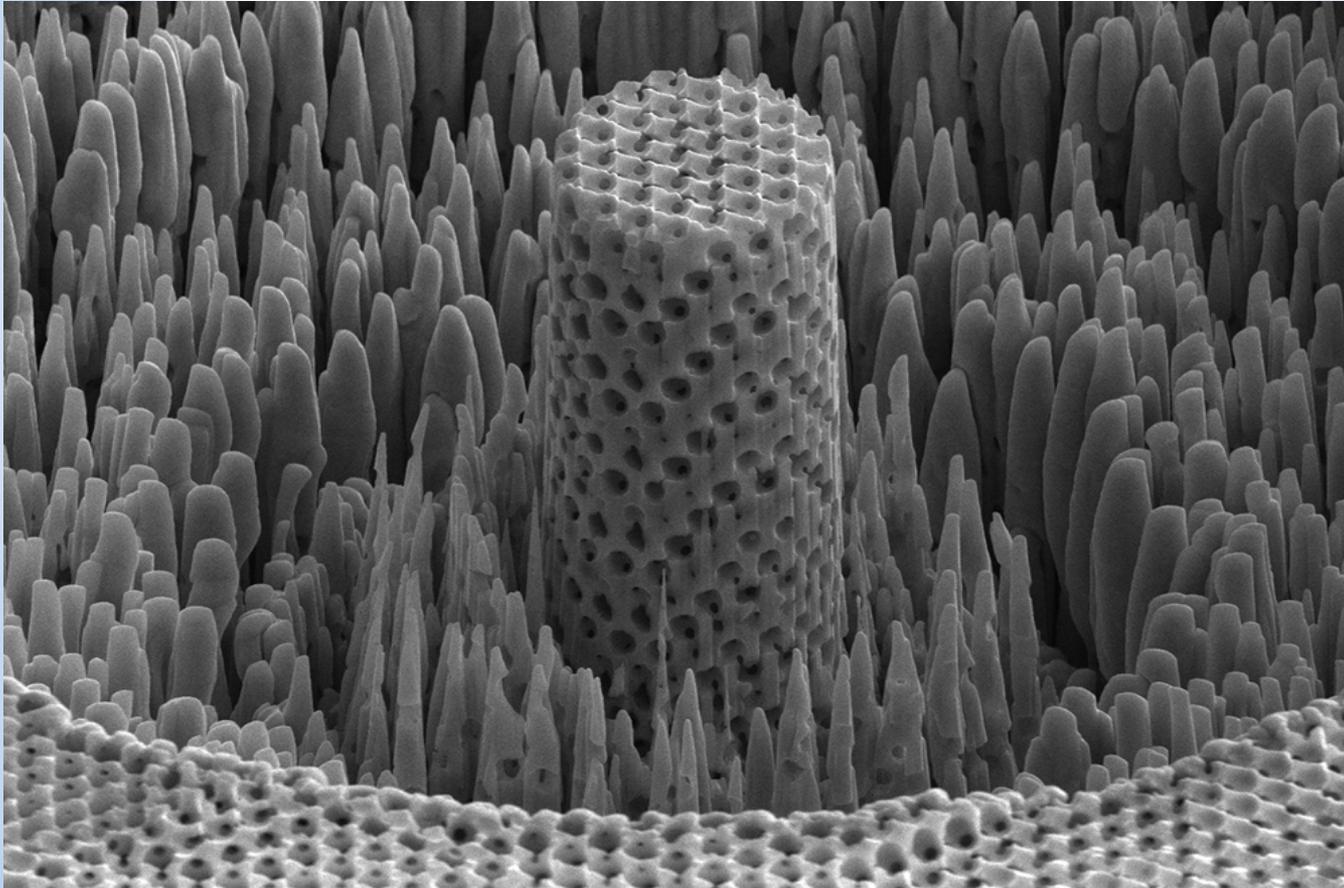
- A. **Holistic view** – *Unity of matter; essential interactions; deep integration of disciplines*
- B. **Common goal** – *Systematic nano-control to get target properties/functions/devices/systems*
- C. **Dynamic pattern** - *Spiral convergence to nanosystems & emerging applications*
- D. **Unifying actions** - *Nanosystem-logic deduction in decisions & problem solving*
- E. **Cross-domain** – *Nano concepts and methods*
- F. **Multi-tasking** - *Concurrent nanoscale phenomena and processes*
- G. **Added-value** - *Confluence of effects leading to novel nanosystems and applications*

PRINCIPLES FOR CONVERGENCE



(applied to NT neural network ecosystem)

'Metallic wood' has the strength of titanium and the density of water



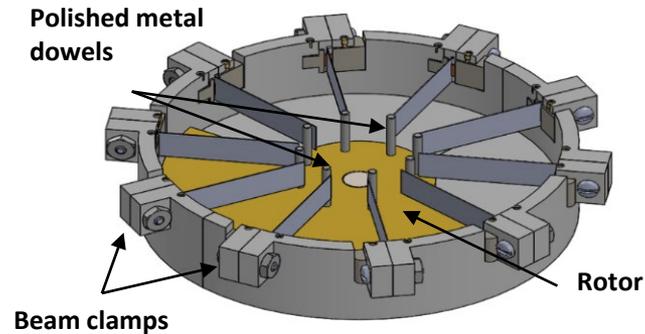
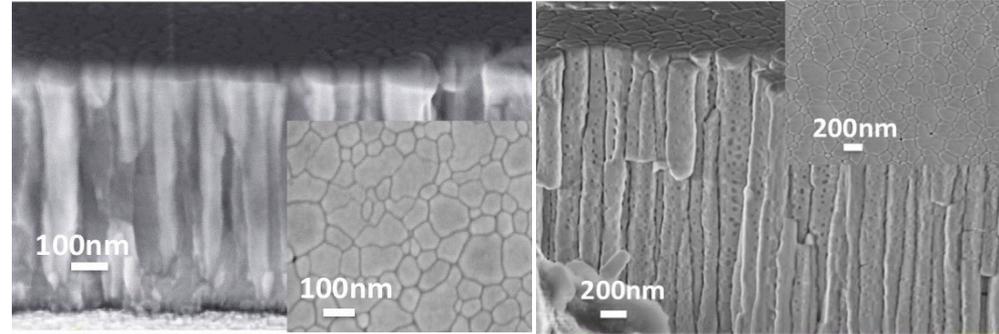
U.Penn, UIUC, U Cambridge; Nature Scientific Reports, Jan 2019

Motion harvesters enabled by nanomaterials

Mechanical energy harvesters convert body motion to electrical energy.

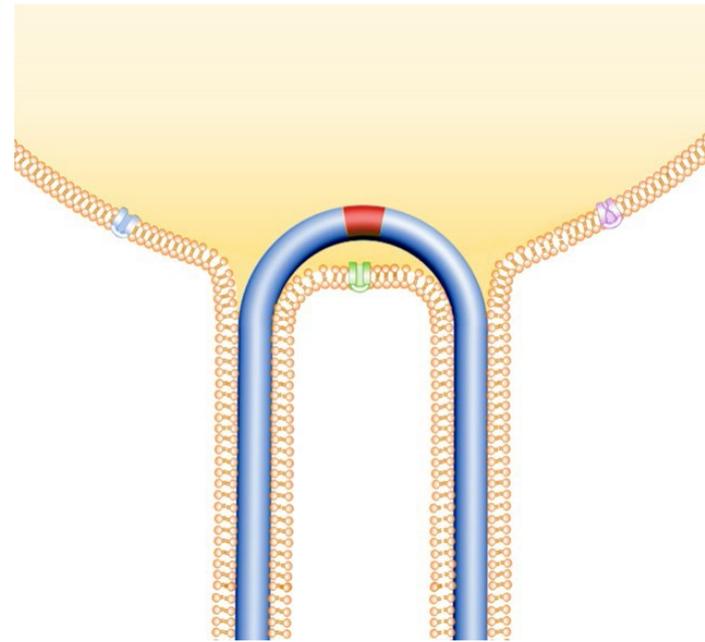
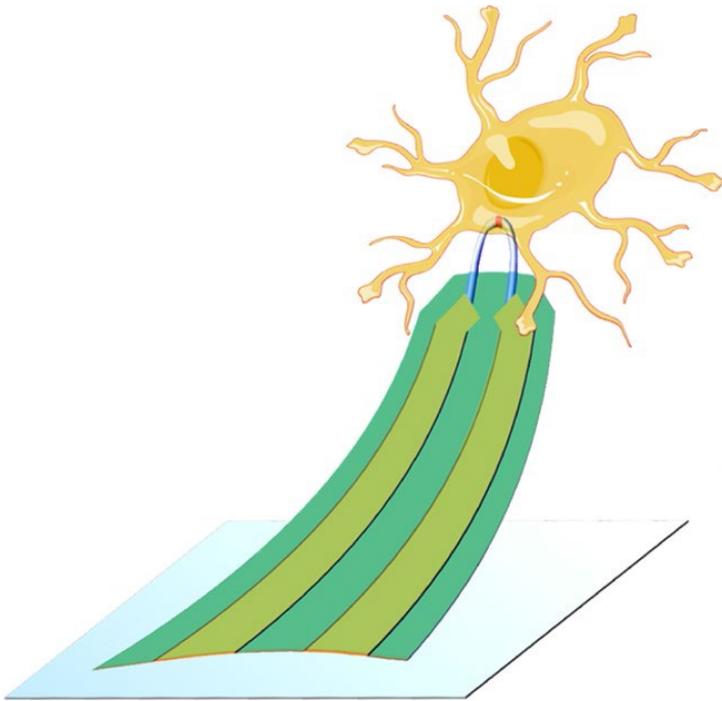
- **Nanostructured lead zirconium titanate piezoelectric materials** deposited on thin Ni foils are strained upon body motion

- **~ 150 microWatts with normal walking**

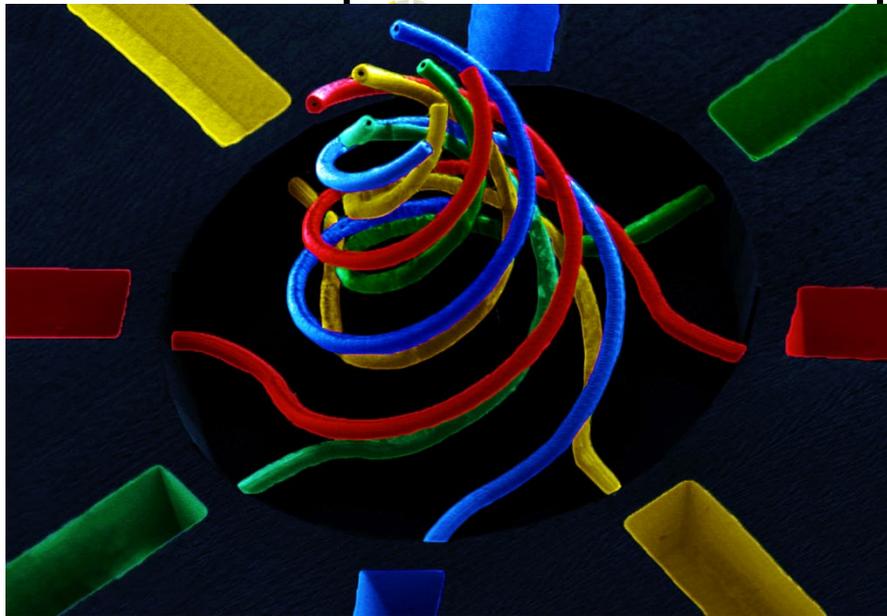


Credit: ASSIST, 2019

Three-dimensional nanowire transistor probes for intracellular recording



Charles Lieber group (Y. Zhao et al, Nature Nanotech 2019)



“3D Nanoprinting” architecturally complex microfluidic channels

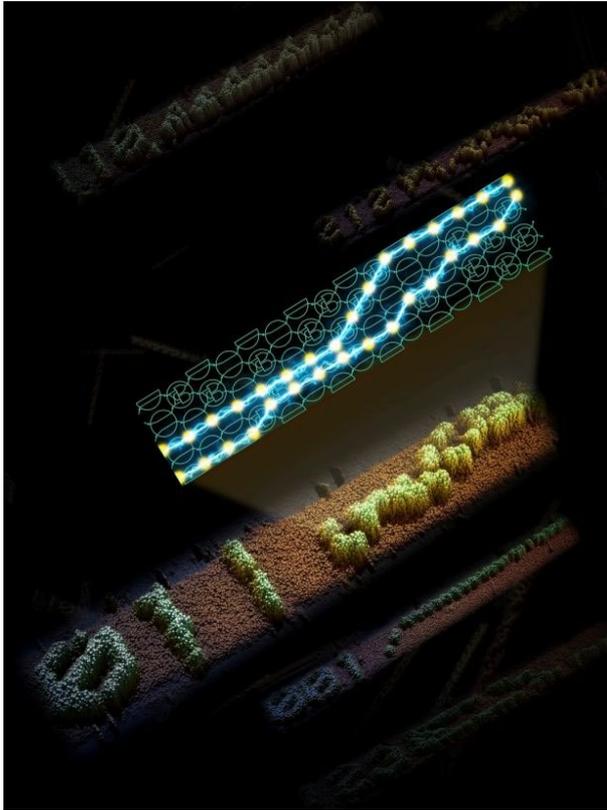
- **3D, interwoven microvessels** with inner diameters $< 10 \mu\text{m}$ and wall thicknesses of $2 \mu\text{m}$
- **The smallest 3D printed microfluidic transistor** (wall thicknesses = 500 nm)

University of Maryland, College Park,
and the University of Utah; CMMI NM
1761395 & 1761273

Caption: False-colored SEM image of eight intertwined 3D nanoprinted tubular microvessels

Image Credit: Ryan D. Sochol Lab, University of Maryland, College Park

A multi-purpose, reprogrammable molecular computer



- “Self-assembly molecular computers” uses artificial DNA
- The research includes developing algorithms to perform programmable functions (similar to a standard computer)

Damien Woods et al., Maynooth University
(NSF 1219274 et al)

A molecular circuit built using DNA (funding by the NSF and NASA). Photograph: Demin Liu (Molgraphics) and Damien Woods (Maynooth University) (2019)

<https://www.irishtimes.com/news/science/monaghan-scientist-involved-in-molecular-computing-breakthrough-1.3832929>

Quantum computing breakthrough: with 53 qubits (nanostructured)

Sycamore processor (Google Oct. 2019) takes about 200s to sample one instance of a quantum circuit a million times— equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years.”

- **Tested only** for “For a suitable computational task of sampling the output of a pseudo-random quantum circuit”;
Not yet confirmed by others.

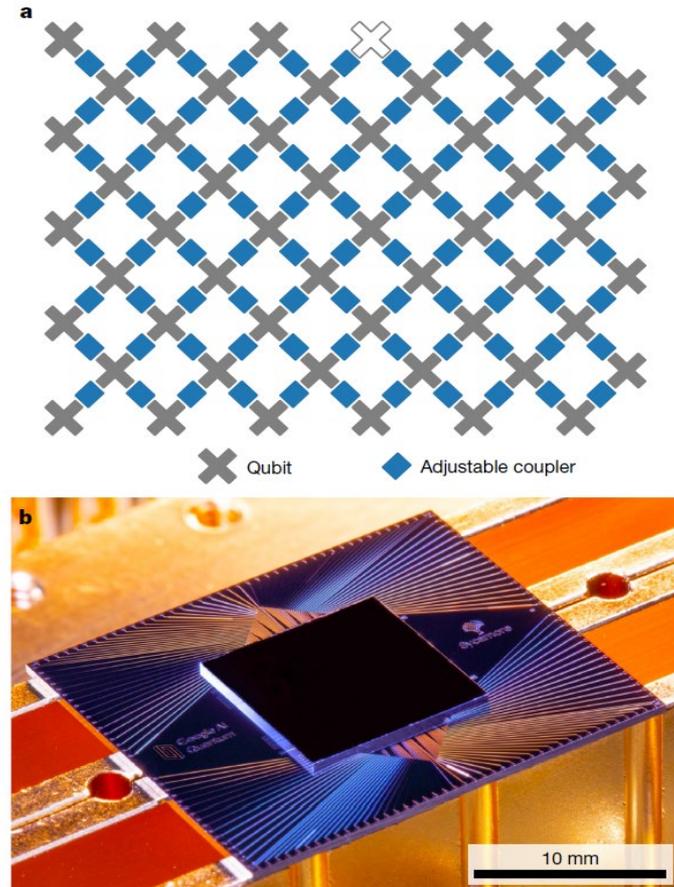


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. b, Photograph of the Sycamore chip.

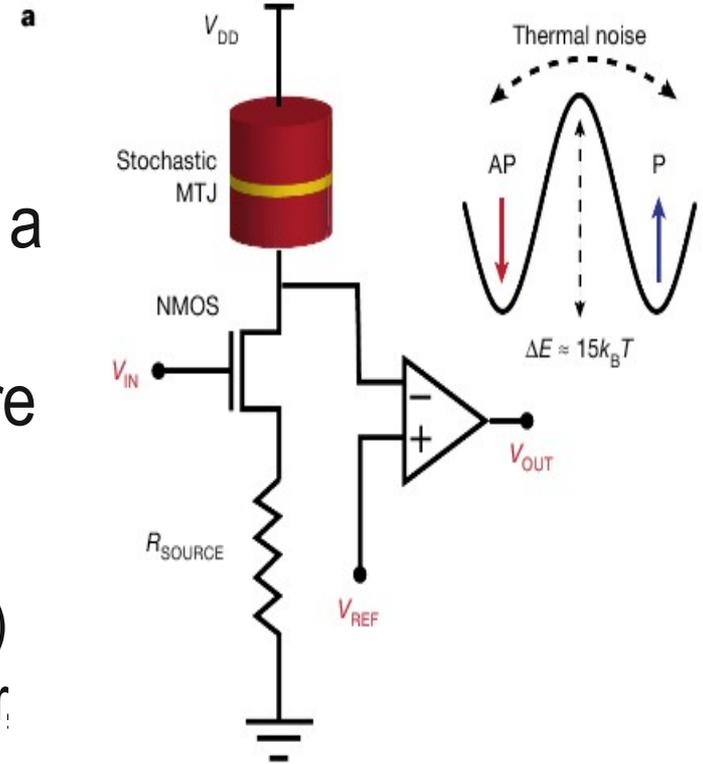
Arute et al., Nature, Oct. 24, 2019

“Poor Man’s Qubit” shown to rival Quantum Computing

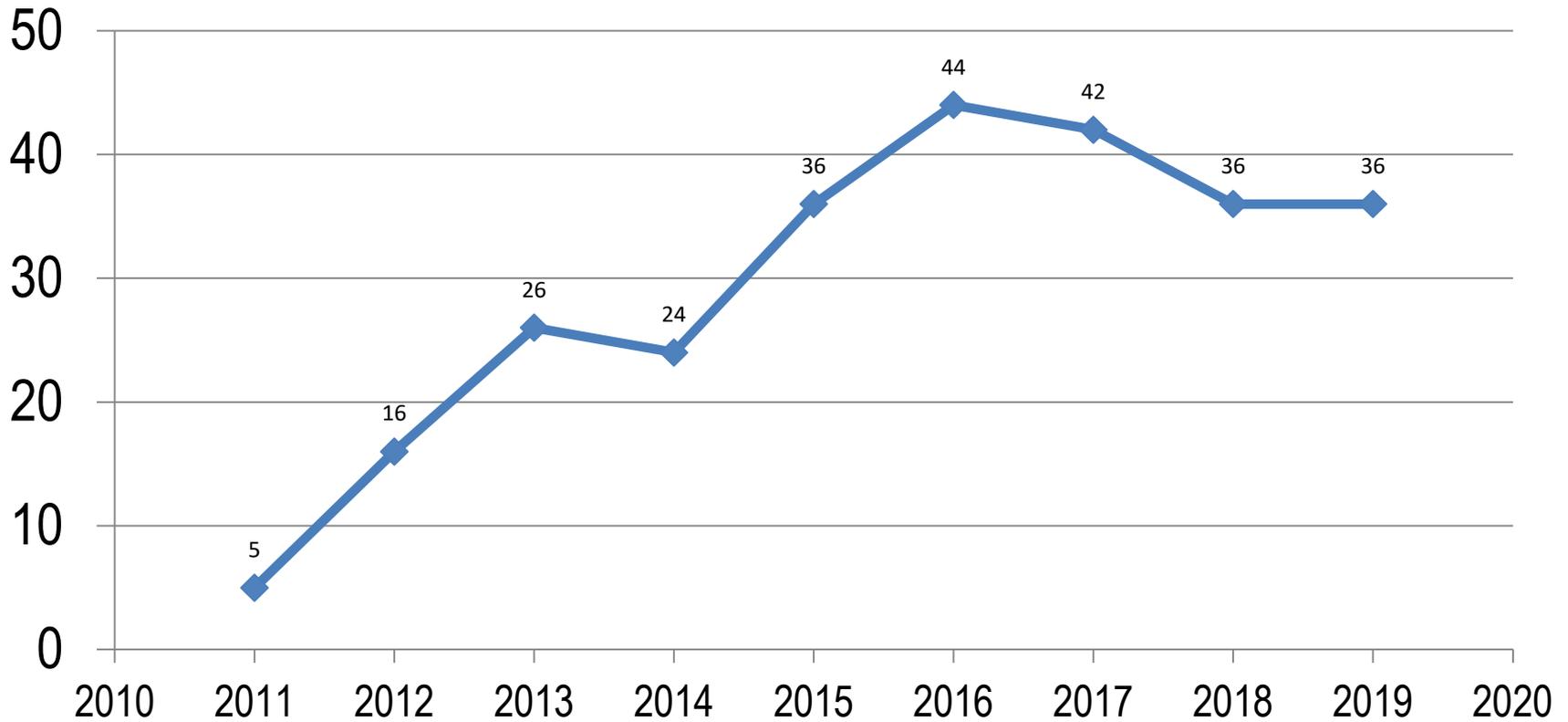
Build an 8 **“P - bit”** computer using stochastic nanoscale magnets

([Nature](#) article. -18 Sept 2019). Can split a large number into prime-number factors, a problem that only quantum computers were previously expected to solve efficiently.

- Initial discovery by Supryio Datta’s team (2017) in the STARnet; C-SPIN Center, ASCENT Center, Purdue University, SRC JUMP, , K. Camsari et al.
- **The nCORE NSF CAPSL center** is investigating P-bits in complementary ways. CAPSL is the Purdue Center for Probabilistic Spin Logic for Low-Energy Boolean and Non-Boolean Computing.



Number of NNI related I-Corps awards FY 2011-2019



Evolution of enzymes (nanobiotechnology)

Frances Arnold, Nobel Laureate, 2018

Using enzymes mutation and selection for fitness advantages via evolution one can produce novel synthetic catalysts for a sustainable chemistry/ chemical engineering

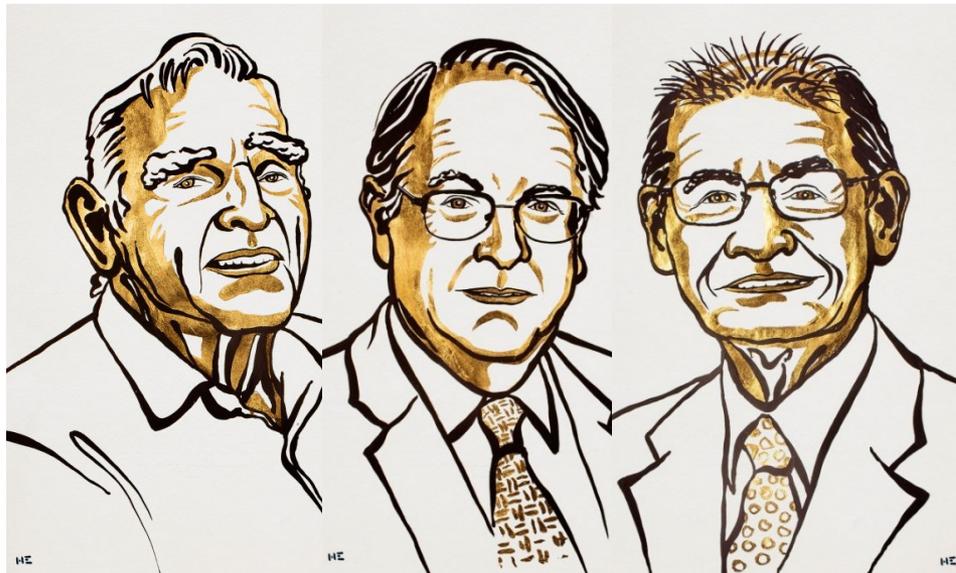


Credit: Directed Evolution: Bringing New Chemistry to Life
Frances H. Arnold, *Angew Chem Int Ed Engl.* 2018 Apr 9; 57(16): 4143–4148



Development of lithium-ion batteries using nanostructured composite materials

Nobel Prize in Chemistry 2019 awarded jointly
to John B. Goodenough, M. Stanley
Whittingham and Akira Yoshino

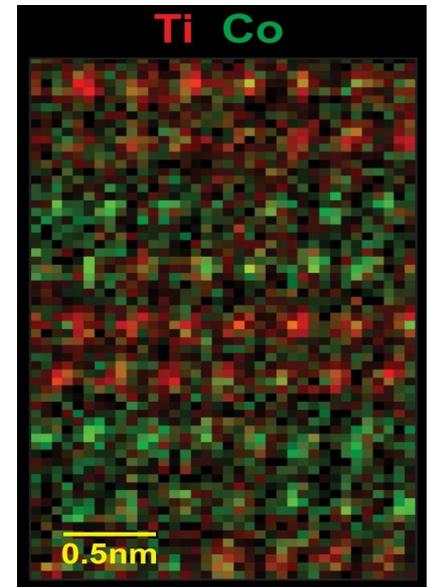


Picoscale science: electron dynamics to diversify and improve nanomaterials

Electronic systems of various kind of atoms can be coupled at the picoscale level by controlling positioning of atoms. Manipulating the orbital energies of valence electrons significantly affects the nanomaterial properties

Example: Sheets of titanium oxide one-atom thick are positioned between sheets of cobalt oxide with the same thickness. The process changes the electronic configuration and magnetic properties of the cobalt oxide sheet.

(Credit: S. Lee, Phys Review Letters 117201, 2019)



NSF Network for
Computational
Nanotechnology:

**Hierarchical
Nanomanufacturing
Node (U. Illinois)**

VISION

To simulate every step of the manufacturing process of a nano-enabled product

MISSION

To be the engine for design, simulation, planning, and optimization of nano-manufacturing processes

GOALS

- *Develop nanoMFG software tools*
- *Experimentally validate all tools*
- *Broadly disseminate*
- *Incorporate diversity at all levels*
- *Train next generation in development and utilization of nanoMFG software tools*
- *Create a sustainable framework*

**Layered
computational
tools
infrastructure**

Nanoscale transport phenomena

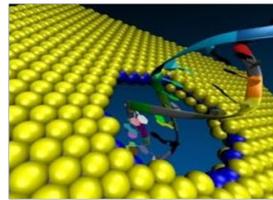
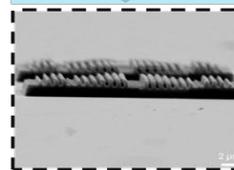
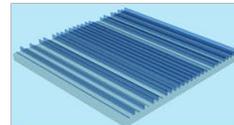


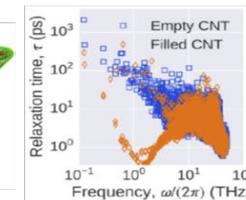
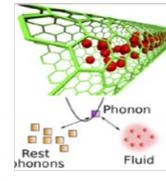
Illustration of a nanopore created in a 2D material by ion bombardment
[N. Aluru]

Process Models



A flat optical lens created by TPL

Multiscale Transport Phenomena



Energy Dissipation in Fluid Coupled Nanoresonators [N. Aluru]

Nanoscale self-assembly

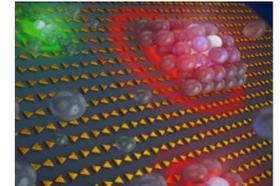


Illustration of plasmon-assisted particle assembly
[K. Toussaint]

Examples of exploratory research

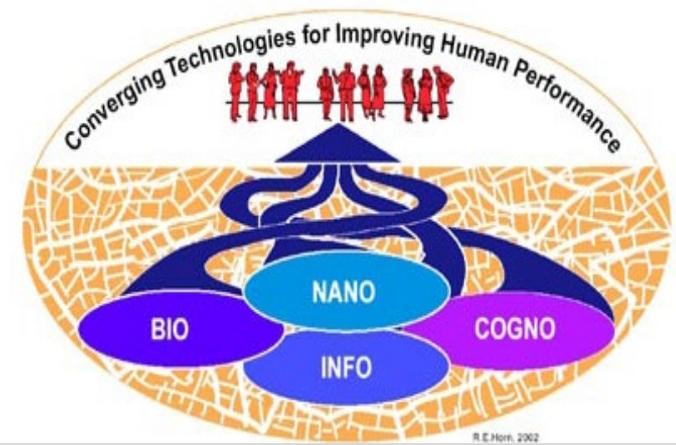
- **Ferroelectric materials, topological insulators,...**
- **Teleportation** of information and quantum calculations
- **Atomically precise manufacturing** (for quantum devices,....)
- **Nanodevices for AI, and AI design of nanosystems**
- **Synthetic biology, DNA editing and replacing**
- **Electronic & quantum biology and medicine**
- **Hierarchical self-assembly systems** that can adapt and evolve according to environmental changes (“room at the top”)
- **Bottom-up agriculture** (molecular food supply)
- **Economical solutions** for medical care, distributed energy conversion and water filtration



Ex I. Nanotechnology Spin-offs

- **Quantum systems** - *Quantum S&T 2003; NQI 2018*
- **Metamaterials** - 2004
- **Plasmonics** – 2004
- **Synthetic biology** - 2004
- **Modeling / simulation** - *Materials Genome Initiative 2011*
- **Nanophotonics** - *National Photonics Initiative 2012*
- **Nanofluidics**
- **Carbon electronics**
- **Nano sustainability**
- **Nano wood fibers**
- **... DNA nanotechnology, Protein nanotechnology, Nanosystems-mesoscale, Quantum BIO, Nano NEURO**

//. Nano-Bio-Info-Cognitive Converging Technologies



NBIC 2001: NSF Workshop “Converging Technologies for Improving Human Performance: Nano-Bio-Information-Cognition”

NBICA 2015: add general purpose “Artificial intelligence” as a foundational emerging field

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



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

OSTP

Brain-like Computing; Smart systems

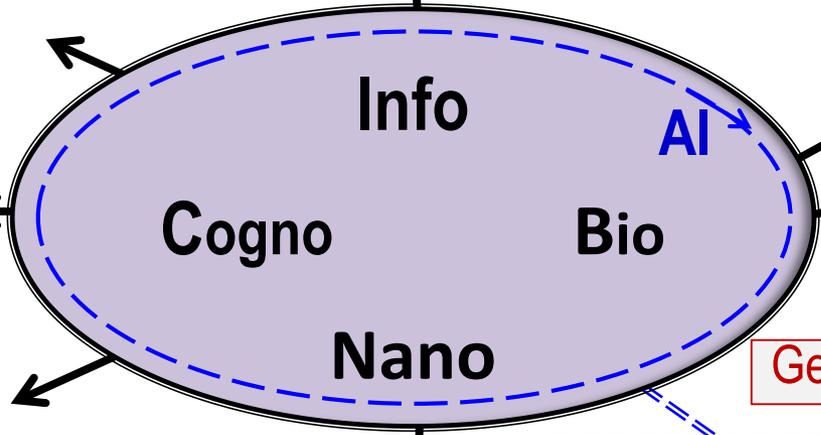
Big Data | National Strategic Computing Initiative | 5G | AI systems

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

Artificial Intelligence

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

National Robotics Initiative

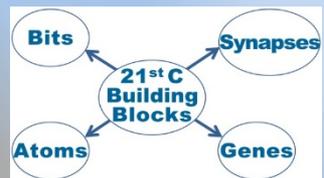


Biology centered
Biomedical / Health focus
Precision Med
Genome(s) | Microbiome

Architecture, Life, Human-technology

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

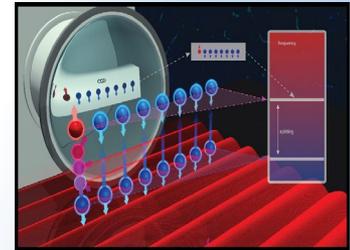
Materials Genome | Photonics | Quantum IS | NNI Grand Challenges



Ref 10: "NBIC", in Handbook of S&T Convergence, 2016

Ex II: 2016- NSF 10 Big Ideas (4 research ideas)

- Understanding the Rules of Life: Predicting Phenotype
- Work at the Human-Technology Frontier
- Data Science
- The Quantum Leap

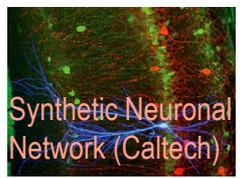


Ex II-III: 2016- NSF 10 Big Ideas (2 research ideas)

- Windows on the Universe: Multi-messenger Astrophysics
- Navigating the New Arctic



Ex II: Understanding the Rules of Life: Predicting Phenotype

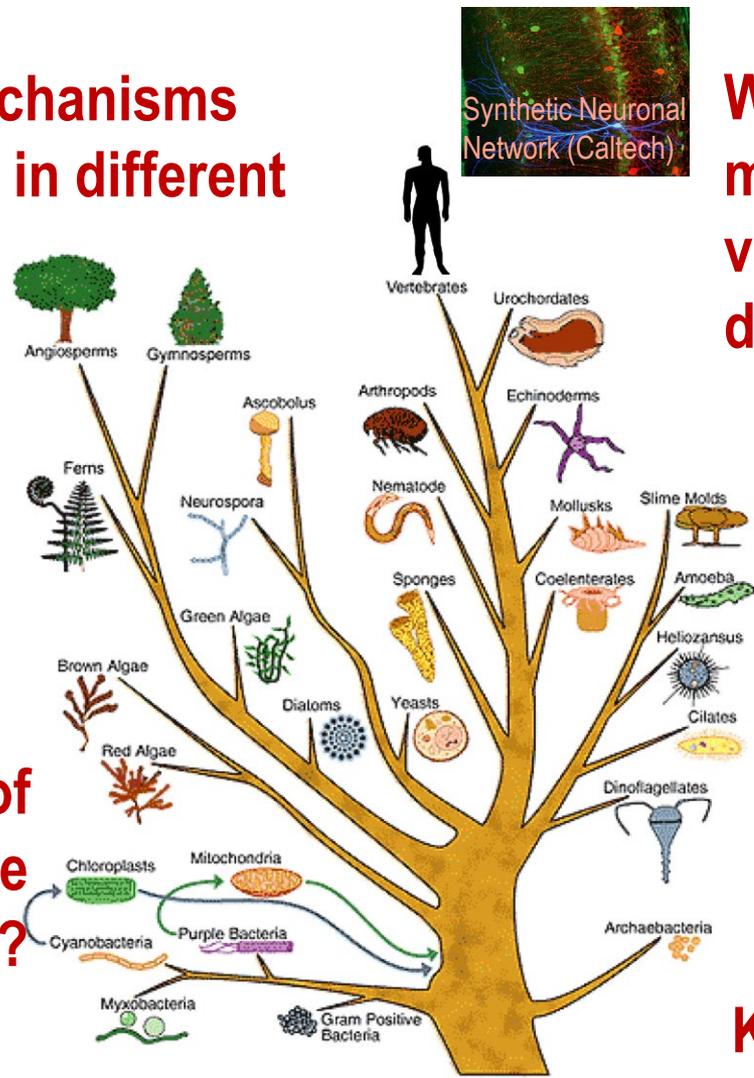


What different mechanisms enable adaptation in different environments

What are the constant mechanisms and the variable mechanisms that define life's challenges?

How do the same basic biochemical building blocks generate the diversity of life?

Could another set of genetic polymers be used to sustain life?



What mechanisms of signaling are used between cells and between organisms; changes in diff. environments?

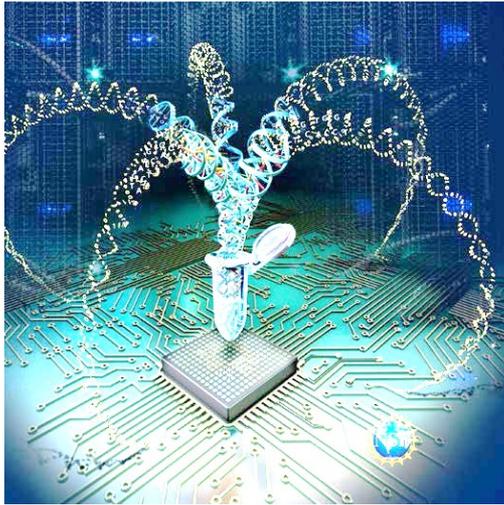
What is the minimal cell?

Key challenge: building a synthetic cell

Understanding from the nanoscale - nanobiosystems, synthetic cells

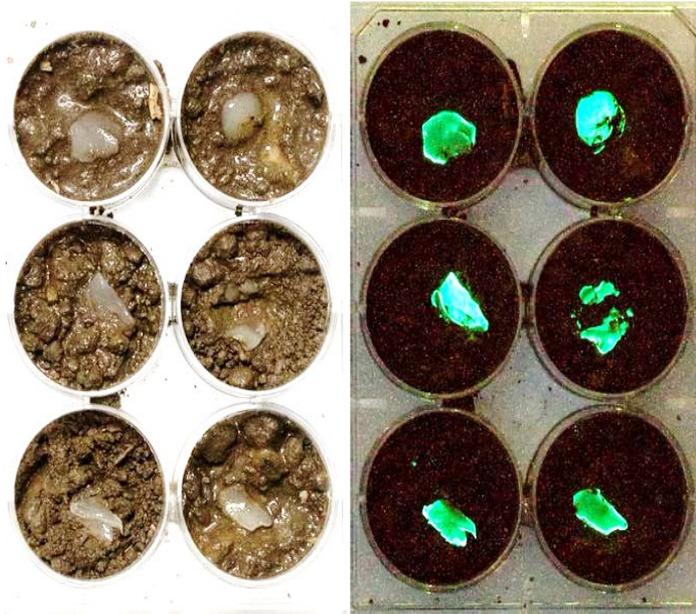


Ex II. “Understanding the Rules of Life” (NSF programs)



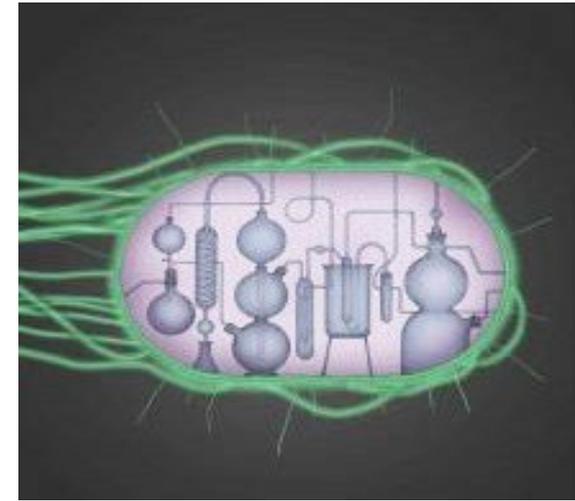
Semiconductor synthetic biology

Image credit: Nicolle Rager
Fuller, NSF



Signals in the soil

Image credit: S. Daunert, S. Deo and E. Dikici, Dept. of
Biochemistry and Molecular Biology and Dr. JT Macdonald
Biomedical Nanotechnology Institute, U. of Miami



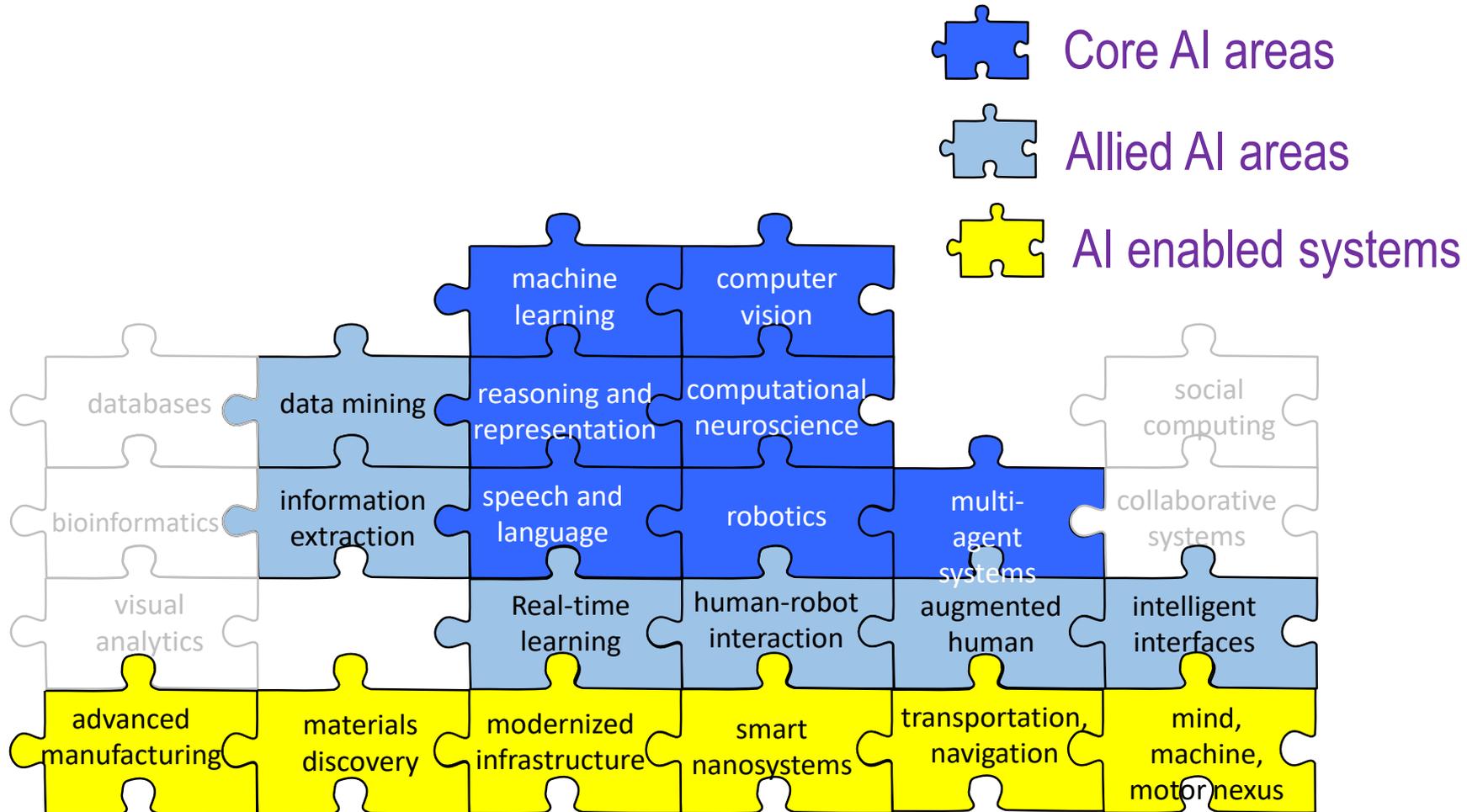
Synthetic cell

Image courtesy PLOS

Understanding from nanoscale cells & nanobiosystems



Ex II: Penetration of Artificial Intelligence in NSF “core” and targeted programs



AI is a foundational S&E field, similar to NNI and ITRD



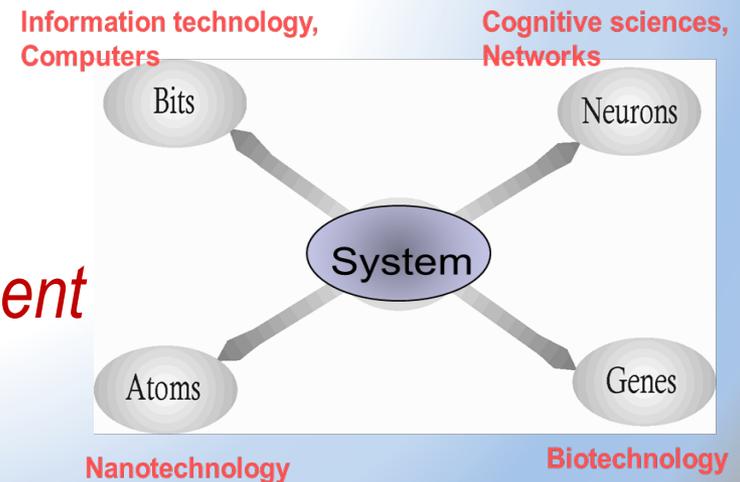
National AI Research Institutes

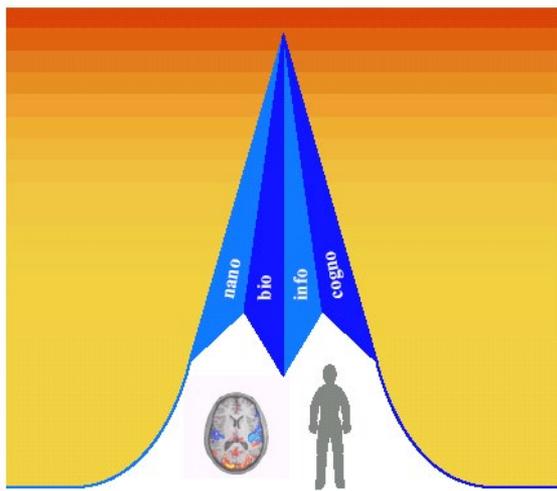
(NSF, FY 2019)

- **Planning grant proposals** in any areas of relevant foundational and use-inspired research
- Themes of **Institutes proposals**
 - Trustworthy AI
 - **Foundations of Machine Learning**
 - **AI-Driven Innovation in Agriculture and the Food System**
 - **AI-Augmented Learning**
 - **AI for Accelerating Molecular Synthesis & Manufacturing**
 - AI for Discovery in Physics
- **President's AI strategy:** <https://www.whitehouse.gov/ai/>

Twelve challenging ideas from 2001 NBIC Report for 2030 that are in reality or in development

- Hierarchically interconnected world using nano-el. - *reality in 2015*
- Non intrusive brain-to-brain communication – *accepted*
- Computer Personal Advisor – Intel.Cogn.Assistant – *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 NBICA - *modules*
- Intelligent environments – *in development*
- ELSI community – *organized in 2013*





CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002



Nature (2002): NBIC - ‘too exploratory’
“Futurists predict body swaps for planet hops”

“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.”

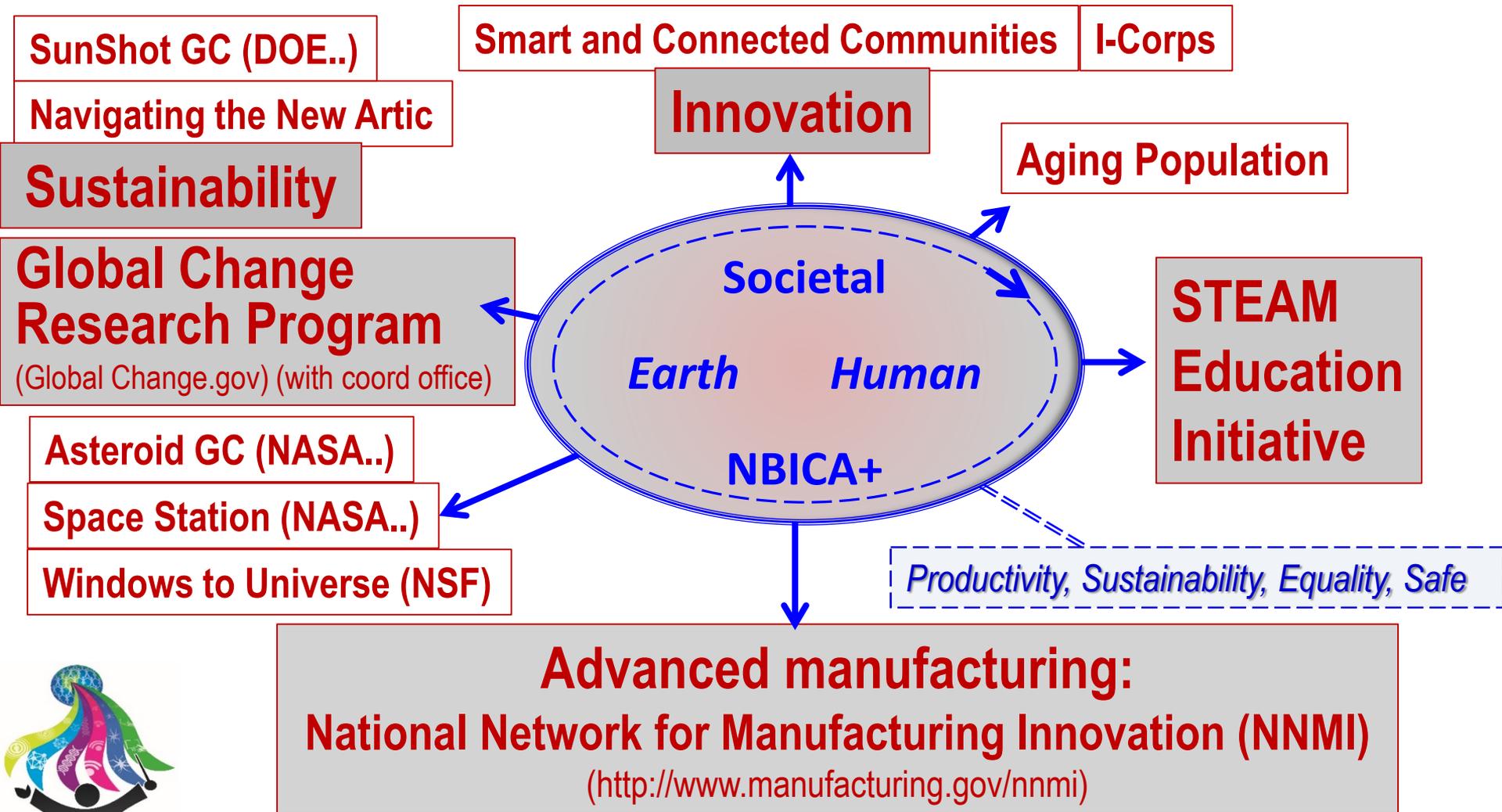
“Improving human performance has been a dream for centuries,” says Mihail Roco, chairman of the government-funded National Nanotechnology Initiative, and lead author of the study ***Converging Technologies for Improving Human Performance***, released on 8 July — says that the **convergence** ... may help to break those limits in the next 20 years.”

III. Global society-oriented initiatives



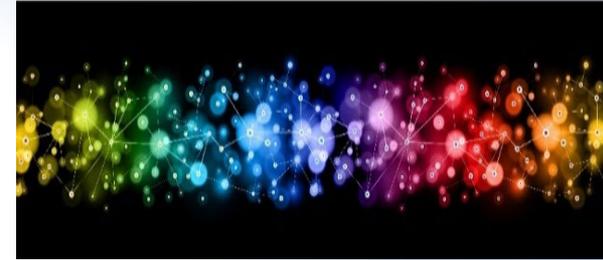
OSTP

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



Ex III: 2016- NSF 10 Big Ideas (4 enabling ideas)

- **Growing Convergent Research at NSF**
- **NSF 2026: Seeding Innovation**
- **INCLUDES: Enhancing Science & Engineering through Diversity and Inclusion**
- **Mid-scale Research Infrastructure**
(I) \$6M-\$20M ; (II) \$20M - \$100M



NSF Convergence Accelerator

Accelerates use-inspired, convergence research from concept to deliverables in areas of national importance

Employs partnerships between academic and non-academic stakeholders

- Pilots in 3 tracks
 - Open knowledge network
 - AI and future jobs
 - National talent ecosystem
- 43 new awards announced in FY 2019



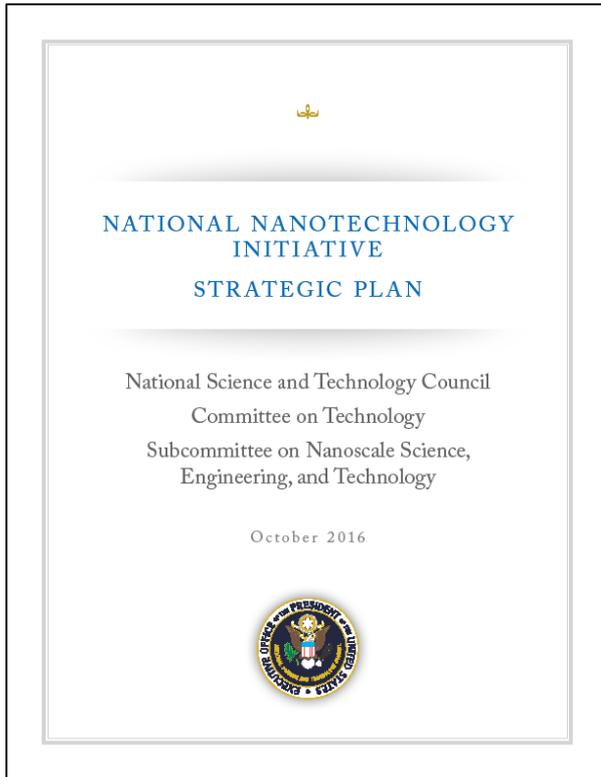
Ex III: **WH-OSTP Industries of the Future**

(March 2019)

- **Artificial Intelligence (AI)** (incl. nanosystems)
- **Advanced Manufacturing** (incl. nanomanufacturing)
- **Quantum Information Science (QIS)** (confluence Nano)
- **5G networks** (incl. using nanosystems)
- **Emerging techs to help aging Americans stay independent** (incl. using nanomedicine and robotics)

NNI at NSF in 2018

I. National Nanotechnology Initiative in 2020



2016-2019; New NNI Strategic Plan to be approved in 2000by WH and be submitted to Congress

(available on www.nano.gov)



2018, 2019 NNI Supplements 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

To be replaced in 2020

Signature Initiatives (2016~2020) + Grand Challenges

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

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

- **FY 2019 - 2021 Budgets** - various planning stages

*FYs 2018 actual ~ **\$568 M** (including other core programs)*

— Fundamental research

> **6,000 active projects** in all NSF directorates

(annual increases ~15% first decade, then ~ constant, with qualitative changes)

— Establishing the infrastructure

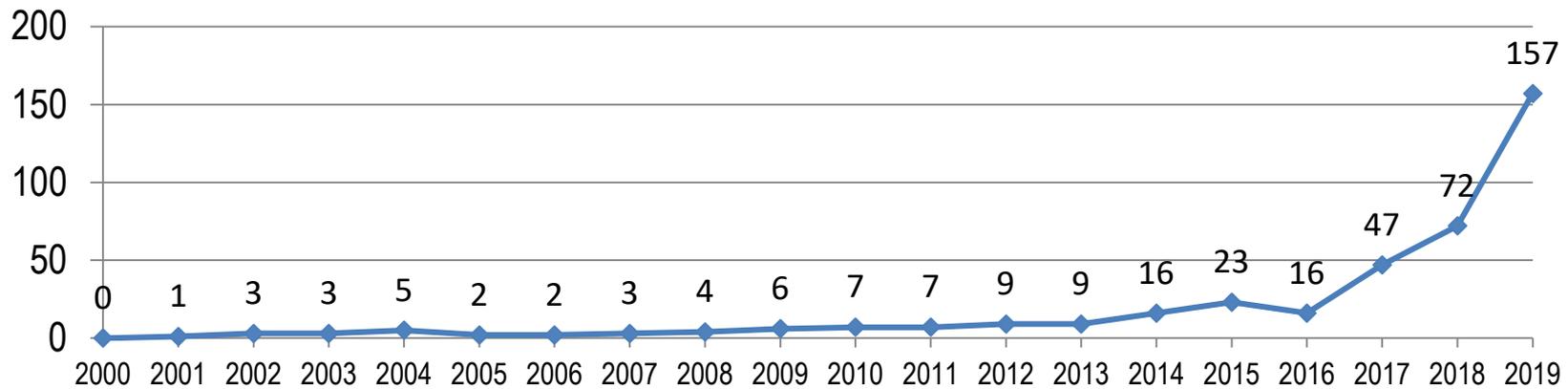
> **30 centers & networks**, general - NNCN, NCN

— Training and education

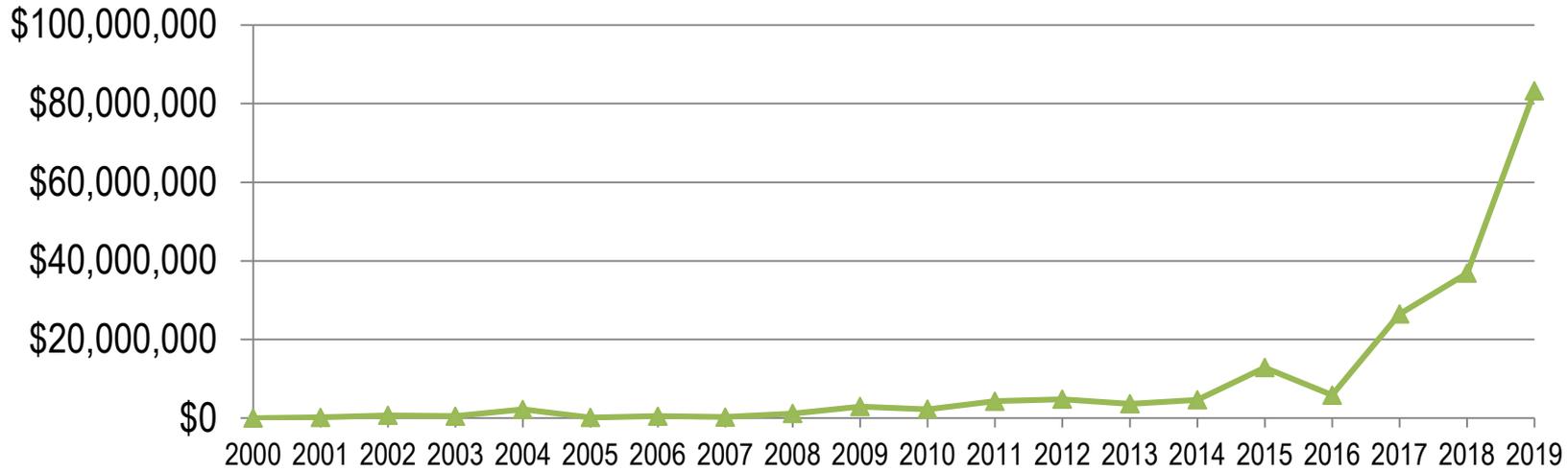
> **10,000 students and teachers/y**; ~ \$50M/y

Confluence of NS&E with artificial intelligence (AI)

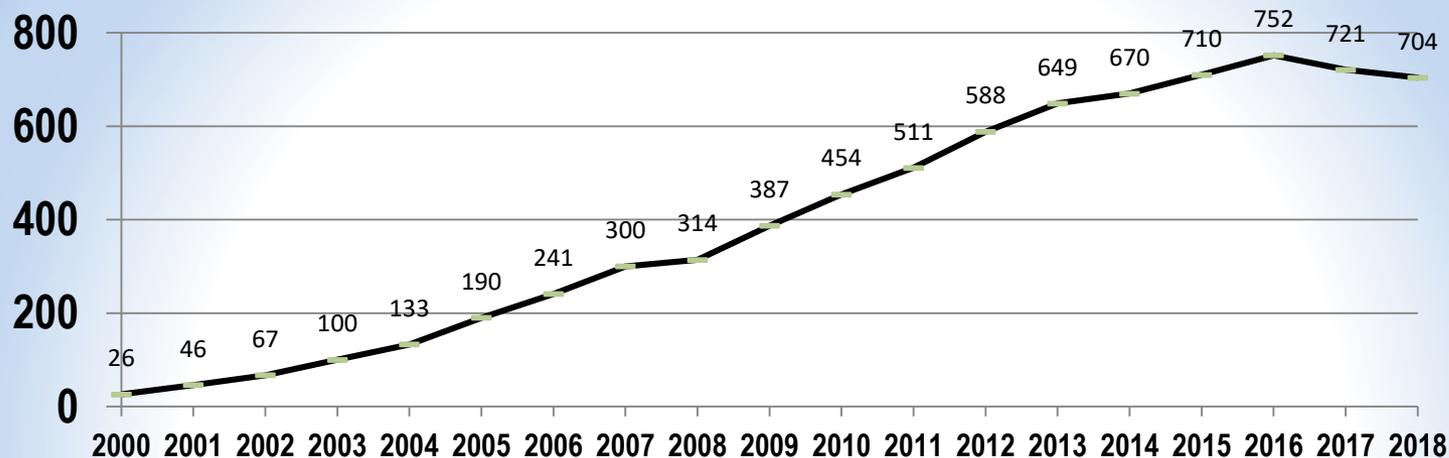
Number of new NS&E with "AI" Awards FY 2000-2019



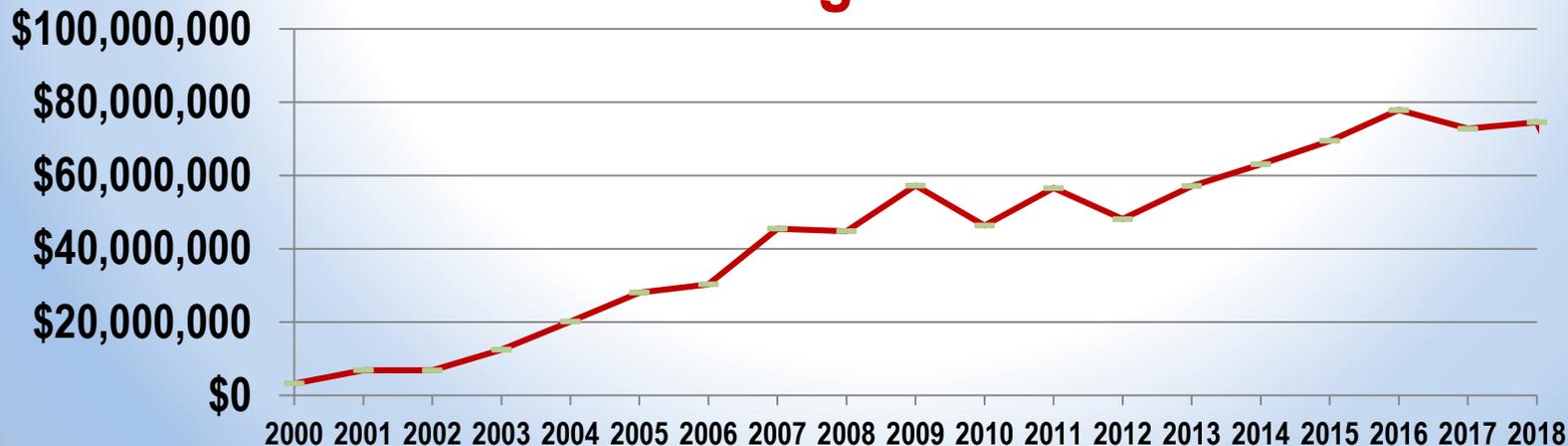
New nano amount for NS&E with "AI" awards FY 2000-2019

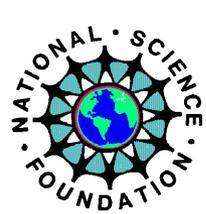


Number of active nanomedicine awards in all categories: FY 2000-2018



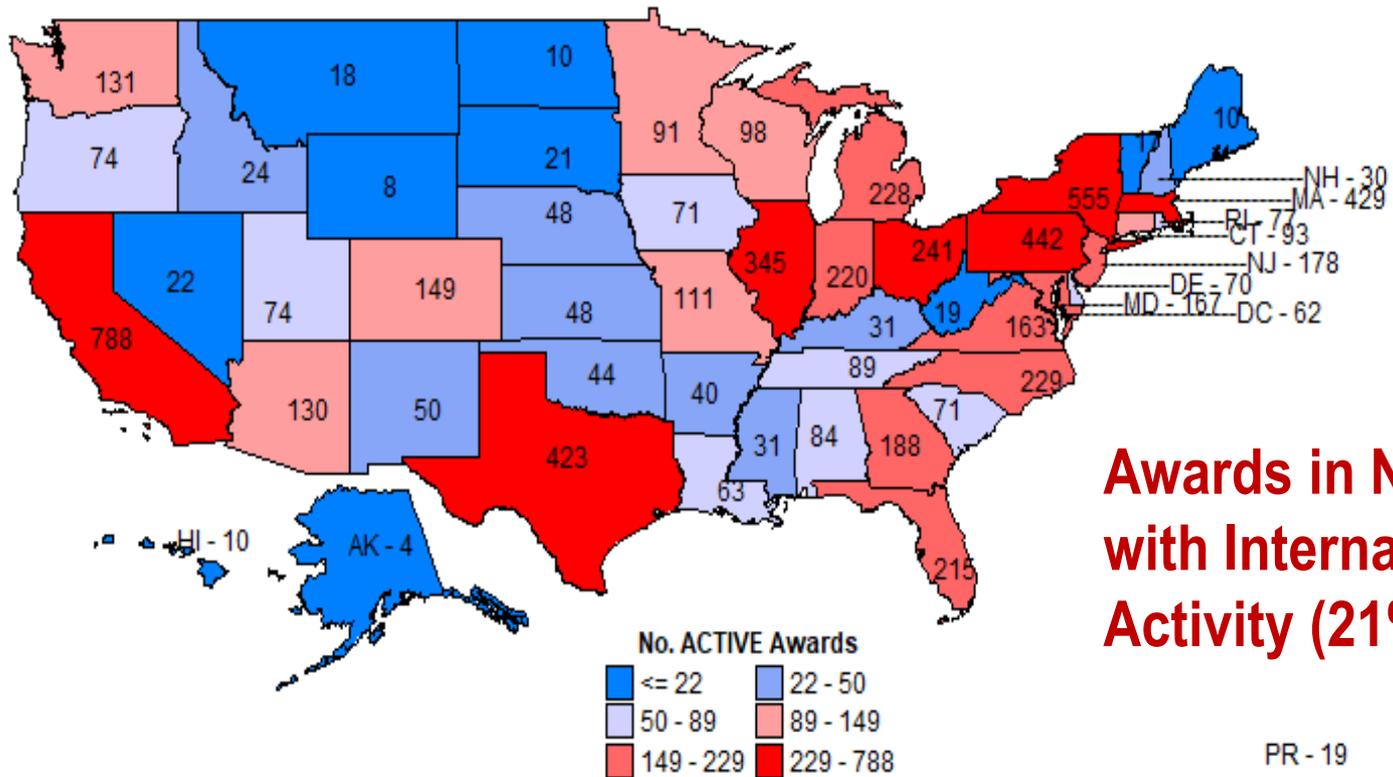
Nano amounts for active nanomedicine awards in all categories: FY 2000 - 2018





NSF's NS&E number active awards per state

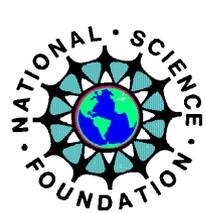
FY 2019: Total Active Awards = 6,853



Awards in Nano with International Activity (21%)

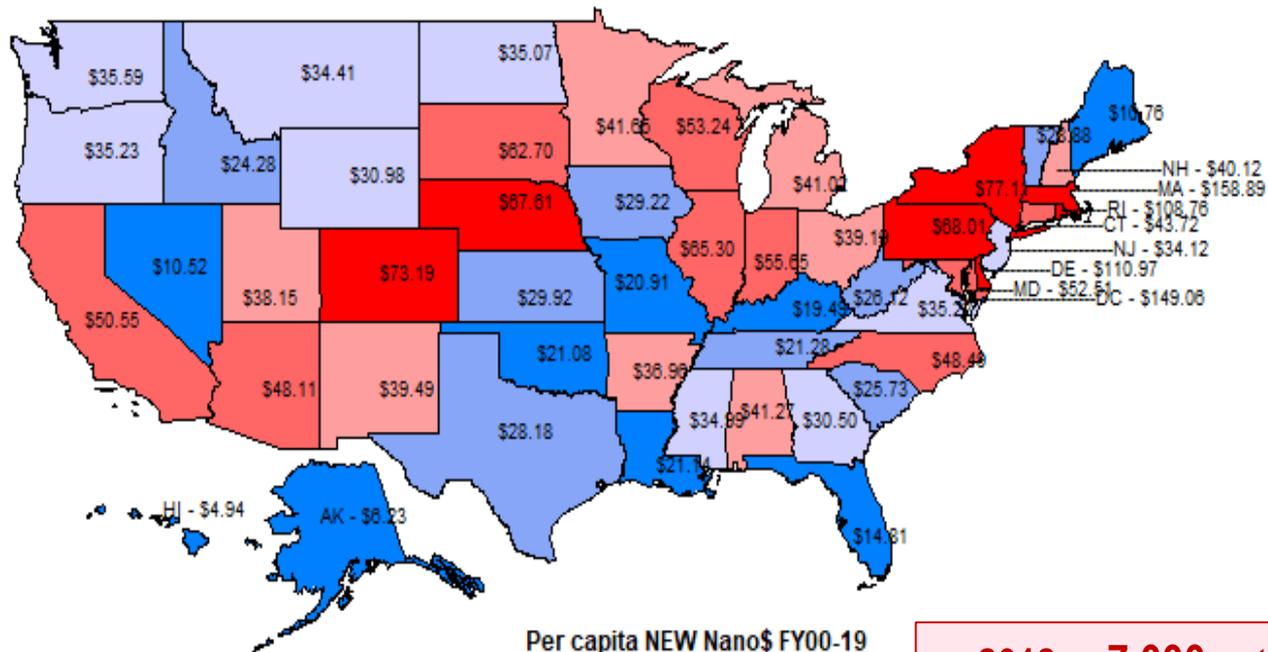
#1 CA 788 awards in 2019

AK 4; AL 84; AR 40; AZ 130; **CA 788**; CO 149; CT 93; DC 62; DE 70; FL 215; GA 188; HI 10; IA 71; ID 24; IL 345; IN 220; KS 48; KY 31; LA 63; **MA 429**; MD 167; ME 10; MI 228; MN 91; MO 111; MS 31; MT 18; NC 229; ND 10; NE 48; NH 30; NJ 178; NM 50; NV 22; **NY 555**; OH 241; OK 44; OR 74; **PA 442**; PR 19; RI 77; SC 71; SD 21; TN 89; **TX 423**; UT 74; VA 163; VT 17; WA 131; WI 98; WV 19; WY 8



NSF's NS&E amount new awards per capita

FYs 2000 - 2019: U.S. average ~ \$44 /capita



2018: ~ 7,000 active awards
(abstracts on www.nsf.gov/nano)

#1 MA \$159 / capita (2000-2019)

AK 6.23; AL 41.27; AR 36.96; AZ 48.11; CA 50.55; **CO 73.19**; CT 43.72; **DC 149.06**; DE **110.97**; FL 14.81; GA 30.50; HI 4.9; IA 29.22; ID 24.28; IL 65.30; IN 55.65; KS 29.92; KY 19.49; LA 21.14; **MA 158.89**; MD 52.51; ME 10.76; MI 41.02; MN 41.65; MO 20.91; MS 34.99; MT 34.41; NC 48.49; ND 35.07; NE 67.61; NH 40.12; NJ 34.12; NM 39.49; NV 10.52; NY 77.11; OH 39.19; OK 21.08; OR 35.23; PA 68.01; PR 27.32; **RI 108.76**; SC 25.73; SD 62.70; TN 21.28; TX 28.18; UT 38.15; VA 35.22; VT 28.88; WA 35.59; WI 53.24; WV 26.12; WY 30.98

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
- Convergence with other foundational technologies to accelerate discovery to create new emerging S&T platforms for societal progress and sustainability

Related publications

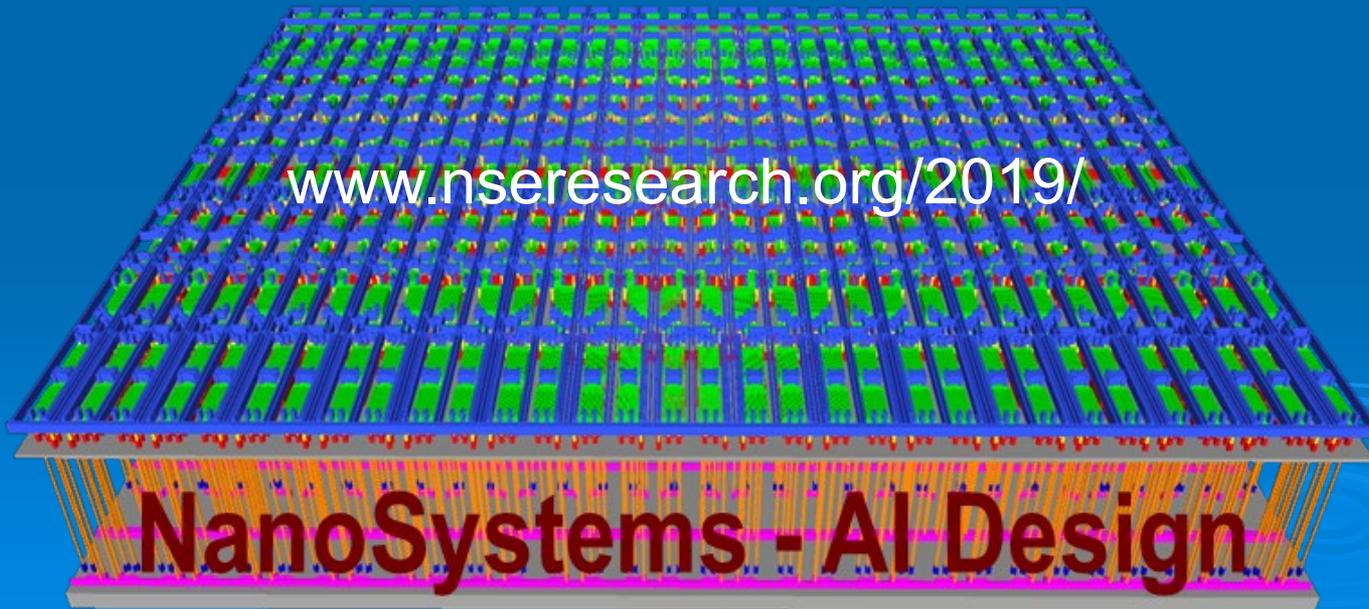
1. **“Coherence and Divergence of Megatrends in Science and Engineering”**
(Roco, JNR, 2002)
2. **“Nanotechnology: Convergence with Modern Biology and Medicine”**,
(Roco, Current Opinion in Biotechnology, 2003)
3. **NANO1: “Nanotechnology research directions: Vision for the next decade”**
(Roco, Williams & 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, Springer Reference, 2016)



NSF Nanoscale Science and Engineering Grantees Conference

Alexandria, December 9-10, 2019

www.nseresearch.org/2019/



NanoSystems - AI Design

Credit: S. Mitra, Stanford U. 2019

RESERVES

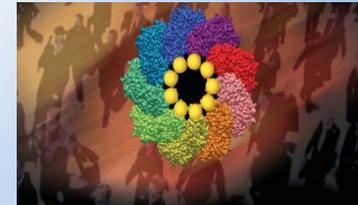


Science and technology convergence

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

Convergence approach:

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



Convergence science – Creating or changing a system for a goal based on *10 theories, 7 convergence principles, and specific methods* (Ref 7-10)

Ex III: **Convergence characterization** **in research and education (at NSF, 2017-2020)**

Convergence is the (intentional) 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.

Ex: **GCR**; Upstream: **Germination**; Downstream: **Innovation Corps**;
CORE; from Up- to Down-stream: **Convergence Accelerators**
www.nsf.gov/od/oia/convergence/index.jsp

Ex III. NSF “INCLUDES” - Development Launch Pilots

Example: The 50K Coalition (NSF 17-522)

Goal: Produce 50,000 diverse engineering graduates by 2025

Utilizing a Systems Approach Designed for Change

Action Network Groups

- Undergraduate Support and Retention
- Public Awareness/Marketing
- Funding and Financial Support
- K-12 Support
- Community College Linkages
- Culture/Climate
- Data Council

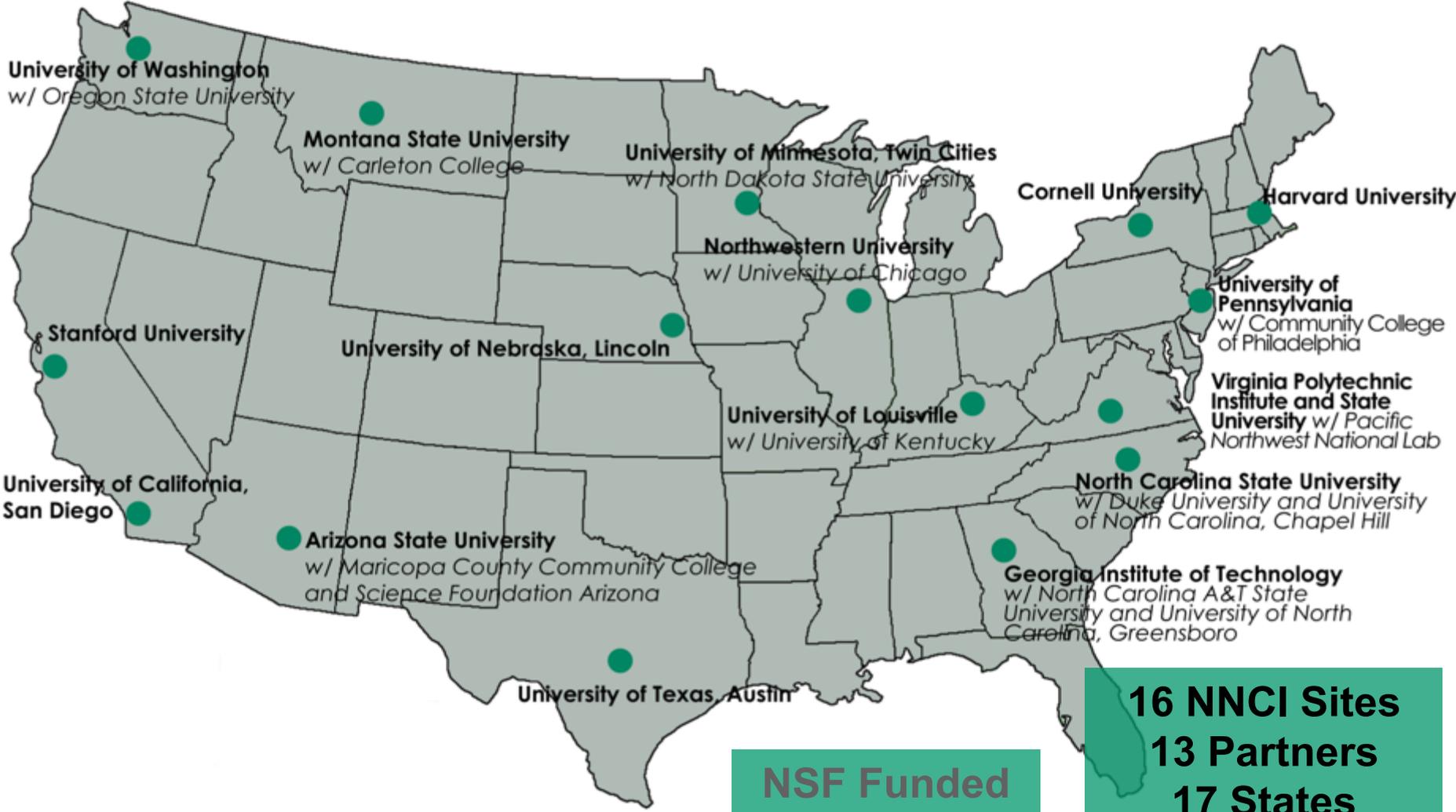
50K Coalition Partners

- 30 colleges and universities
- 21 professional engineering societies
- 3 community colleges
- 5 corporations



A part of the NSF INCLUDES National Network

National Nanotechnology Coordinated Infrastructure (NNCI)



**NSF Funded
2015-2020
\$81M total**

**16 NNCI Sites
13 Partners
17 States
68 Facilities
>2000 Tools**

A cyber ecosystem for science

