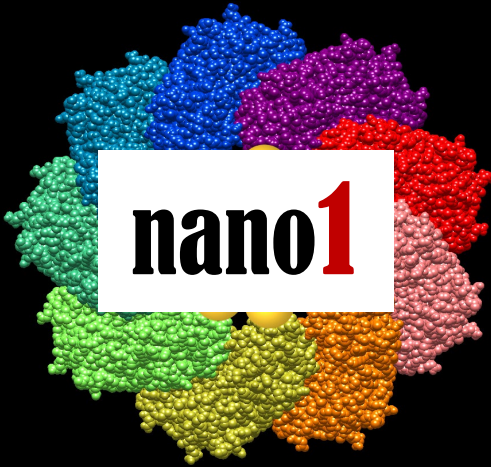


2000



2010



2020



2040

NSF nanoscale science and engineering at 20 years of NNI

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

*Nanotechnology Frontiers at 20 years of NNI
Proceedings, December 1, 2020, www.nseresearch.org/2020/*

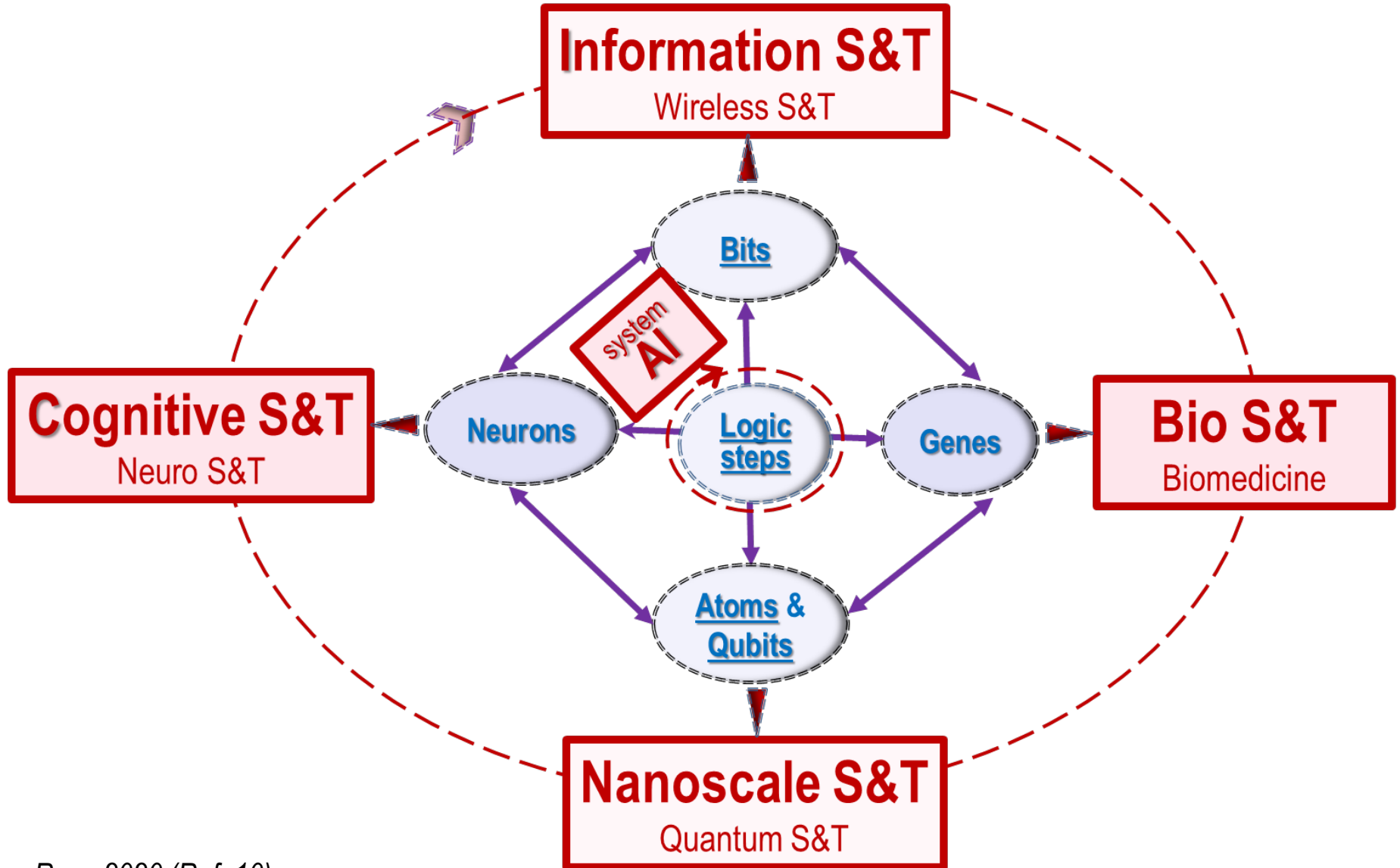
Outline

- **Long view of global nanotechnology development (2000-2040)**
 - *basics, system integration, divergence, diffusion*
- **International context**
 - *publications, patents, people, revenues*
- **NSF contributions**
 - *research, education, infrastructure outcomes*
- **Several challenges and trends**
 - *emerging topics, platforms, societal implications*

Nanotechnology R&D – last two decades

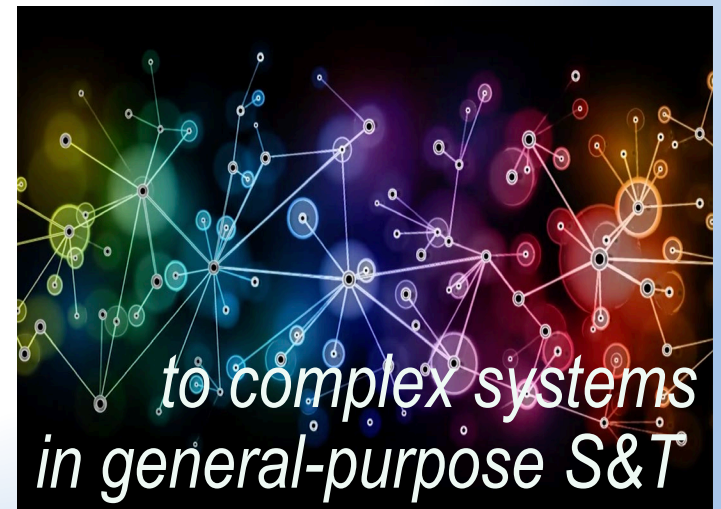
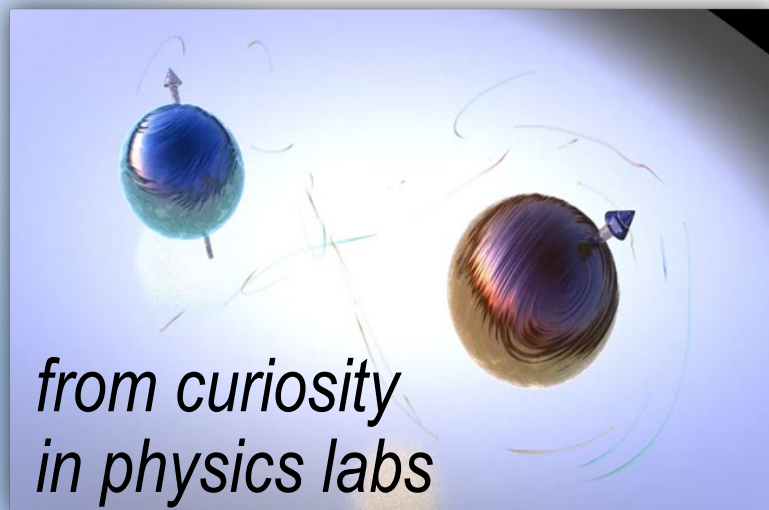
- **Importance of the unified and transforming definition in 2000:** *responsible* control & change at the nanoscale for society
- **Nanotechnology is a foundational, general-purpose S&E field** - enabling NBICA. **It is a global science initiative.**
- **Nanotechnology today continues its growth, with ~20 spin-off areas** such as metamaterials, synbio and quantum IS
- After 2020, nanotechnology promises to become **a primary S&T platform for investments & venture funds**

Nano is a foundation of the *global S&T system*, which is based on 5 elemental building blocks

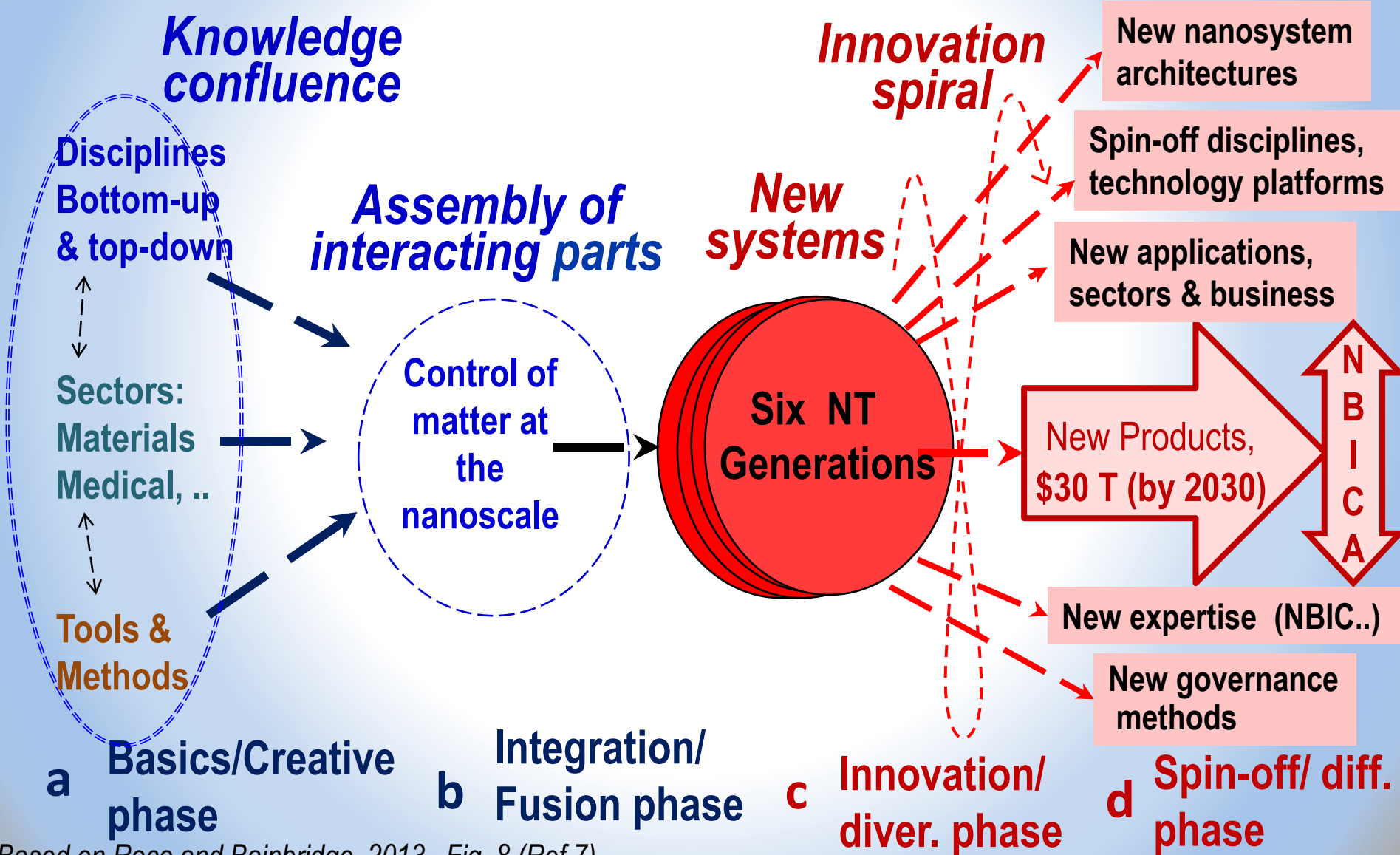


Long view of establishing nanotechnology

2000 - 2040



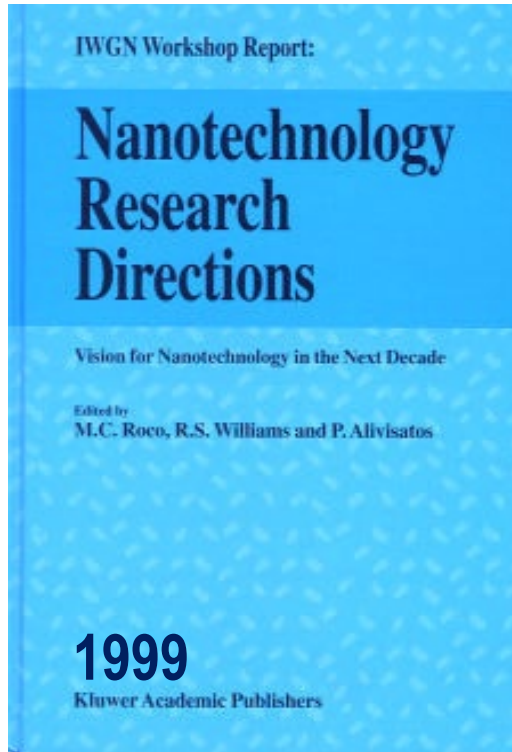
2000-2040 **Convergence-Divergence** cycle for establishing nanotechnology



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

Nanotechnology: global vision reports

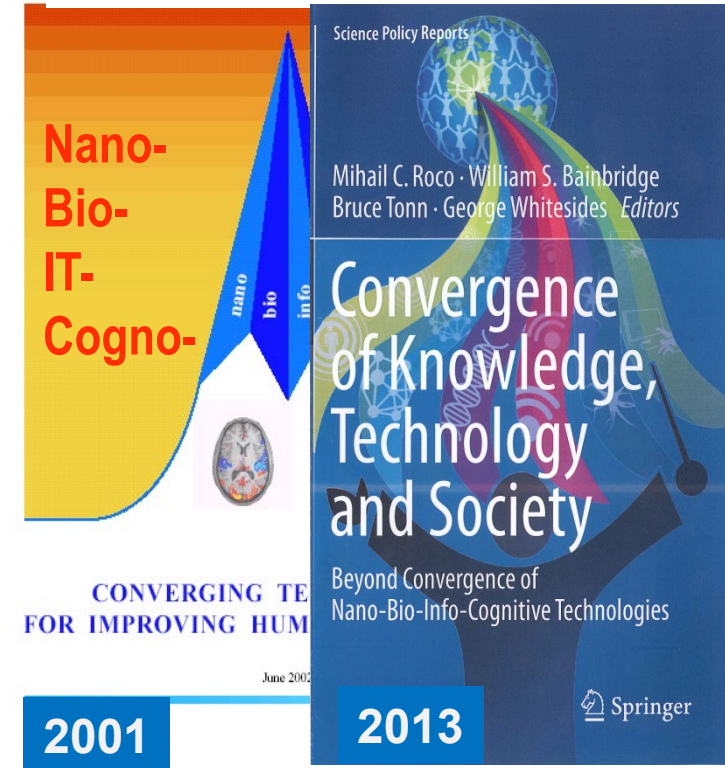
nano1 (2001-2010)



nano2 (2011-2020)



NBIC1&2 (2011-2040)

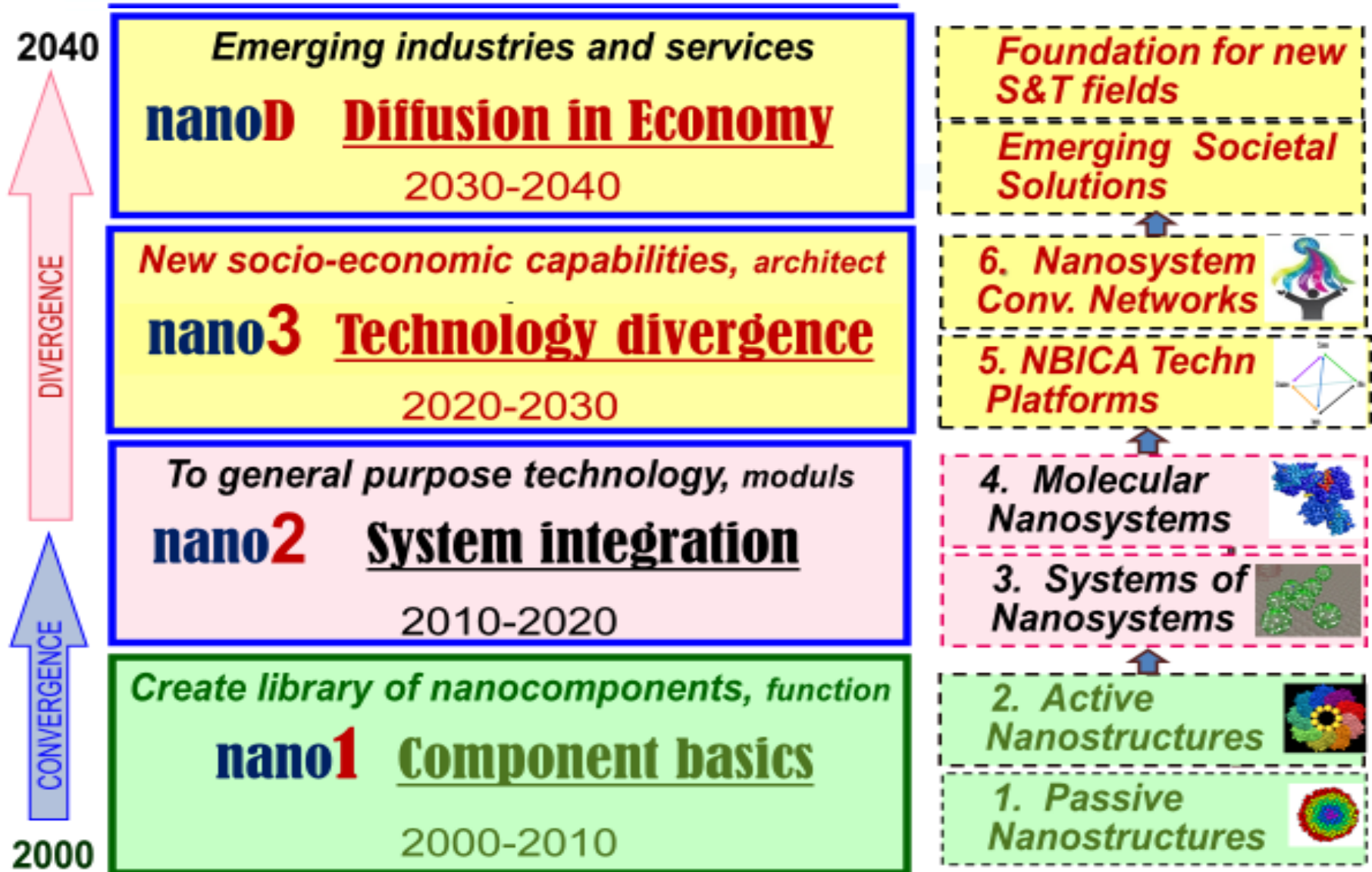


40 year vision: changing focus and priorities in 4 stages
- from basics, to system integration, divergence, diffusion

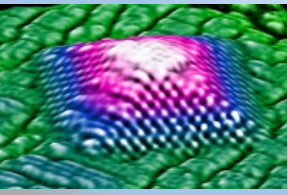
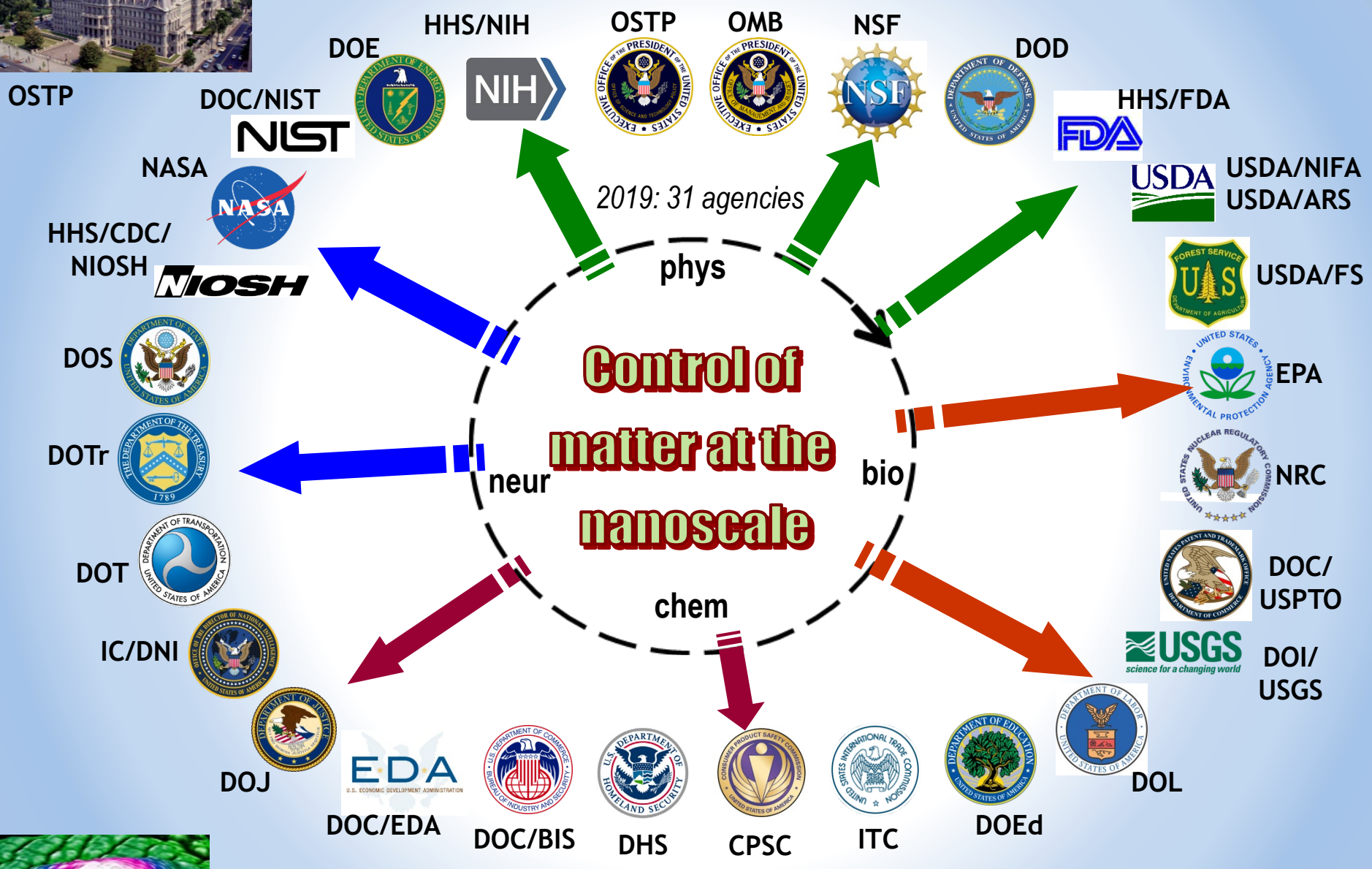
Input from >40 countries, Used in > 80 countries; Reports on scienceus.org/wtec/ (Refs 2-5)

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 4 STAGES

GENERATIONS OF NANOPRODUCTS
(prototypes stage)



Nanotechnology programs: S&T divergence



U.S. National Nanotechnology Initiative, 2000-2030

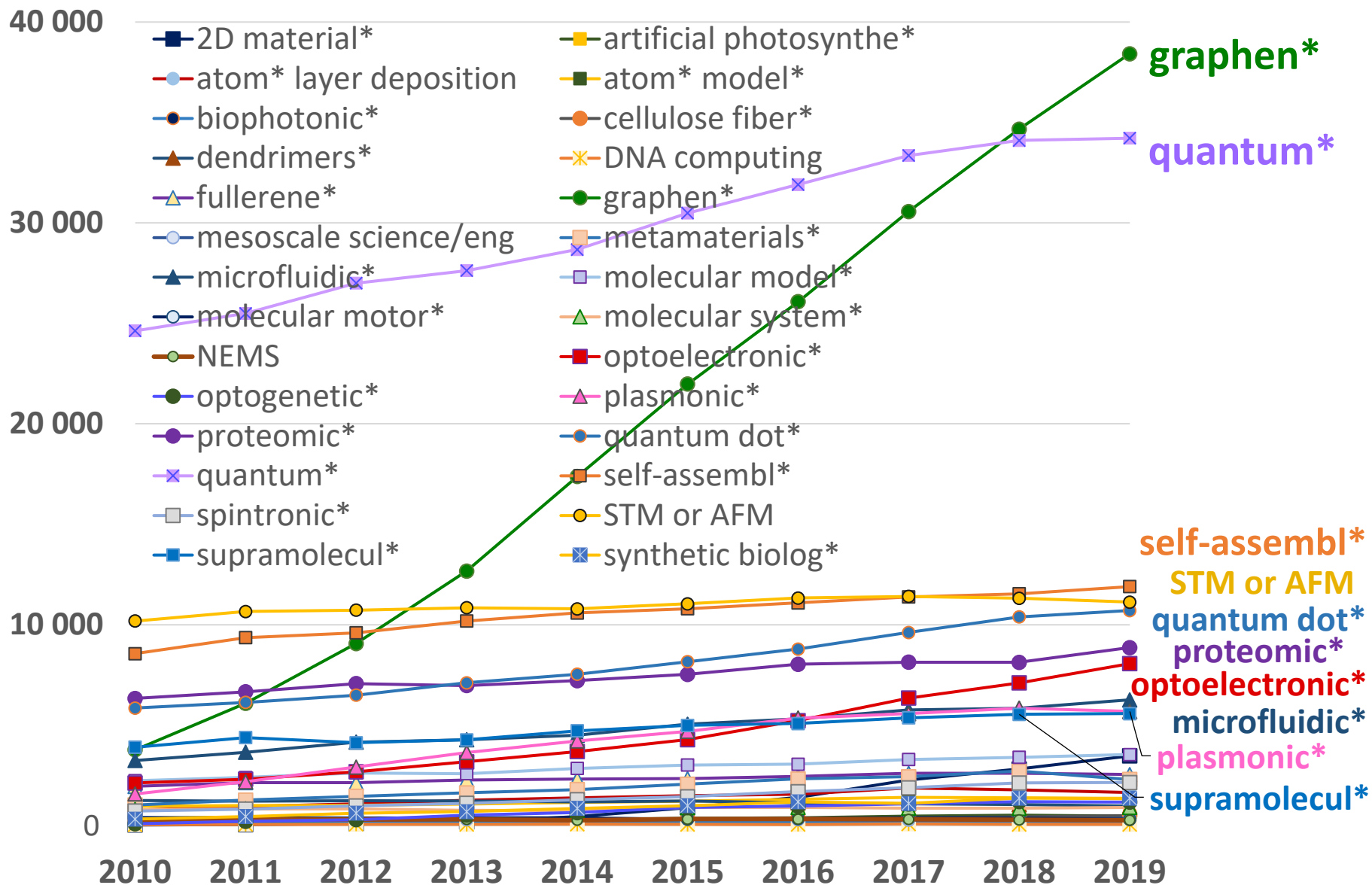


Nanotechnology spin-offs areas

- **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**

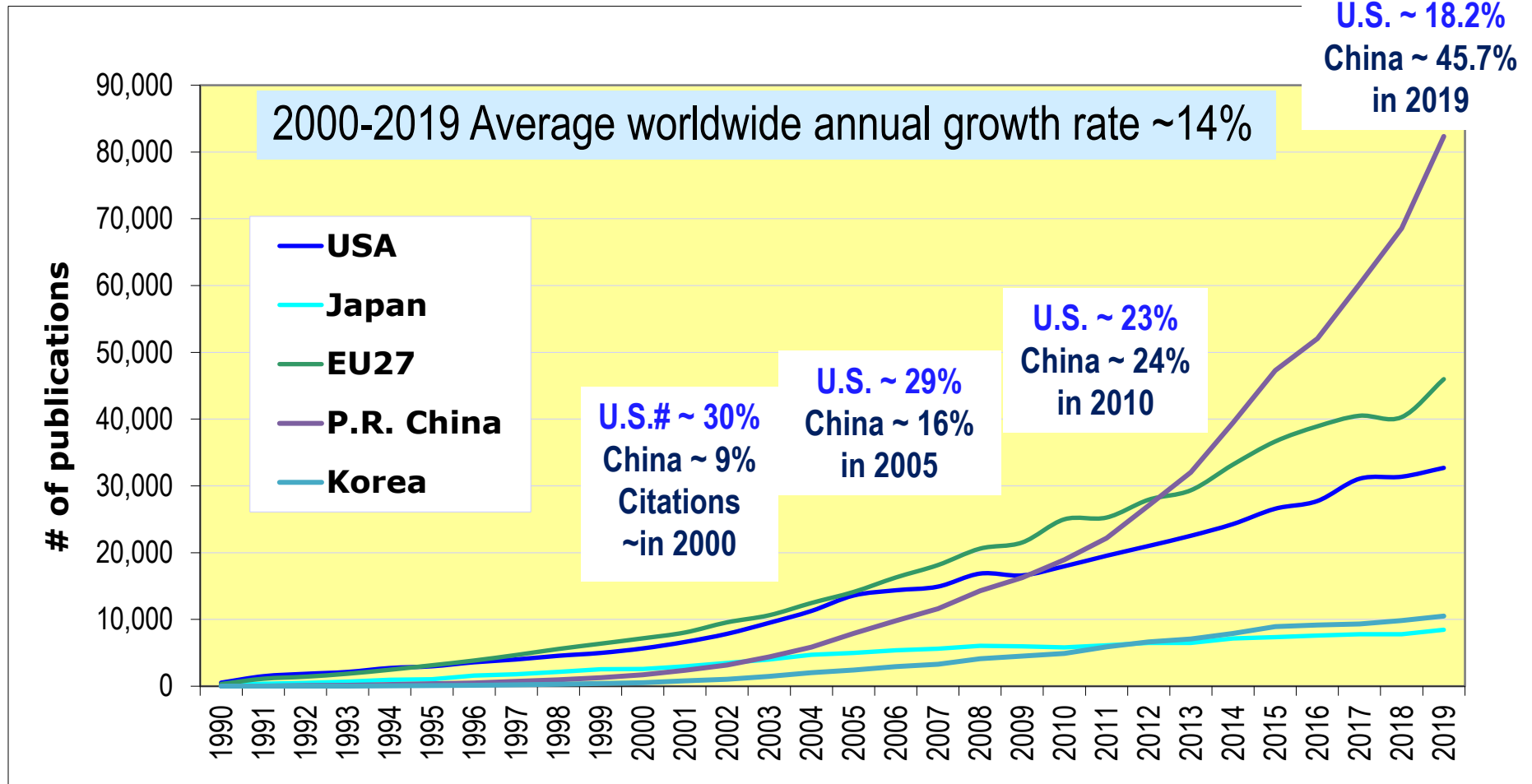
International context:
publications, patents, people, revenues

Nanotechnology topics in WoS from World: 2010-2019



Nanotechnology papers in the WoS: 1990 - 2019

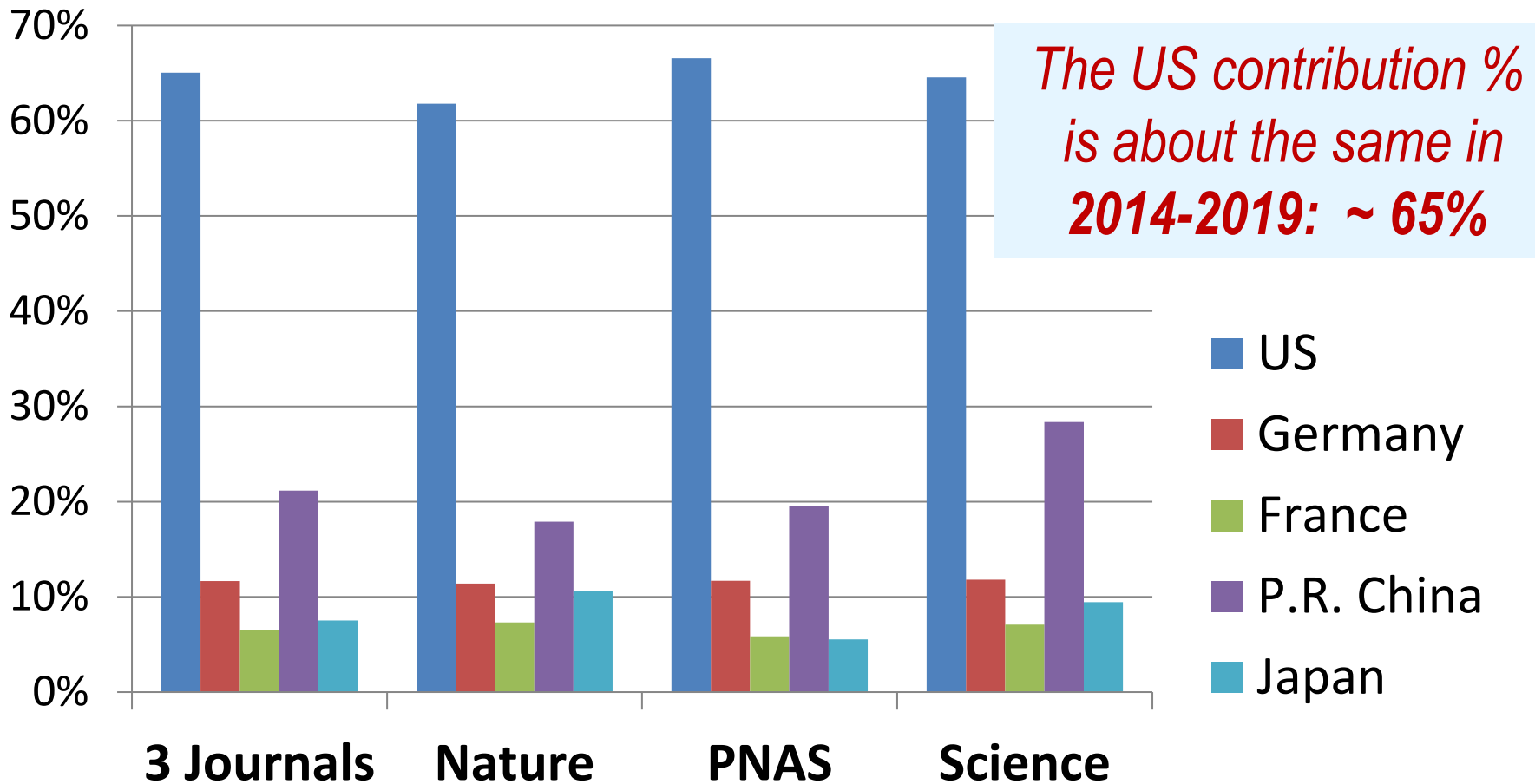
"Title-abstract" search for nanotechnology by keywords (update from NANO 2020, Fig 1; Ref 3)



Rapid, uneven growth per countries

Five countries' contributions to Top 3 journals in 2019

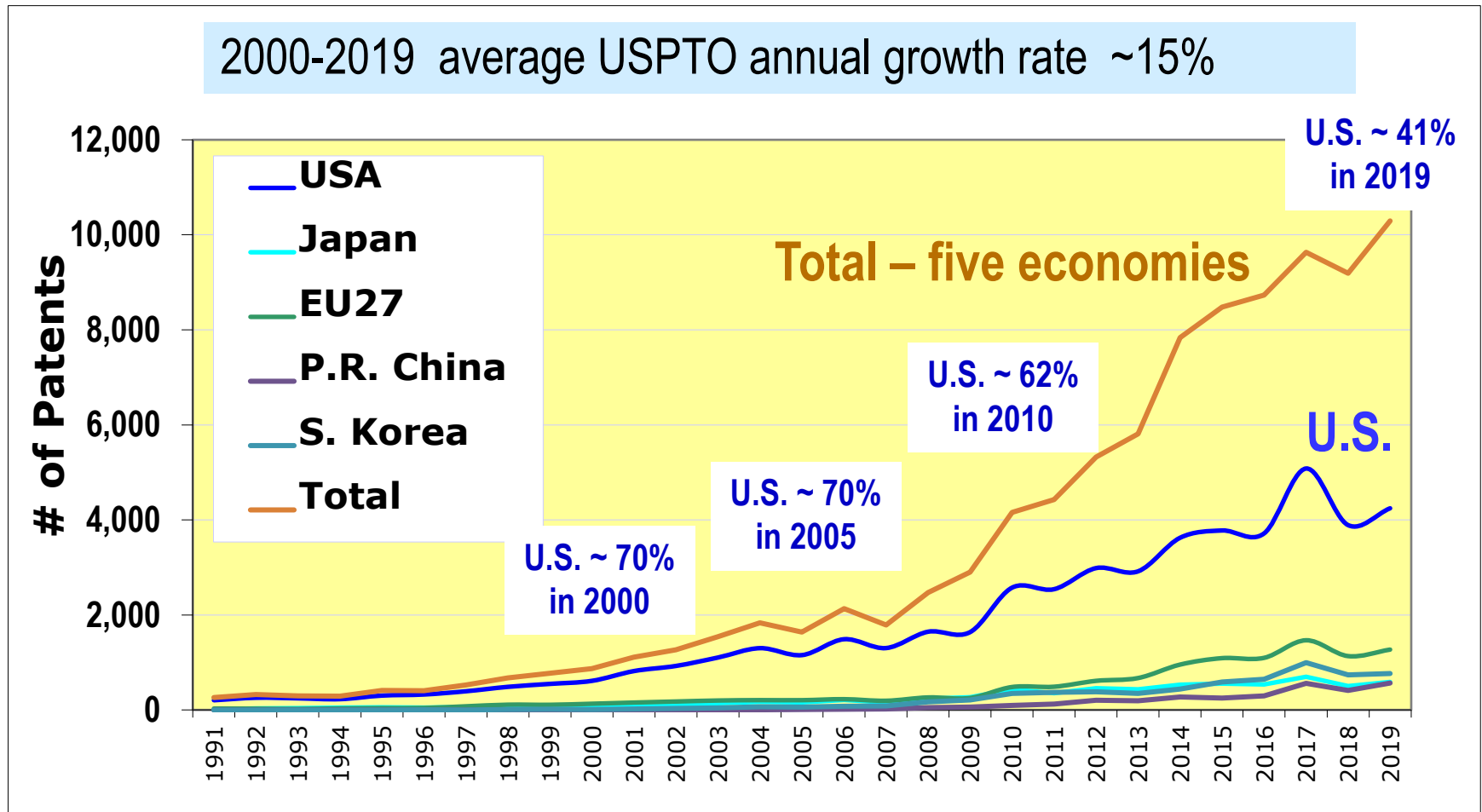
"Title-abstract" search for nanotechnology by keywords (update from NANO 2020, Fig 1; Ref 3)



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

Nanotechnology patents at USPTO: 1991-2019

“Title-abstract-claims” search of nanotechnology by keywords , Zhu et al, Ref 7 (data May 2020)

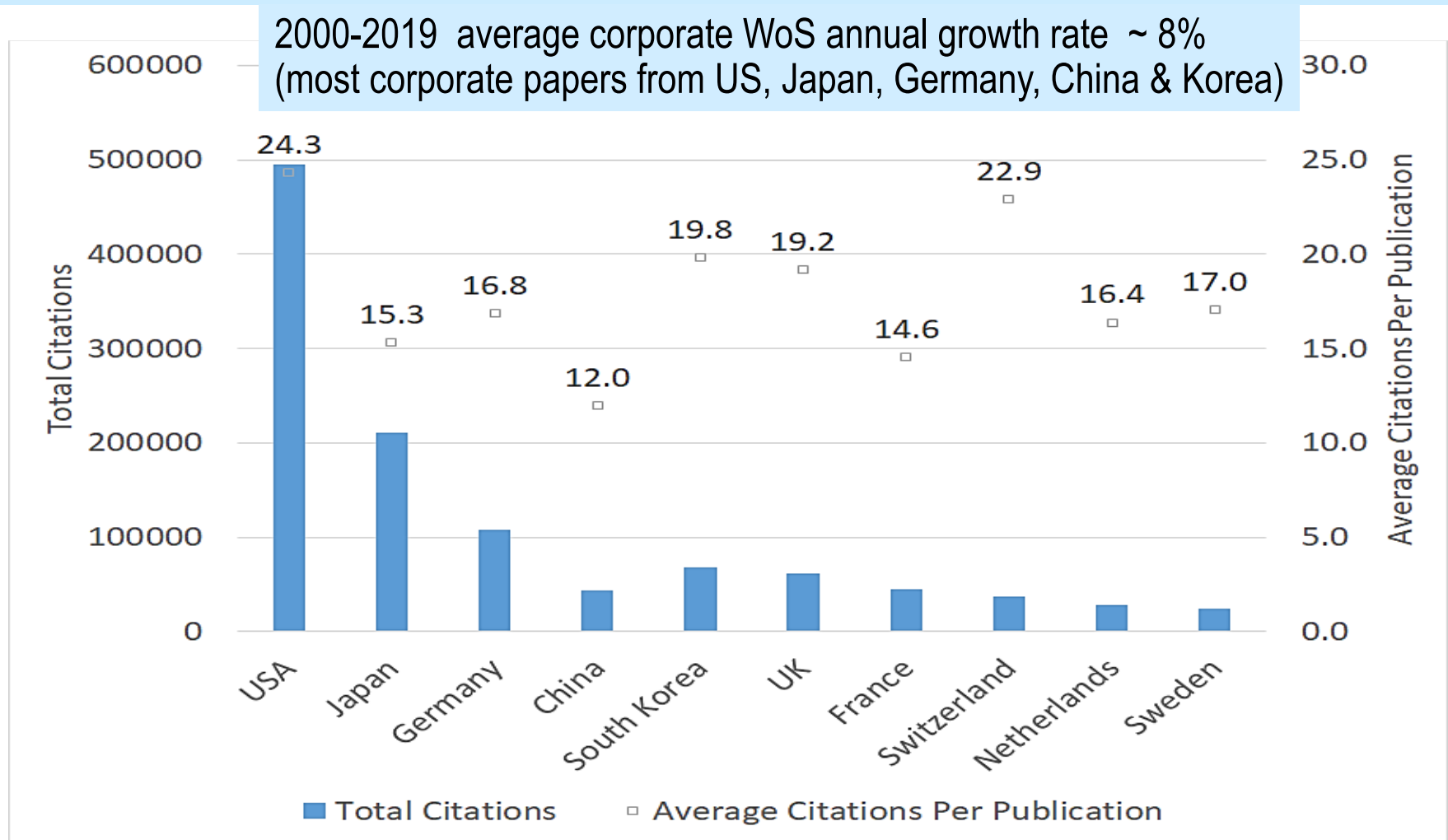


U.S. patent authors maintain the lead at USPTO in 2019

Summary estimates and growth rates of key nanotechnology indicators worldwide: 2000-2019

World	People -primary workforce	WoS papers	WIPO patent applic.	Revenues Est.	R&D Funding (gov + private)	Venture Capital
2000 <i>(survey)</i>	~ 60,000	18,953	2,158	~ \$30 B	~ \$1.2 B	~ \$0.21 B
2010 <i>(survey)</i>	~ 660,000	78,987	23,510	~ \$335 B	~ \$18 B	~ \$1.3 B
2000-2010 average growth	~ 27%	~ 15%	~ 27%	~ 27%	~ 31% (gov. 26%)	~ 30%
2019 <i>(lower- bound est.)</i>	~ 5 M	216,316 <i>(~ 6% of all)</i>	67,000	~ \$2,500 B <i>(up % of GDP)</i>	multiple platforms	multiple platforms
2010-2019 average growth	~ 25%	~ 11%	~ 11%	~ 25%		
2000-2019 average growth	~ 26%	~ 14%	~ 20%	~ 26%		

Number of corporate WoS publication citations by top ten countries: 2000-2019 *(Porter et al. 2020)*



Source: A. Porter and N. Newman (Search Technology), R. Ward, J. Youtie, and P. Shapira (Georgia Institute of Technology), analysis of 53,200 global nanotechnology corporate publications (April, 2020) extracted from Clarivate Web of Science. Nanotechnology search terms based on Wang, Z., Porter, A. L., Kwon, S., Youtie, J., Shapira, P., Carley, S. F., & Liu, X. (2019). Updating a search strategy to track emerging nanotechnologies. *Journal of Nanoparticle Research*, 21(9), 199. Top 10 countries based on counts for the 1991-2019 period.

Illustrations of NSF contributions

Trend: 3D NanoSystems

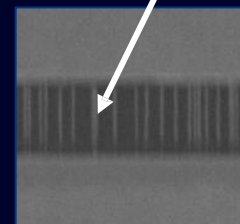
Example

Abundant data: Terabytes / second



Millions of sensors

CNTs

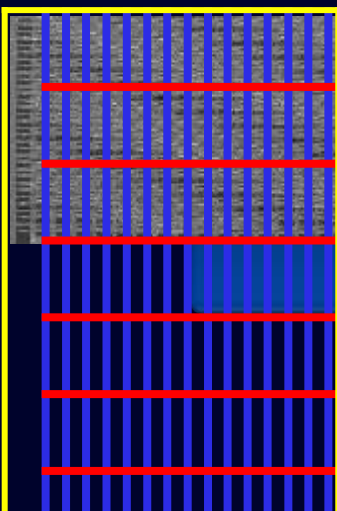


Ultradense vertical connections

Memory

1 Megabit RRAM

CNT computing logic
Classification accelerator



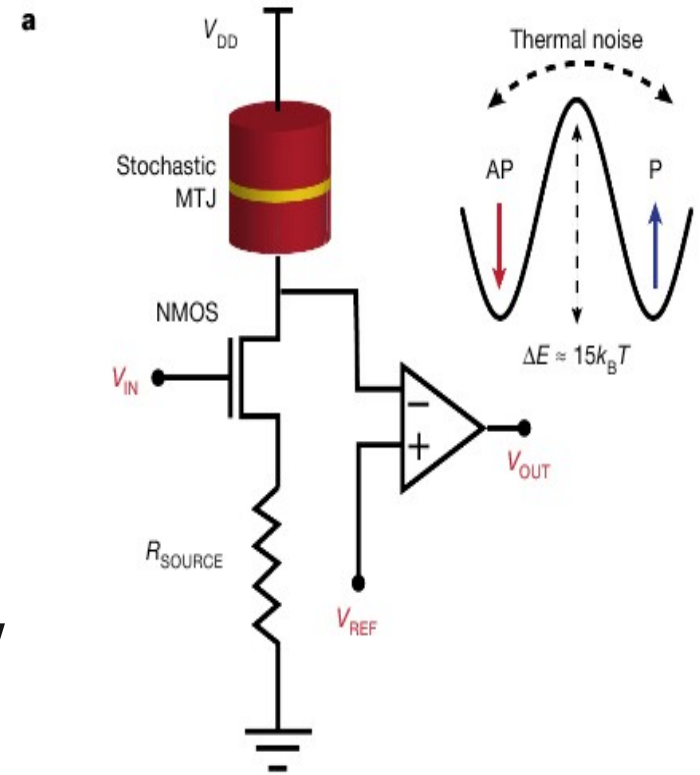
Credit: S. Mitra, Stanford U., 2019 (Ref 8)

Trend: Exploit probabilistic features: stochastic magnets, qubits, entanglement,...

Example: **8 "Probabilistic - bit"**
computer using stochastic
nanoscale magnets
([Nature](#) article. -18 Sept 2019).

Addressing problems that only
quantum computers were previously
expected to solve efficiently.

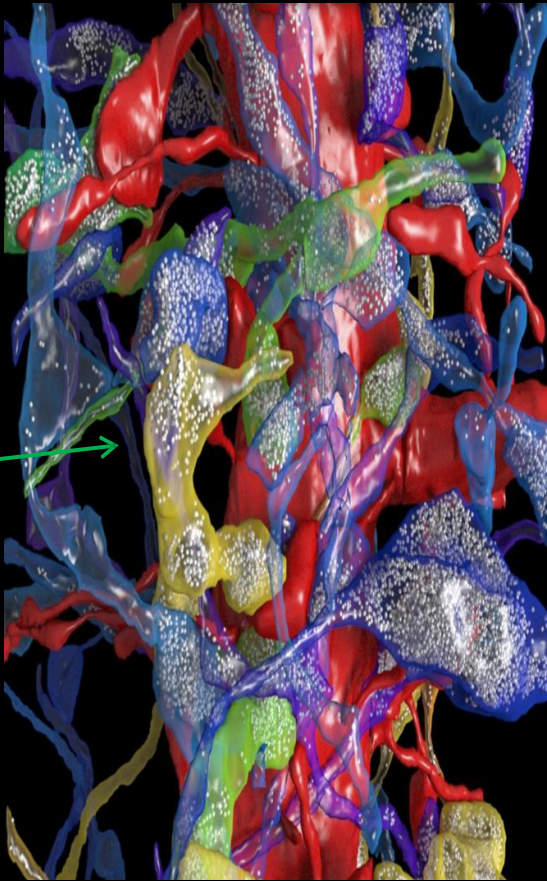
Initial discovery by Supryio Datta's team (2017) (Ref. 8)



Trend: Nanoscale processes in brain

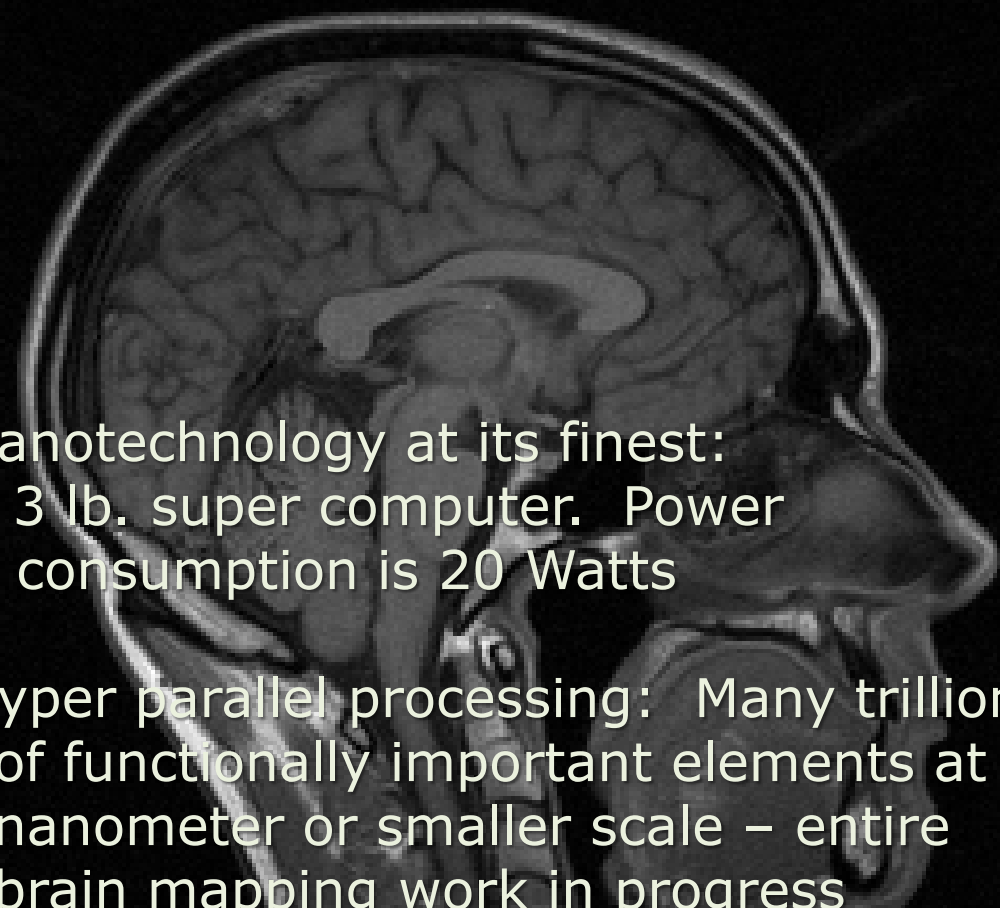
Example: Magnetic Resonance Image of human head

4 x 4 x 30 nm view



Nanotechnology at its finest:
3 lb. super computer. Power
consumption is 20 Watts

Hyper parallel processing: Many trillions
of functionally important elements at
nanometer or smaller scale – entire
brain mapping work in progress



Trend: Nanobiotechnology

Example: Evolution of enzymes

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



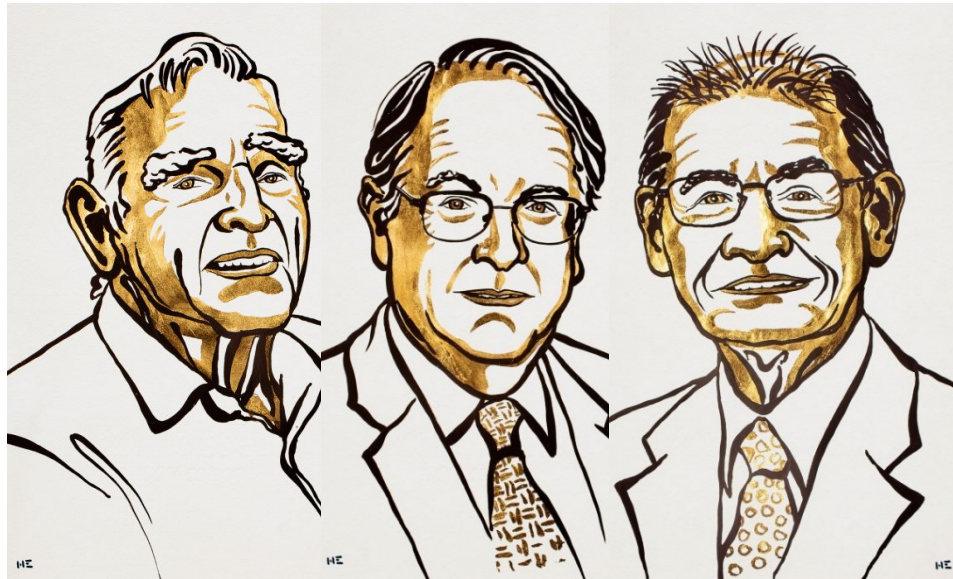
Credit: Directed Evolution: Bringing New Chemistry to Life
Frances H. Arnold, *Angew Chem Int Ed Engl.* 2018 Apr 9; 57(16): 4143–4148



Trend: Nano for energy

Example: **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



<https://www.nobelprize.org/prizes/chemistry/2019/summary/>

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

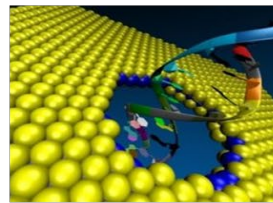
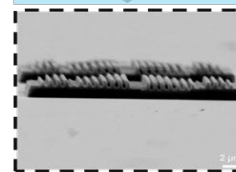
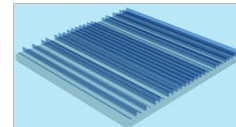


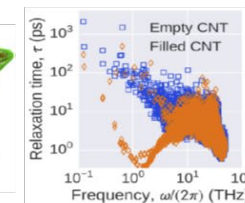
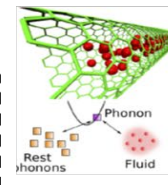
Illustration of a nanopore created in a 2D material by ion bombardment
[N. Aluru]

Process Models



A flat optical lens created by TPL

Multiscale Transport Phenomena



Energy Dissipation in Fluid Coupled Nanoresonators [N. Aluru]

Nanoscale self-assembly

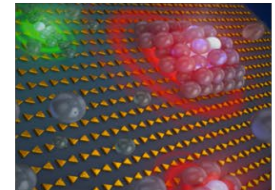
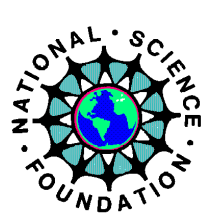


Illustration of plasmon-assisted particle assembly
[K. Toussaint]

U. Illinois, Award: 1720701, <http://nanomfgnode.illinois.edu/>

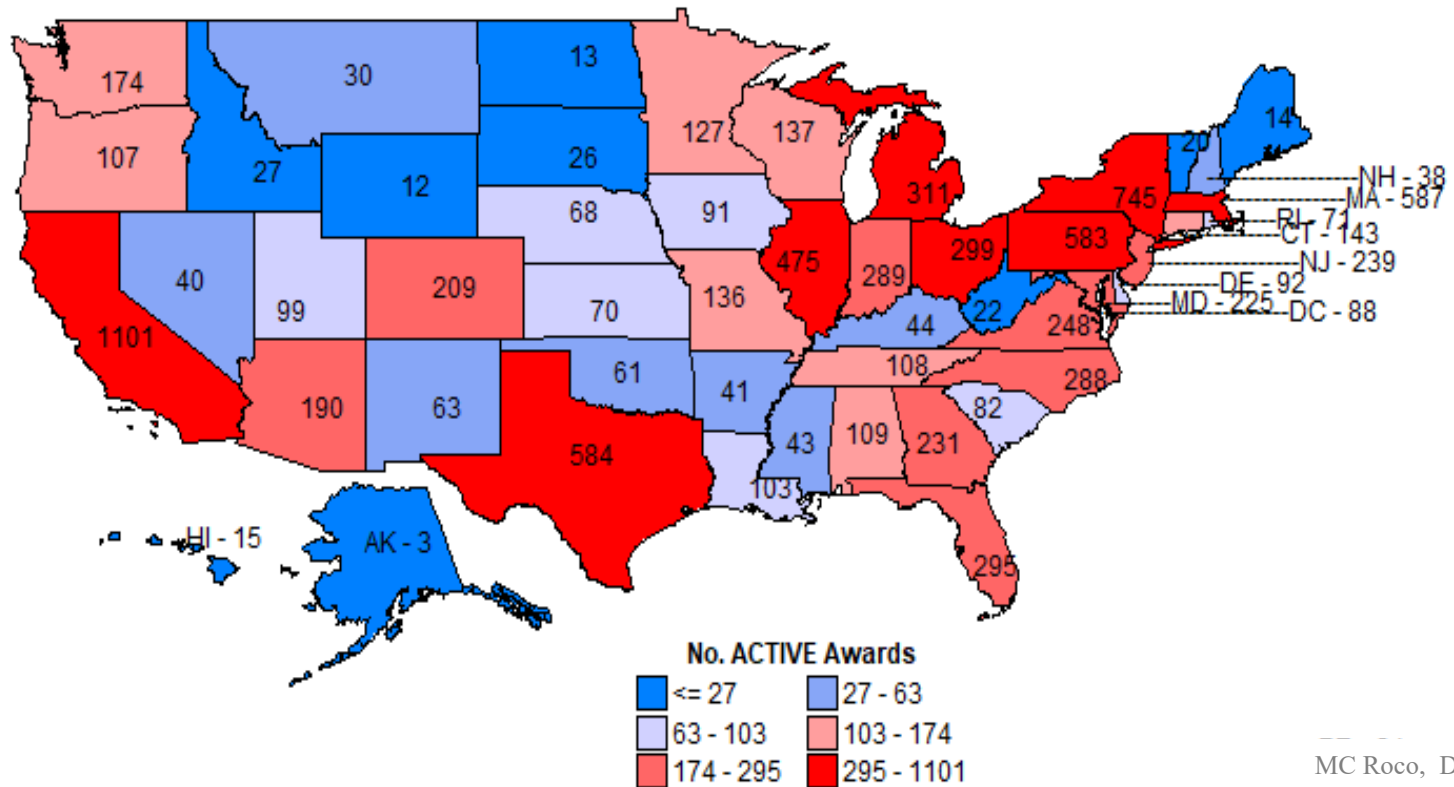
Other topics with accelerated research in 2020

- US and global priorities, with international collaborations -
- **Foundation for the industries of the future**
Example: Quantum, AI, Bio-econ, Wireless, Adv Manu
- **COVID19 Diagnostics, Treatment, Vaccines, dispersion** (several NSF's DCLs and core programs)
Example: Nano-based vaccine manufacturing
- **Critical Aspects of Sustainability (CAS):**
Micro- and Nanoplastics (MNP, DCL NSF 20-050):
Example: transport phenomena and nano-EHS issues
- **Nanotechnology in agriculture:** nano-EHS issues



NSF's NS&E number active awards per state

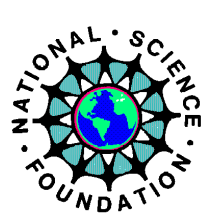
FY 2020: Total Active Awards - over 8,000



MC Roco, Dec 1 2020

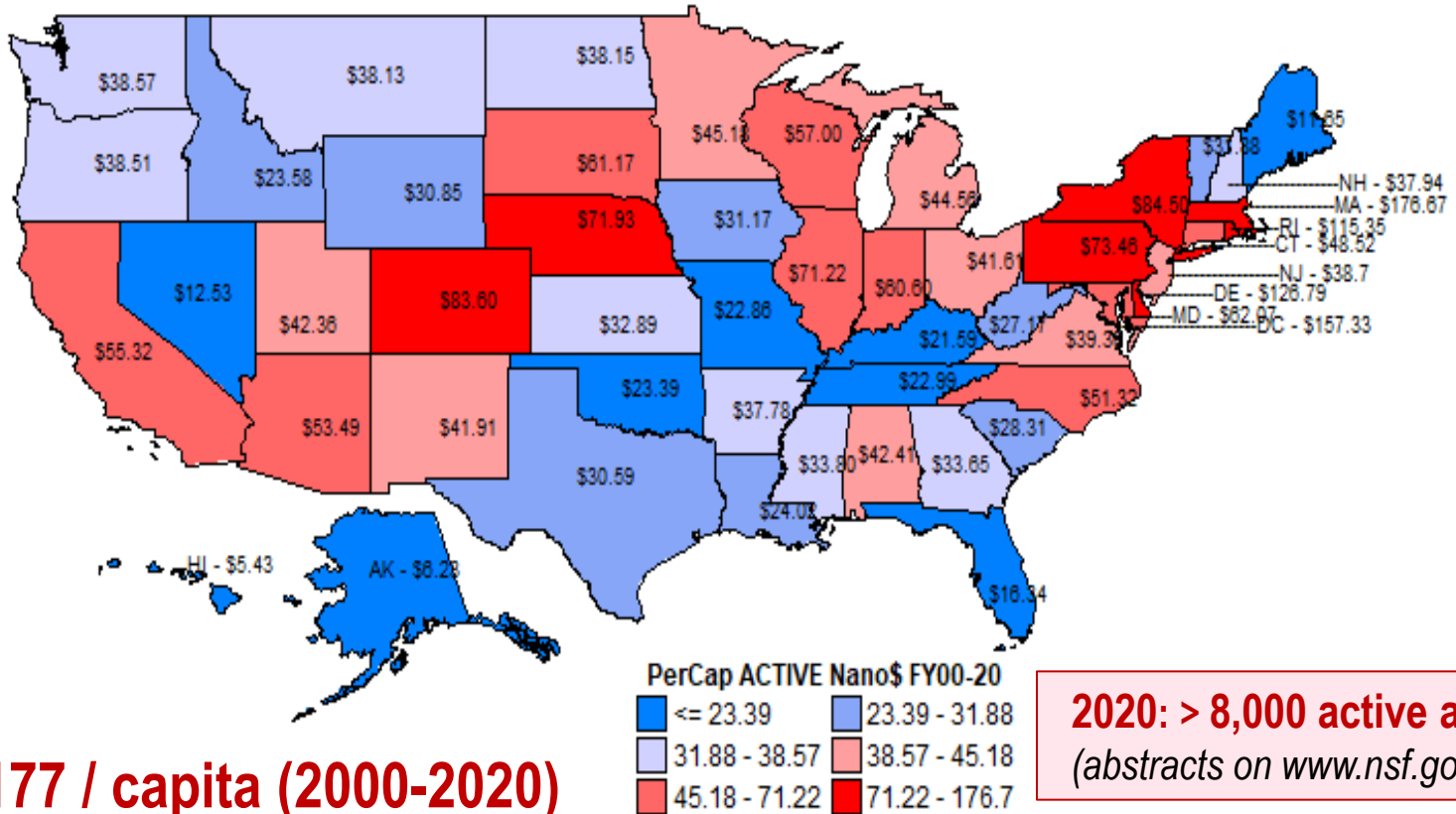
#1 CA 1,101 awards in 2020

AK 3; AL 109; AR 41; AZ 190; **CA 1,101**; CO 209; CT 143; DC 88; DE 92; FL 295; GA 231; HI 15; IA 91; ID 27; IL 475; IN 289; KS 70; KY 44; LA 103; **MA 587**; MD 225; ME 14; MI 311; MN 127; MO 136; MS 43; MT 30; NC 288; ND 13; NE 68; NH 38; NJ 239; NM 63; NV 40; **NY 745**; OH 299; OK 61; OR 107; **PA 583**; PR 24; RI 71; SC 82; SD 26; TN 108; **TX 584**; UT 99; VA 248; VT 20; WA 174; WI 137; WV 22; WY 12



NSF's NS&E amount new awards per capita

FYs 2000 - 2020: U.S. average ~ \$47.5 /capita

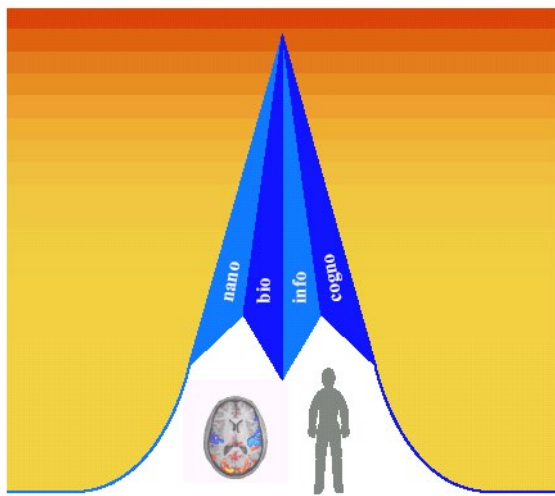


2020: > 8,000 active awards
(abstracts on www.nsf.gov/nano)

MC Roco, Dec 1 2020

AK 6.23; AL 42.41; AR 37.78; AZ 53.49; CA 55.32; **CO 83.60**; CT 48.52; **DC 157.33**; **DE 126.79**; FL 16.34; GA 33.65; HI 5.43; IA 31.17; ID 23.58; IL 71.22; IN 60.60; KS 32.89; KY 21.59; LA 24.02; **MA 176.67**; MD 62.07; ME 11.65; MI 44.56; MN 45.18; MO 22.86; MS 33.80; MT 38.13; NC 51.32; ND 38.15; NE 71.93; NH 37.94; NJ 38.70; NM 41.91; NV 12.53; NY 84.50; OH 41.61; OK 23.39; OR 38.51; PA 73.46; PR 23.81; **RI 115.35**; SC 28.31; SD 61.17; TN 22.99; TX 30.59; UT 42.36; VA 39.30; VT 31.88; WA 38.57; WI 57.00; WV 27.17; WY 30.85

#1 MA \$177 / capita (2000-2020)



CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002



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

2002: “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.”

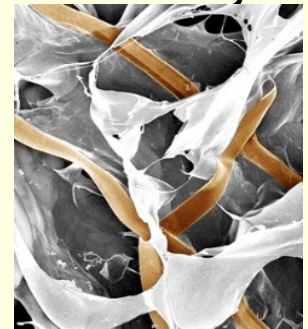
“Improving human performance has been a dream for centuries,” says Mihail Roco, chairman of the government-funded National Nanotechnology Initiative, and lead author of the study ***Converging Technologies for Improving Human Performance***, released on 8 July — says that the **convergence ... may help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

Challenges of nanotechnology development in 2020

NS&T continue to be driven by exploratory research. Topical examples are:

- **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

- **New system architectures:** guided self-assembling structures, evolutionary architectures, biomimetics--based, biorobotics-based, neuromorphic, adiabatic switching for IT, quantum systems... to be invented.
- **Nano-Bio-Info-Cognition-AI technology platforms, such as for hierarchical modular nanomanu. and personalized nanomed.**
- Genetic/single cell, neurotechnology, robotics -
to improve human potential
- High productivity - high return **in all industry sectors**



Convergence science & technology in the time spiral:

three hierarchical S&T platforms (2000-2040)

III. CKTS: Convergence of Knowledge, Technology and Society

(NBICA solutions + diffusion in economy)

II. NBICA: Nano-Bio-Info-Cogno-AI

(Converging foundational technologies)

I. - Nano: Nanotechnology

- IT: Information, networking, digitization

- AI: Artificial intelligence systems

(General-purpose S&T fields / tools)

Challenge: Create nano-inspired solutions and tools for the industries of the future

- **Artificial intelligence (AI)** – use and design nanosystems
- **Quantum Information S&T** - a part of nanoscale S&T
- **Advanced Wireless (5G, IoT)** - including use nanosystems
- **Advanced Manufacturing** - a focus on nanomanufacturing
- **The Bioeconomy** - a focus on nanobiotechnology
- **Sustainable society** – for materials, water, energy, env
- **Independent aging** – includes nano-medicine & robotics
- **Increase human capacity** – physical, mental, group

Challenge: Nano-inspired solutions require skilled people and physical infrastructure

- **Integrated centers for more efficient, responsible transition from fundamentals to technology platforms & applications**

Ex: US/NNCI, France/Minatec, Japan/Net, NL/IMEC, China

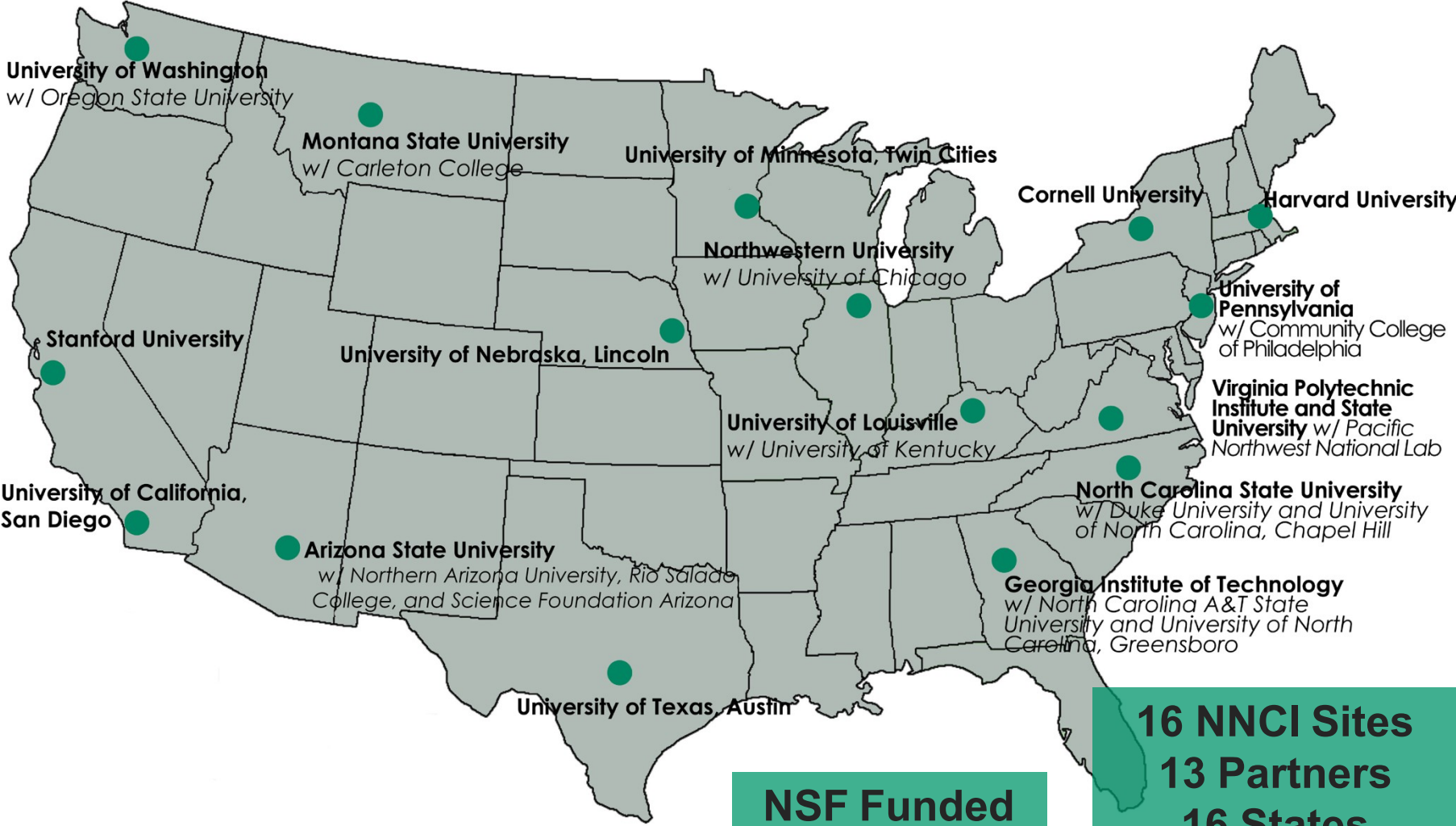
- **High performance facilities**

Ex: **High Magnetic Field Beamline at Cornell Univ. (2020)**
mid-scale infrastructure investment

- **Human resources, new organizations**

Ex: **Micro-Nano Technology Education Center, Pasadena City College, July 1, 2020-**; for Community Colleges together

National Nanotechnology Common Infrastructure Network 2020



**NSF Funded
2015 - 2025
\$165M total**

**16 NNCI Sites
13 Partners
16 States
69 Facilities
>2,200 Tools**

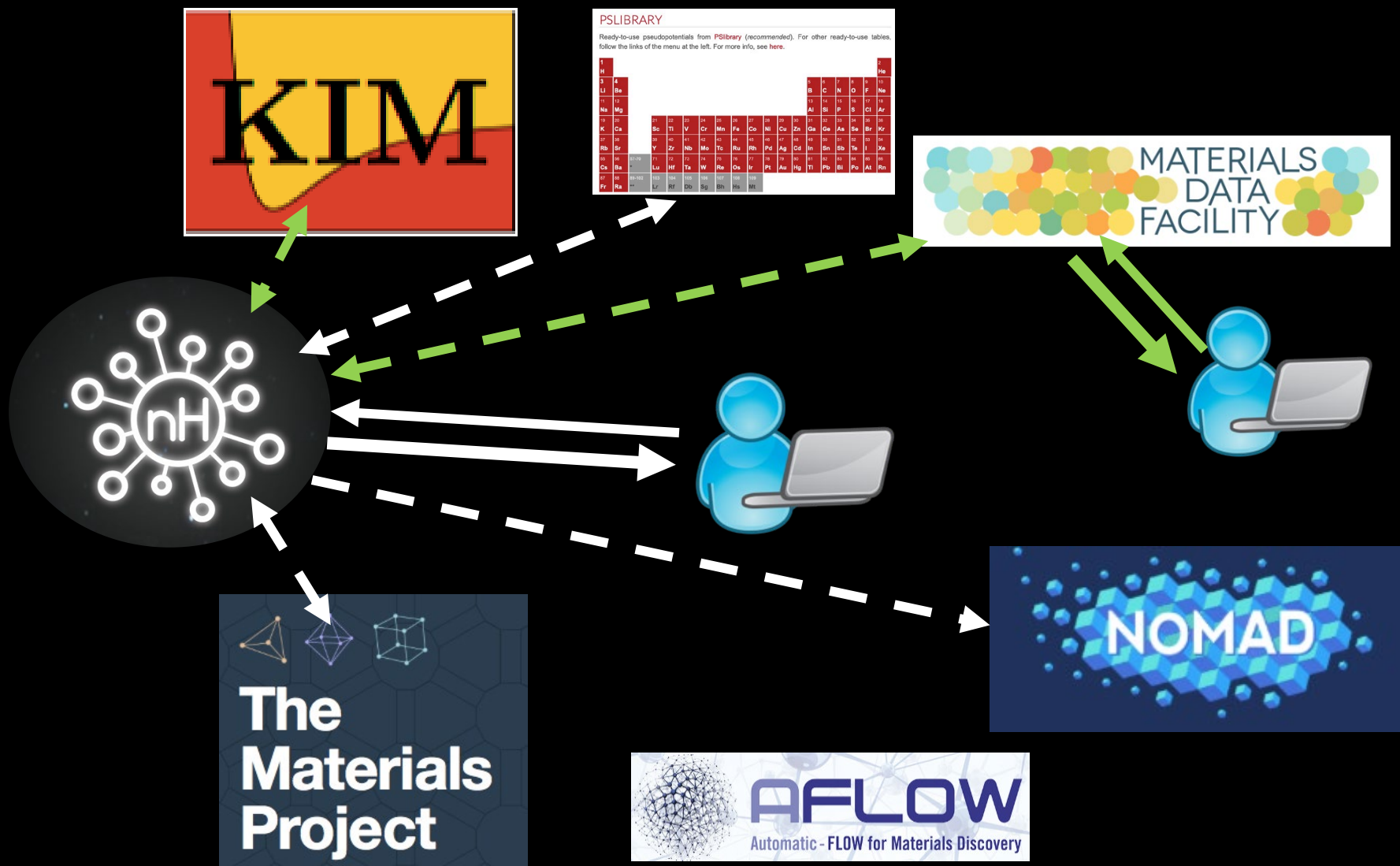


NSF and DOE Quantum Research Centers 2020



<https://science.osti.gov/Initiatives/QIS/QIS-Centers>

A cyber ecosystem for nano science & engineering



Women in Nanotechnology

<https://www.nano.gov/womens-history-month>



Angelique Johnson



Julia Greer



Saniya LeBlanc



Michelle Bradbury



Paula Hammond



Marcie Black



Celia Merzbacher



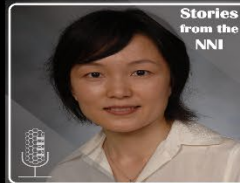
LaShanda Korley



Christina Lomasney



Sangeeta Bahtia



Qilin Li



Jennifer Miller



Tina Brower Thomas



Lynn Bergeson

#WomenInNano
#WomenInScience

Several non-technical challenges

Funding challenge: as the use of nanotechnology has diffused in economy, there focus on upstream concepts, common fundamental research, and new methods needs to be maintained

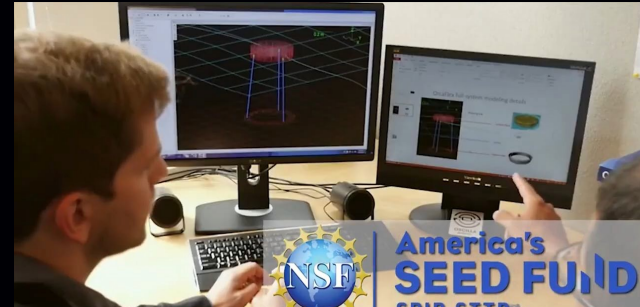
Collaboration and competition challenge: as applied research and development increase, the tension between collaboration and competition increases

Translational speed challenge: as the benefits of R&D are invers proportion with the time of implementation, building a flexible, general-purpose infrastructure for fast design, nanomanufacturing and people training is essential

Translational opportunities at NSF: Knowledge leads to action



I-CORPS



Americas Seed Fund SBIR.STR



Convergence Accelerator



CyberCorps



Civic Innovation Challenge

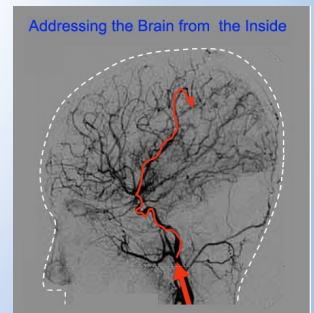


- Evolutive nano-bio-AI-robotic systems
- Use *hybrid bio-nanosystems* (viruses, bacteria, ..), synthetic biology & neurotechnology
- Control of DNA , RNA, tissues at the nanoscale
- Human enhancement, including physic-medical, brain potential, behavior, individualized medicine, others
- Earlier detection of illnesses, artificial organs & expand life expectancy
- Intelligent working and urban environments



Challenge: Novel technologies from the nanoscale require new responsibilities

- **New implications of emerging technologies/ outcomes**
- **Need for integration of R&D and translation**
- **Expand education pipeline:** cross-fields, anticipatory, inclusive
- **Nano-EHS revisited:** for larger nano- structures, composites, devices; affected by digital technologies, AI and robotics, effects on bio- and eco- ethics
- **Nano-ELSI is increasingly important:** ethical, economic, legal, safety, human development
- **Nano-convergence:** essential changes in evaluating and governing the risk, new organizations, and a global view



Several S&T trends

- Explore foundational principles not yet understood
- Hierarchical manufacturing using modular NBICA
- Sustainability nanotechnology: recycle, water, energy, materials, clean environment, nano metals & plastics..)
- Gene editing in medicine, agriculture, energy
- Brain-to-brain and brain-machine communication
- Quantum entanglement, communication and computing
- NT for smart systems: general purpose AI and Int-Aug
- Convergence with other foundational technologies

Related publications

1. ***“Nanotechnology: Convergence with Modern Biology and Medicine”***, (Roco, Current Opinion in Biotechnology, 2003)
2. ***NANO1: “Nanotechnology research directions: Vision for the next decade”*** (Roco, Williams & Alivisatos, WH, 1999, also Springer, 316p, 2000)
3. ***NANO 2020: “Nanotechnology research directions for societal needs in 2020”*** (Roco, Mirkin & Hersam, Springer, 690p, 2011a)
4. ***NBIC: “Converging technologies for improving human performance: nano-bio-info-cognition”*** (Roco & Bainbridge, Springer, 468p, 2003)
5. ***CKTS: “Convergence of knowledge, technology and society: Beyond NBIC”*** (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)
6. ***“The new world of discovery, invention, and innovation: convergence of knowledge, technology and society”*** (Roco & Bainbridge, JNR 2013a, 15)
7. ***“International perspective on nanotechnology papers, patents, and NSF awards (2000–2016)”*** (Zhu, Jiang, Chen & Roco, JNR 2017, 19-370)
8. ***Proc. NSF NSE Grantees Dec. 2019***, available on www.nseresearch.org/2019/
9. ***“Overview: Affirmation of Nanotechnology between 2000 and 2030”*** (MC Roco, Ch.1 in Nanotech. Commercialization, Wiley, Ed. T. Mensah et al., 2018)
10. ***“Principles of convergence in nature and society and their application: from nanoscale, digits, and logic steps to global progress (MC Roco, JNR 2020, 22:321)***