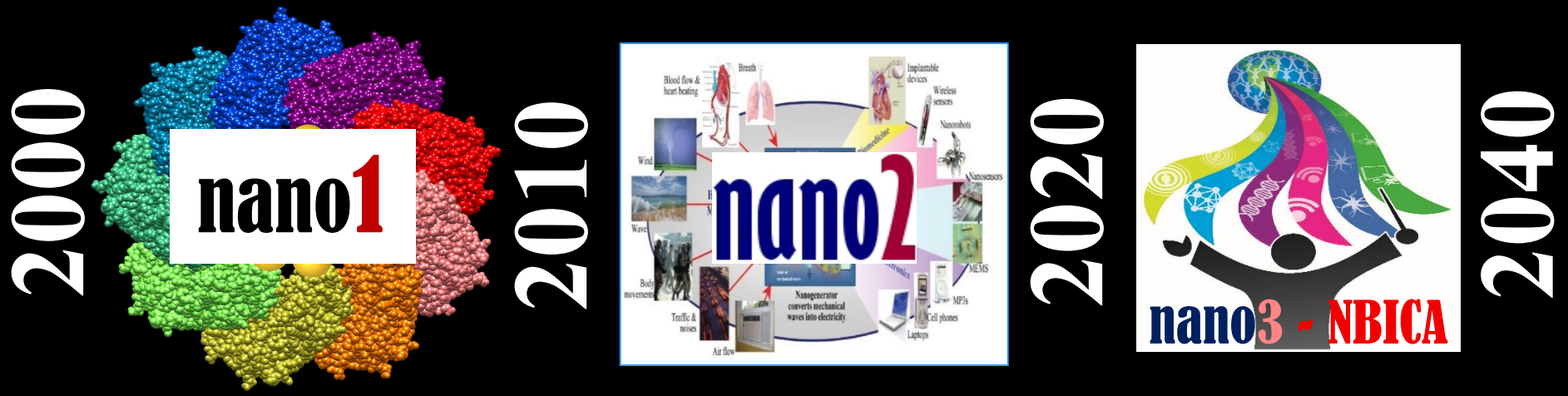


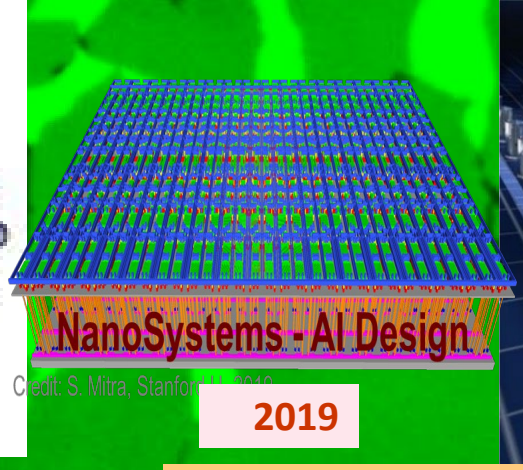
NANOTECHNOLOGY and Global Emerging S&T System

Mihail C. Roco
National Science Foundation and National Nanotechnology Initiative

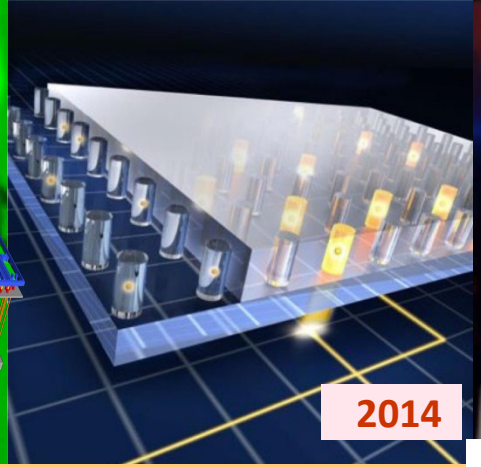
23rd NSF Nanoscale Science and Engineering Grantees Conference
December 7-8, 2023, Westin Hotel

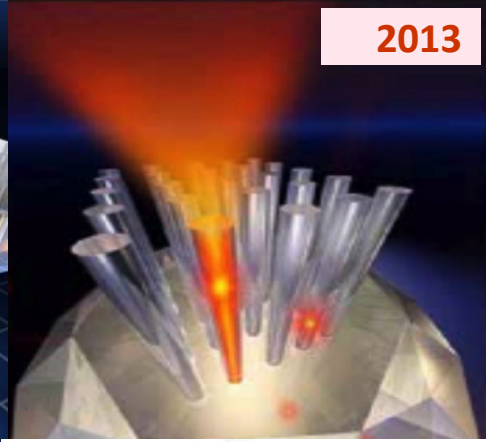
ICONIC NANO MOZAIC

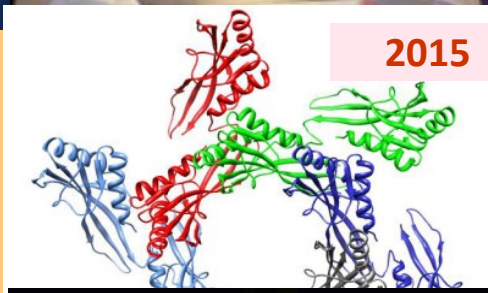

2012



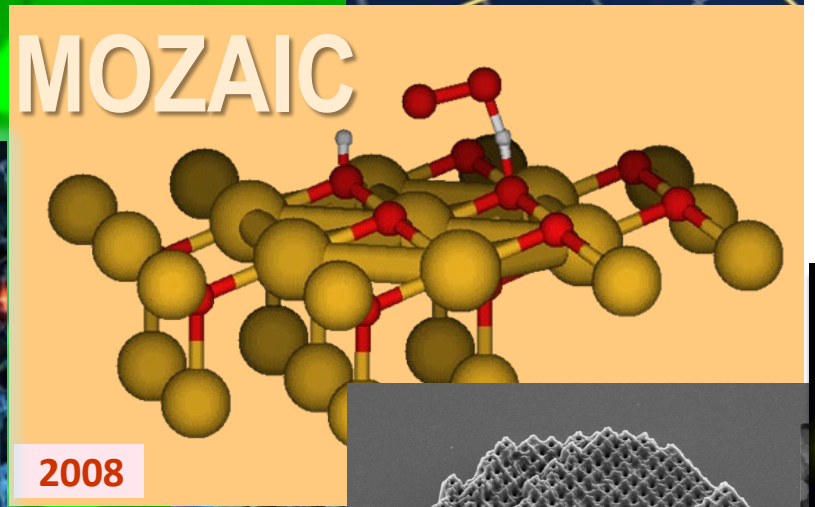
Credit: S. Mitra, Stanford U., 2019
2019


2014

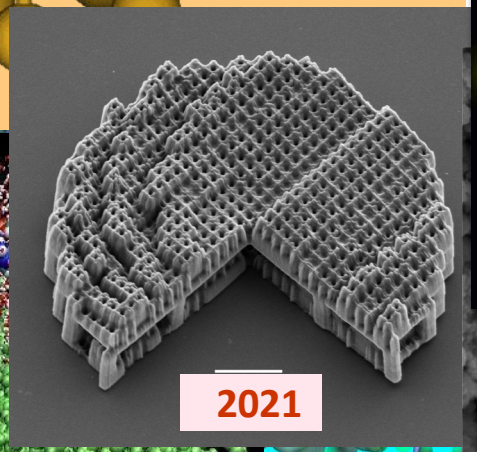

2013

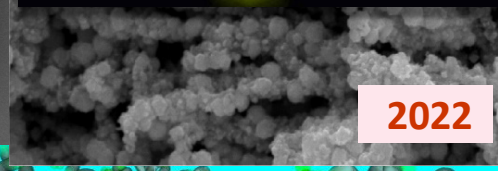

2015


2018


2008

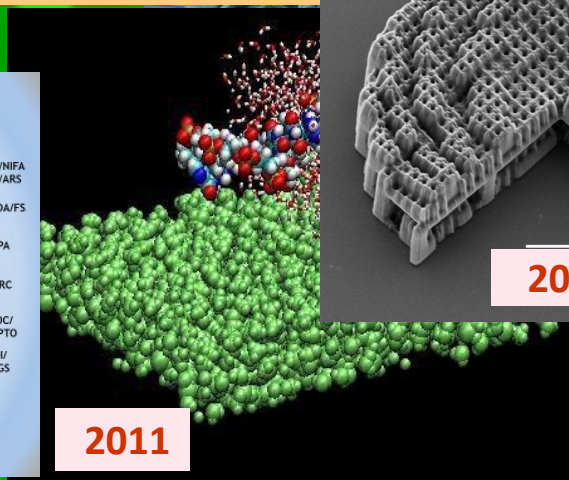

2023

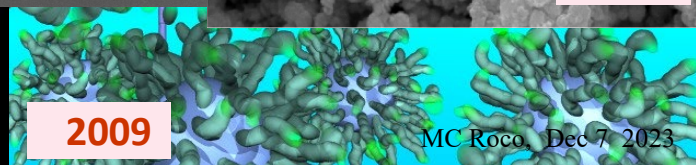

2021


2022

2017

2010

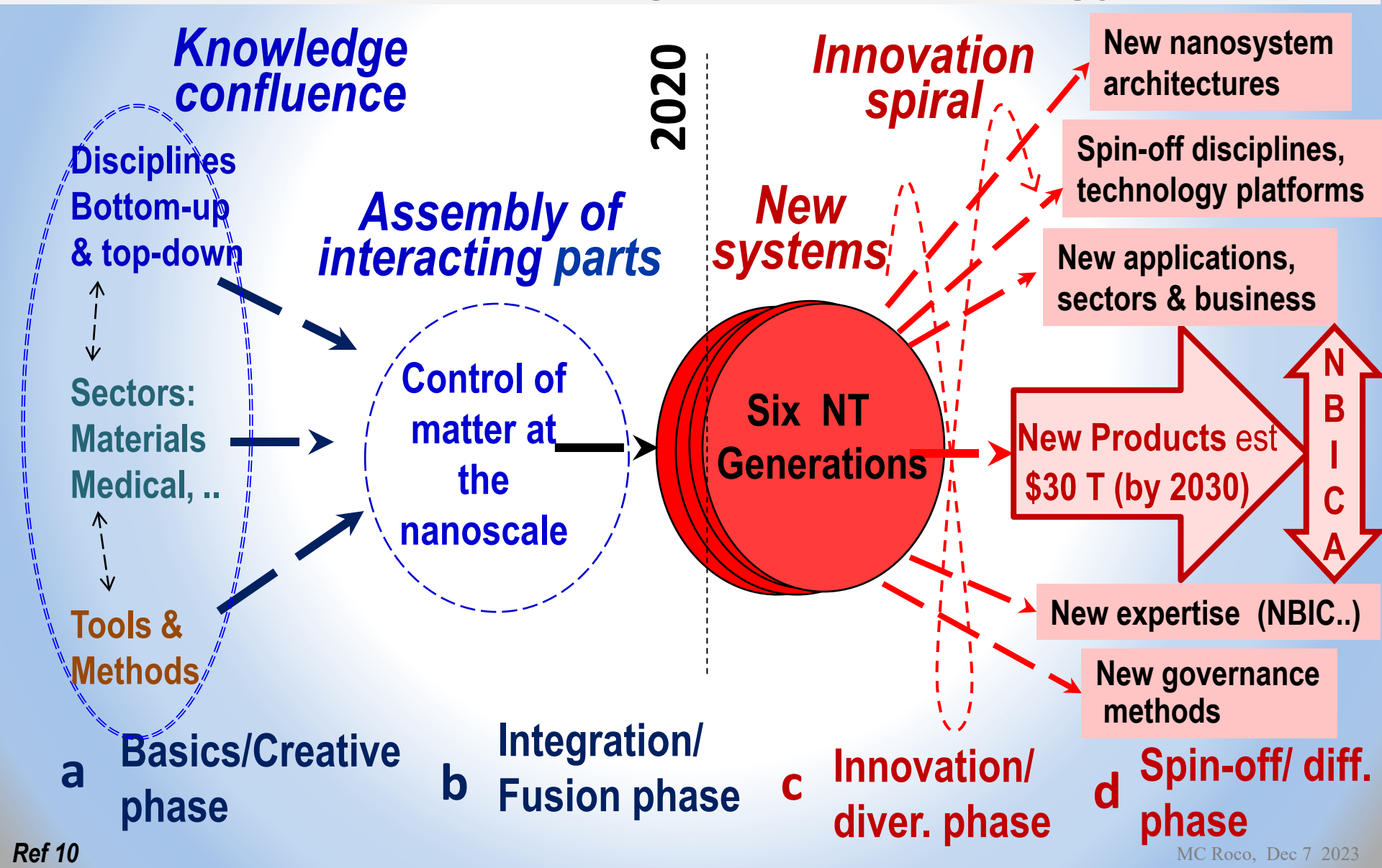

2011


2009

Outline

- **2000-2040 nanotechnology perspective**
  in the international context
- **A foundation for the global S&T system**
  illustrated by contributing NSF programs
- **New horizons after 2020**
  converging and emerging technologies

2000-2040 Convergence-Divergence cycle for establishing nanotechnology



Ref 10

40-year vision for establishing nanotechnology in 4 stages

GENERATIONS OF NANOPRODUCTS
(prototypes stage)

2040

DIVERGENCE

Emerging industries and services

nanoD Diffusion in Economy

2030-2040

New socio-economic capabilities, architect

nano3 Technology divergence

2020-2030

To general purpose technology, moduls

nano2 System integration

2010-2020

CONVERGENCE

Create library of nanocomponents, function

nano1 Component basics

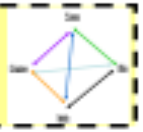
2000-2010

Foundation for new S&T fields

Emerging Societal Solutions

6. Nanosystem Conv. Networks

5. NBICA Techn Platforms

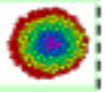


4. Molecular Nanosystems

3. Systems of Nanosystems

2. Active Nanostructures

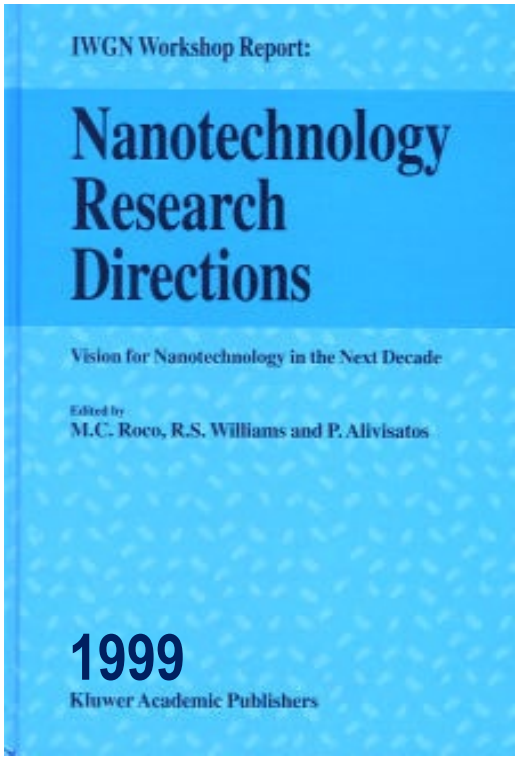
1. Passive Nanostructures



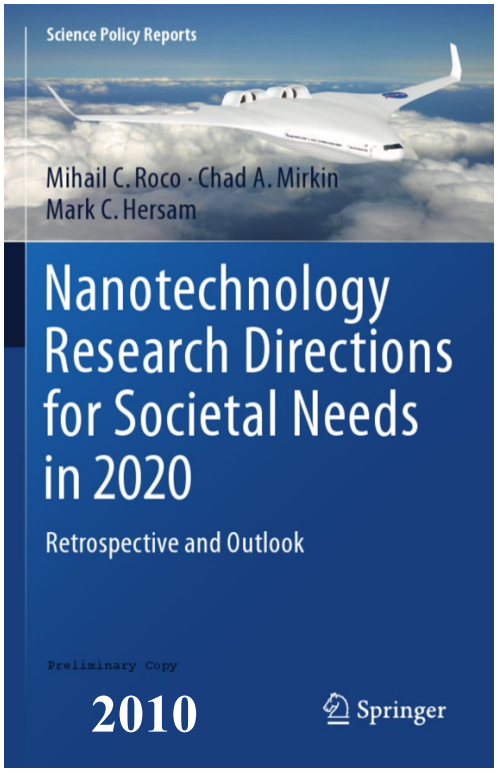
MC Roco Sept 29 2020

Nanotechnology: four vision-setting reports

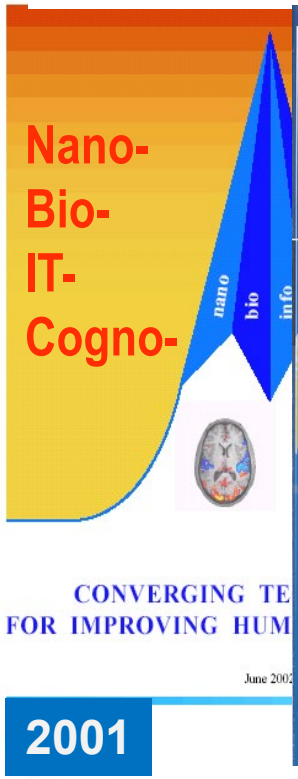
nano1 (2001-2010)

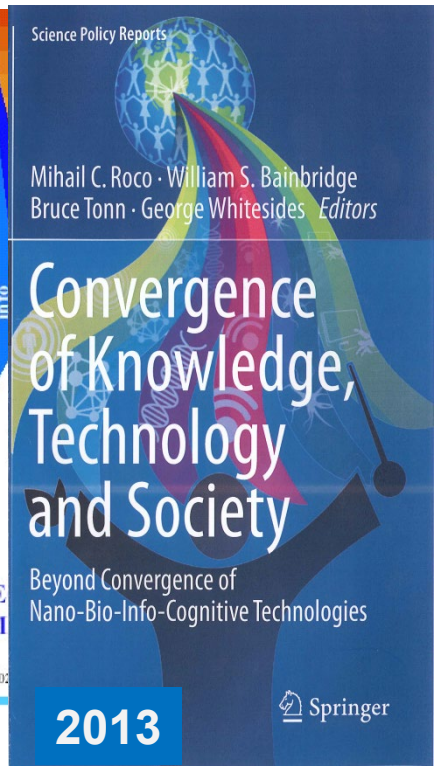


nano2 (2011-2020)



NBIC1&2 (2011-2040)





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

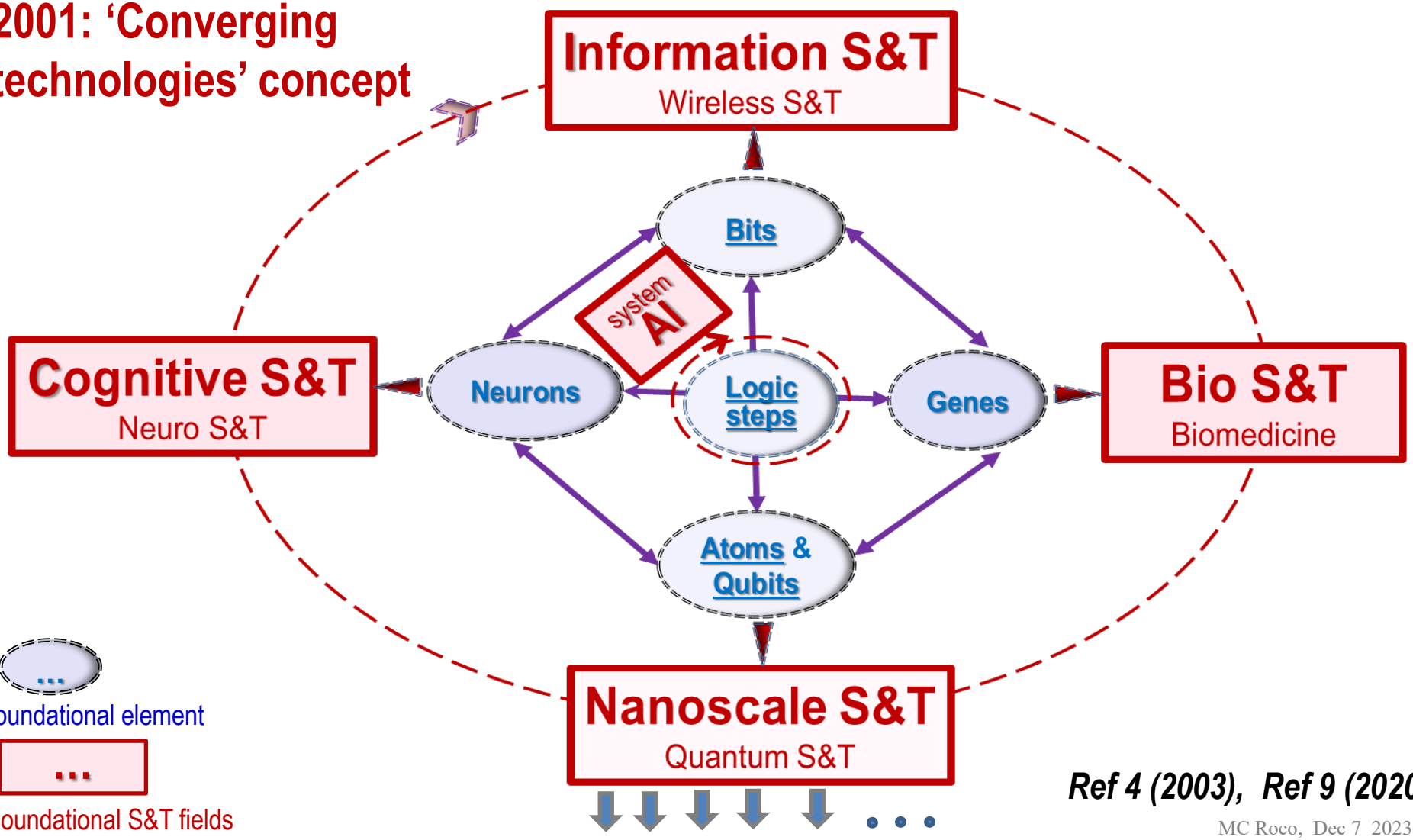
Input from >40 countries, Used in > ***80 countries****; Reports freely available* ***(Refs. 2-5)***

NANO is a foundation for converging S&T system

Foundation fields**: Nano, Bio, Information, Cognitive, and system AI- **(NBICA)

***from 5 foundation elements**: atoms/qubits, genes, bits, neurons, logic steps*

2001: 'Converging technologies' concept



Ref 4 (2003), Ref 9 (2020)

Nanotechnology spin-off S&T areas

2000-2020 (top 20 topics) *(i)*

- **Quantum systems** - *Quantum S&E 2003; expansion **NQI** 2018*
- **Nano-Environment, *EHS & ELSI* 2003; *NNI WG* 2005**
- **Metamaterials** – *2004*
- **Plasmonics** – 2004
- **Nanomedicine** – 2004 (NIH focused program nano for cancer)
- **Synthetic biology** – 2004 (NSF increase of awards)
- **Nanoelectronics Research Initiative** 2005; 2015; CHIPS 2022
- **Nano antennas and devices for wireless,** 2006
- **Modeling / simulation** - *Materials Genome Initiative 2011*
- **Nanophotonics** - *National Photonics Initiative 2012*

Nanotechnology spin-off areas

2000-2020 (top 20 topics) *(ii)*

- **Nanofluidics**
- **Carbon-based electronics**
- **Nano sustainability**
- **Nano wood fibers, nanocellulose**
- **Nano-AI** 2017 steep increase of awards and publications
- **DNA nanotechnology, Protein nanotechnology**
- **Nano neurotechnology**
- **Nanosystems-mesoscale**
- **Quantum biology**
- **Nano plastics**
- **Nano in plants ….**

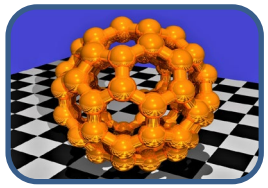
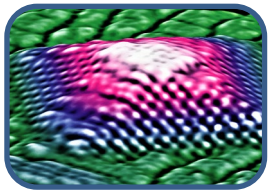
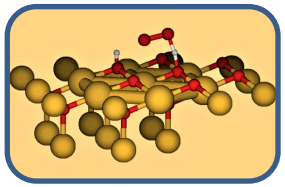
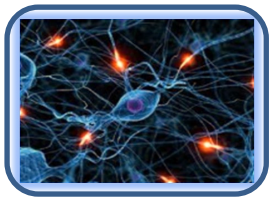
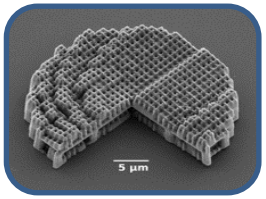
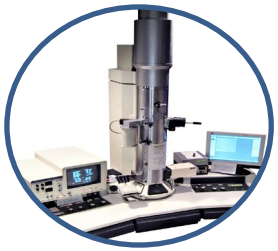
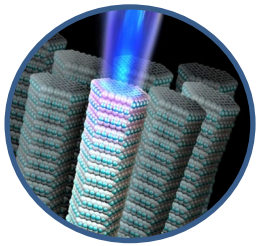
NNI divergence of nanotechnology

MC Roco, Dec 7 2023

U.S. National Nanotechnology Initiative, $40B, by 2023

Knowledge divergence: 80 countries have created nano R&D programs

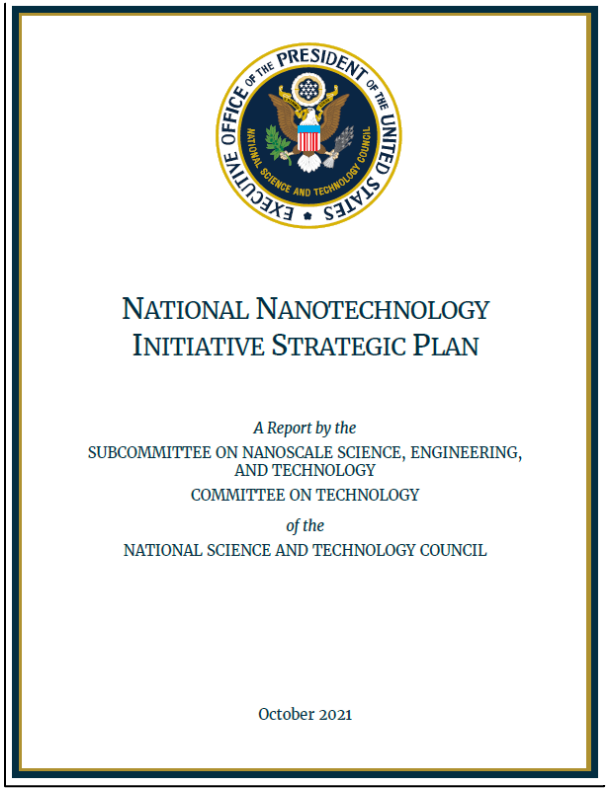
Investment Impact: Examples of discovery-innovation in nanotechnology (NNI)

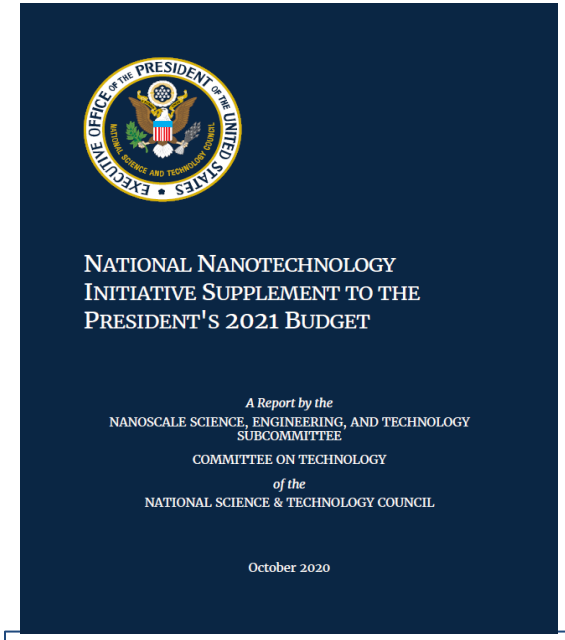
	1970-1980s:	1990s:	2000s: NNI –	2010s: NNI –	2020s: NNI –
	ATOMIC CLUSTERS, SUPTRAMOLECULES	CERAMIC, METAL & POLYMER NANO STRUCTURES; NANOPARTICLES	NSEC, NIRT, NRI, NSEE, NANO-BIO, QUANTUM, MANUFACTURING, ENVIRONMENT, ETHICS	INTEGRATION AT NANO, NSF-SRC SEMICONDUCTORS, NEUROMORPHICS	NANO FOUNDATION, NEW S&E PLATFORMS FOR CONVERGING TECHNOLOGIES
NSF INVESTMENTS					
CURRENT IMPACTS	 ATOMIC & ELECTRON MICROSCOPY; C60 MATERIALS	 COMPOSITE MATERIALS, NANOTUBES, NANOWIRE LASERS	 HIGH MEMORY DEVICES, TARGETTED DRUGS, FIRST QUANTUM DEVICE, NANO-MEDICINE; ESTABLISHED NANO-ECOSYSTEMS	 2D SYSTEMS, ENERGY, SYNBIO, COMPUTERS, CELLS, SENSORS, SUSTAINABLE SOCIETY	 PERVASIVE IN ALL SECTORS OF ECONOMY: Ex: AVIATIC NANOSYSTEMS, LIGHTS, VACCINES

REF: www.nseresearch.org/2021

MC Roco

National Nanotechnology Initiative in 2023





PCAST report on NNI

NAS/NRC report on NNI

2023 Annual NNI Supplement to the President's Budget: ~ $2 B

2021-2026 NNI Strategic Plan

Note: The actual NNI investment **by 2023 ~ $40 billion**, including $1.7 billion from BARDA in 2021

- HEHI
- Nano-plastics
- Nanotechnology for Sensing
- Water Sustainability Through Nanotechnology

Networks, Comunities of research, Webinars, Videos, …

Signature Initiatives (2011~2022) ; National Nanotechnology Challenges

NNI 2001-2023

- Involved **35 federal agencies** (in 20 departments and independent federal agencies), and enabled over **2,200 recorded collaborative interagency activities**
- Funded over **$40 billion in R&D (2021-2023) in coordinated initiative**
- Established over **70 international collaborations** in at least 18 countries in the past decade
- **Collaboration and nanotechnology penetration in key industries**: semiconductors and computers, nanostructure catalysts, pharmaceutical and molecular medicine, coatings, energy, water res.,…

Public Law No: 108-153

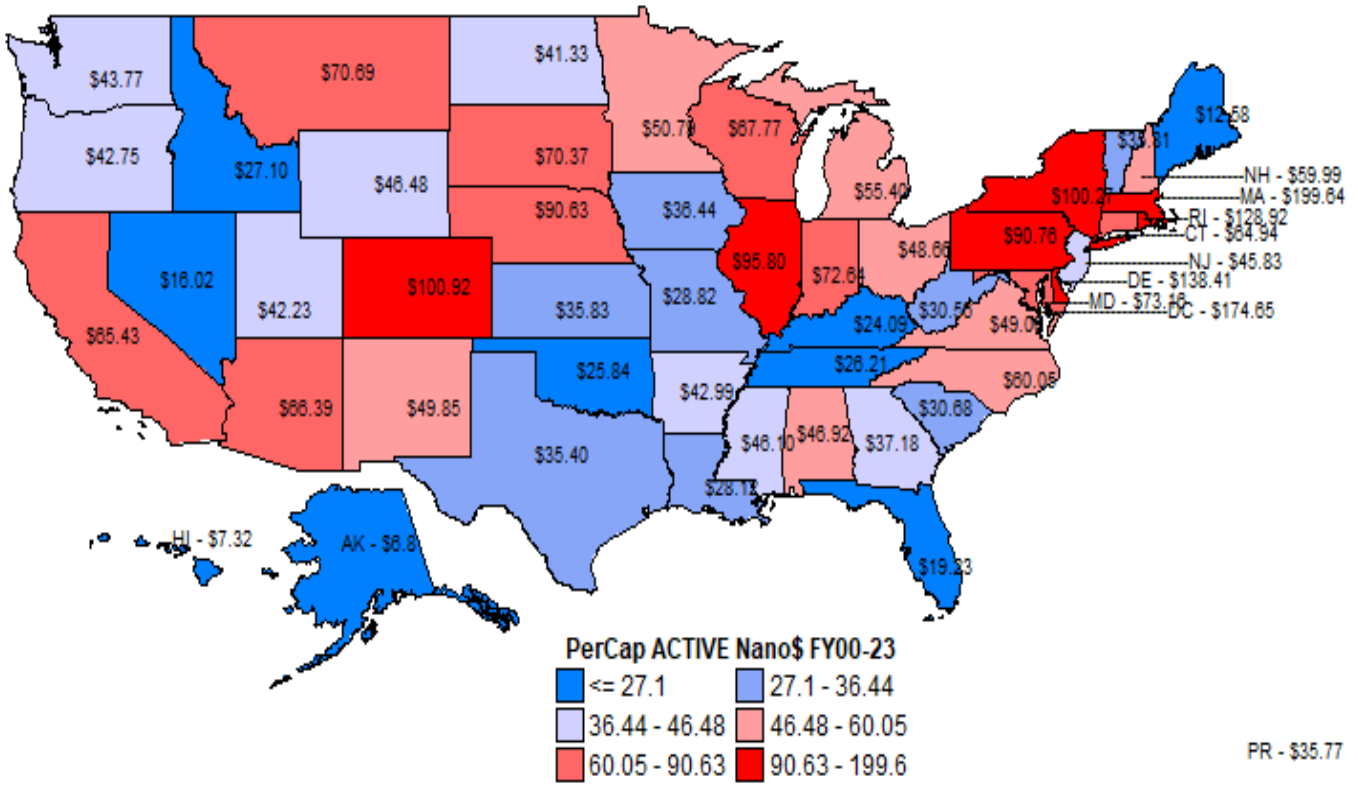
https://www.congress.gov/bill/108th-congress/senate-bill/189;
https://www.congress.gov/bill/108th-congress/senate-bill/189/text

NNI Retrospective video at 20 years:

http://www.nseresearch.org/2021/nni-retrospective.htm

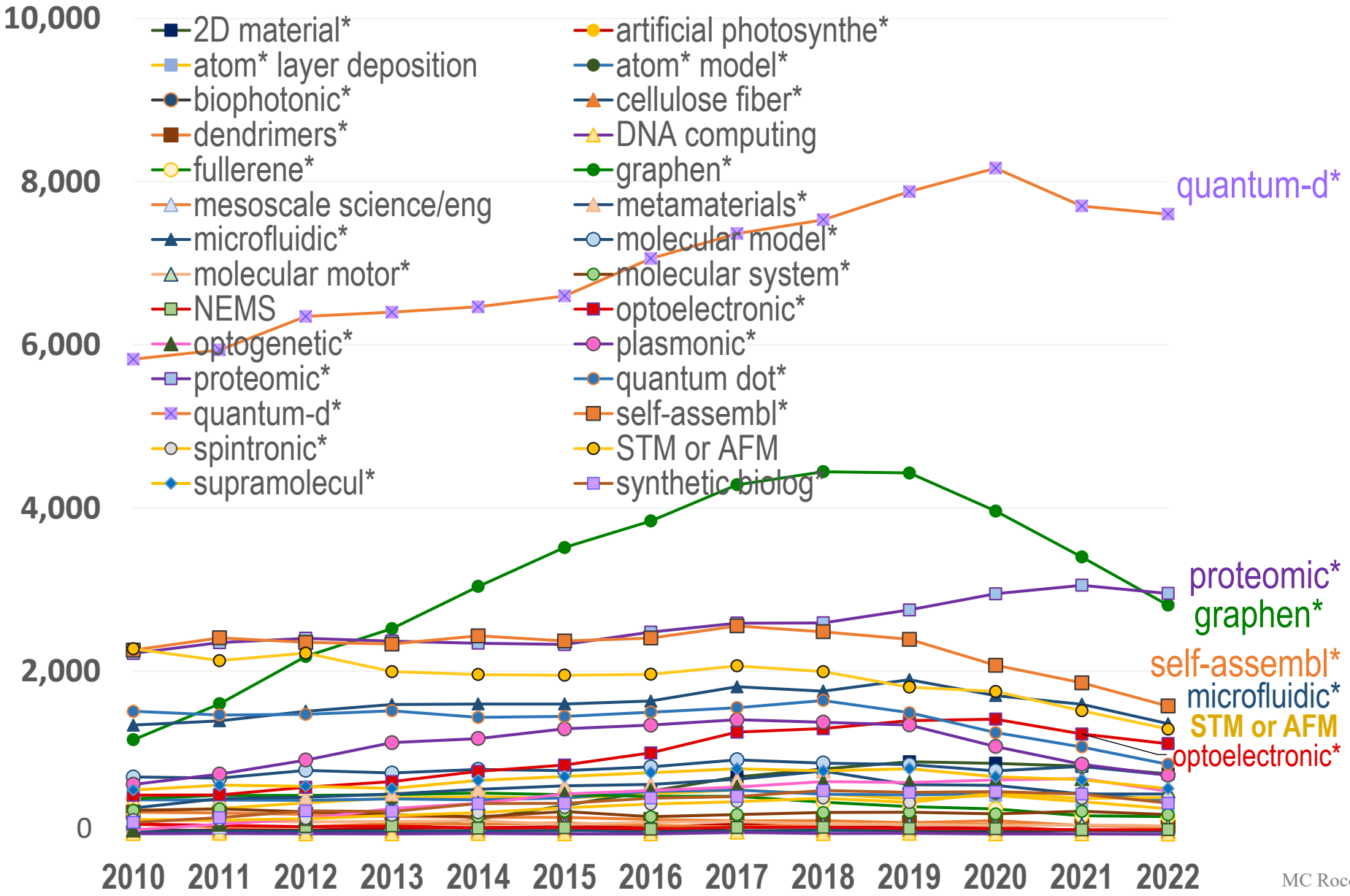
NSF's NS&E amount new awards per capita

FYs 2000 - 2023: U.S. median ~ $56.6 /capita



AK 6.80; AL 46.92; AR 42.99; AZ 66.39; CA 65.43; CO 100.92; CT 64.94; **DC 174.65**; DE 138.41; FL 19.23; GA 37.18; HI 7.32; IA 36.44; ID 27.10; IL 95.80; IN 72.64; KS 35.83; KY 24.09; LA 28.12; **MA 199.64**; MD 73.16; ME 12.58; MI 55.40; MN 50.79; MO 28.82; MS 46.10; MT 70.69; NC 60.05; ND 41.33; NE 90.63; NH 59.99; NJ 45.83; NM 49.85; NV 16.02; NY 100.27; OH 48.66; OK 25.84; OR 42.75; PA 90.76; PR 35.77; **RI 128.92**; SC 30.68; SD 70.37; TN 26.21; TX 35.40; UT 42.23; VA 49.00; VT 35.81; WA 43.77; WI 67.77; WV 30.56; WY 46.48

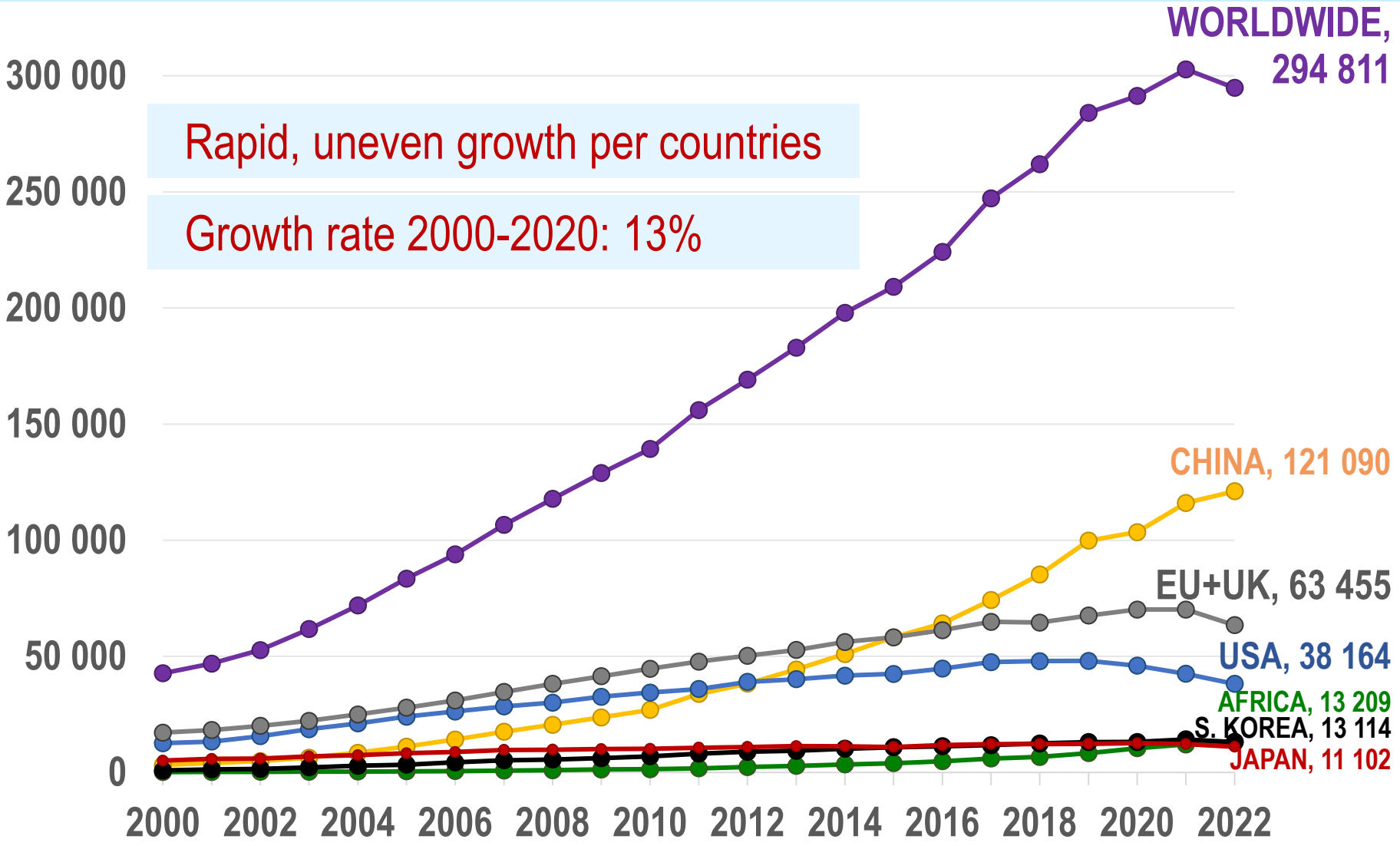
Nanotechnology topics in WoS from U.S. authors (2010-2022)



MC Roco,
Dec 7 2023

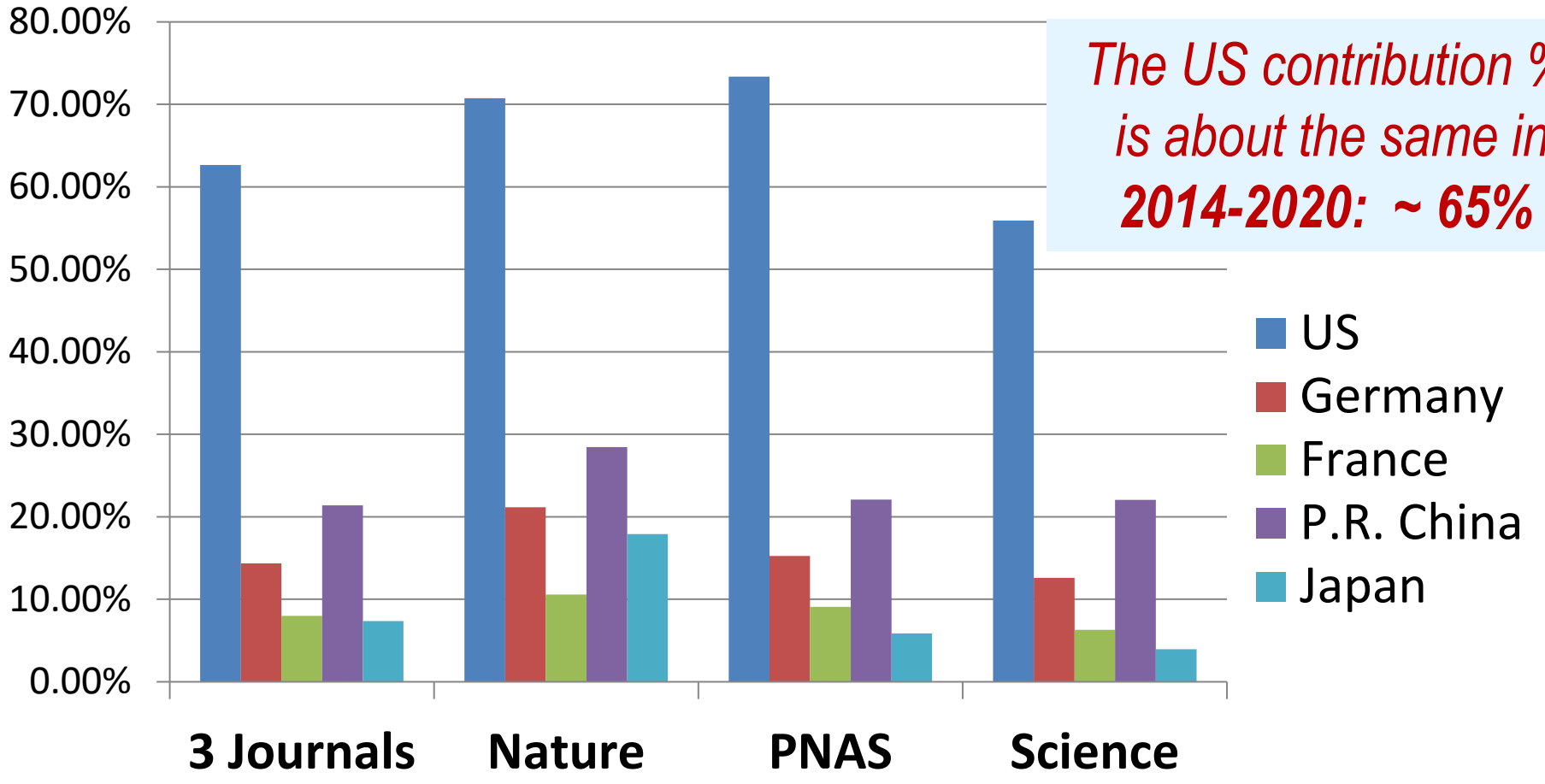
Nanotechnology papers in the WoS: 2000 - 2022

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



Five countries' contributions to Top 3 journals in 2020

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



The US contribution % is about the same in ***2014-2020: ~ 65%***

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

Longitudinal expert-based nanotechnology revenue estimations *(with publications from 2000 to 2023)*

Approach: *revenues from products and services where nanotechnology is condition for their competitiveness; expert evaluation of introduction in production (% of total)*

Year	Main input sources *reported annually, nseresearch.org, 2001-2023*	World ($B/yr)	US ($B/yr)
2001	Publ.: "Societal implications of nano…" (Springer 2001) & "Long view of nanotechnology …" (Roco, JNR 2011)	**~ 30**	**~ 13**
2005	Mitsubishi Research Inst., Deutsche Bank, Dow, IBM, Hoechst, (Nano2 Springer 2011), (Roco, JNR 2005)	~ 120	~ 42
2010	Report Lux Research (2014), (Nano2 Springer 2011), (Roco, in book Mensah, Willey 2018)	~ 335	~ 110
2013	Reports Lux Research (2014, updated in 2015, 2016)	**~ 1,190**	**~ 284**
2020	Publ.: (Mensah 2018), "NNI at 20 years" (Roco JNR 2023), Proc. "20 years of NNI" (nseresearch.org/2020)	~ 3,000	~ 750
2023	*Extrapolation* of the growth rate approximated in 2020-22 from "Economic Impact Analysis" (Parnin Group 2023) in 2020-23: ~10% /year	**~ 4,000**	**~1,000**

2023 Nobel Prizes - related to nanotechnology

- "*Discovery of **quantum dots** and a method for reliably producing them at a high quality*" - optics, quantum
  M.G. Bawendi, L.E. Brus and A.I. Ekimov, 2023 (***Chemistry***)

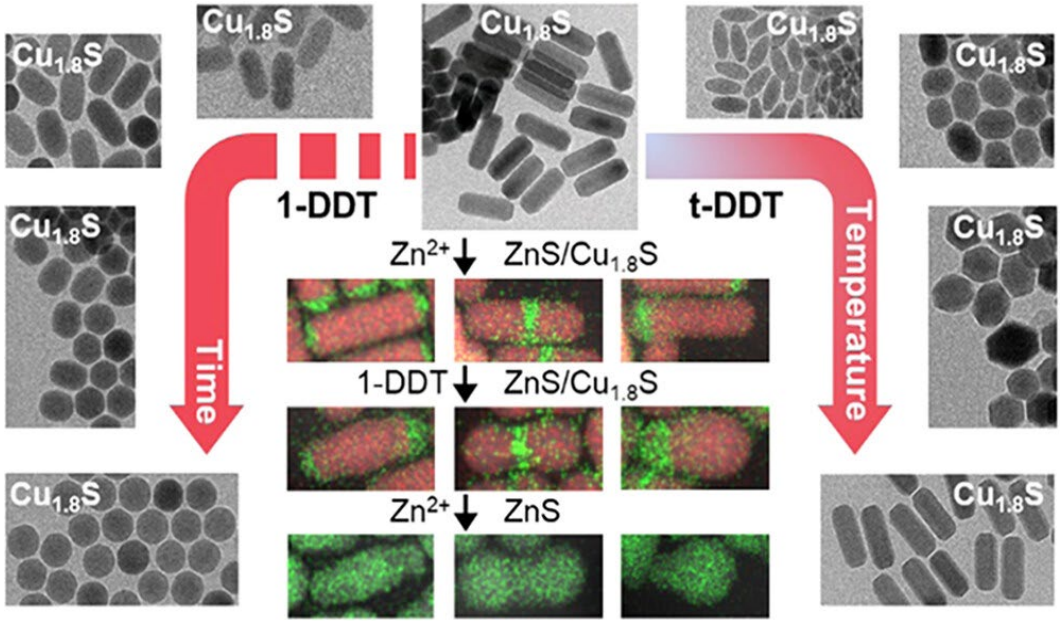
- "*Experimental methods that generate attosecond pulses of light for the study of **electron dynamics in matter***" - new tools for exploring the world of electrons inside atoms and molecules.
  P. Agostini, F. Krausz and A. L'Huillier (***Physics***)

- "*Discoveries concerning nucleoside base modifications that enabled the development of effective **mRNA vaccines** against COVID-19.*" – used for vaccines
  K. Karikó and D. Weissman, 2023 (***Medicine***)

Establishing nanotechnology foundations continue

Ex.: Investigations for novel nanomaterials – <u>still combinatorial, semi-empirical correlations for design</u>

Example: Synthetic control of nanoparticle shape and morphology is used for controlling a wide range of functions, including the optical, photophysical, catalytic, and electronic properties



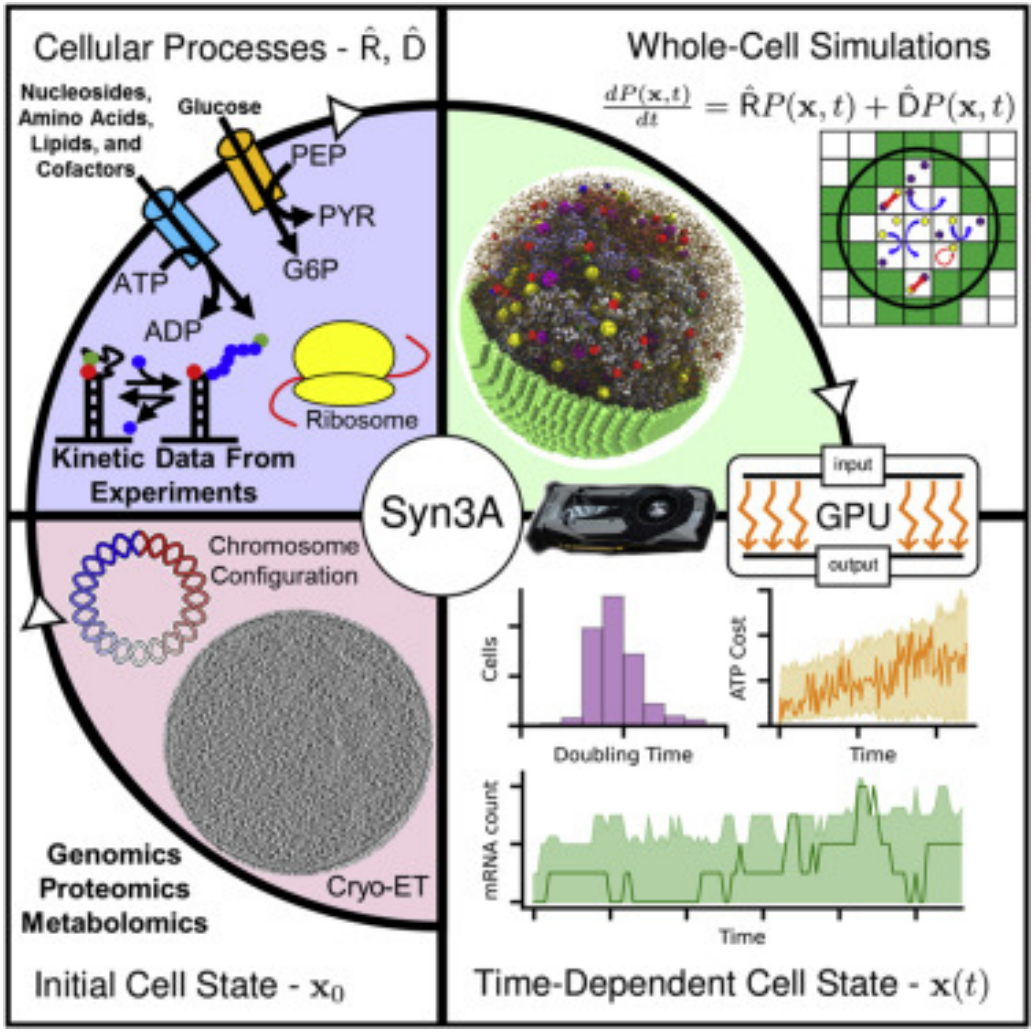
Young, H. L.; McCormick, C. R.; Butterfield, A. G.; Gomez, E. **D.; Schaak, R. E., Postsynthetic Thiol-Induced Reshaping of Copper Sulfide Nanoparticles.** ***Chem. Mater.*** **2022, *34*, 24, 11014–11025.**

NSF/DMR-2210442, Cation exch. pathways for constructing metal chalcogenide nanoparticle libraries

Ex.: Creating complex systems from the nanoscale

(via experimental, modeling)

Ex.: **From 3D atomic simulation to behavior of living 'minimal cell'**



Built a living "minimal cell" with a genome stripped down to its barest essentials -- and a computer model of the cell that mirrors its behavior.

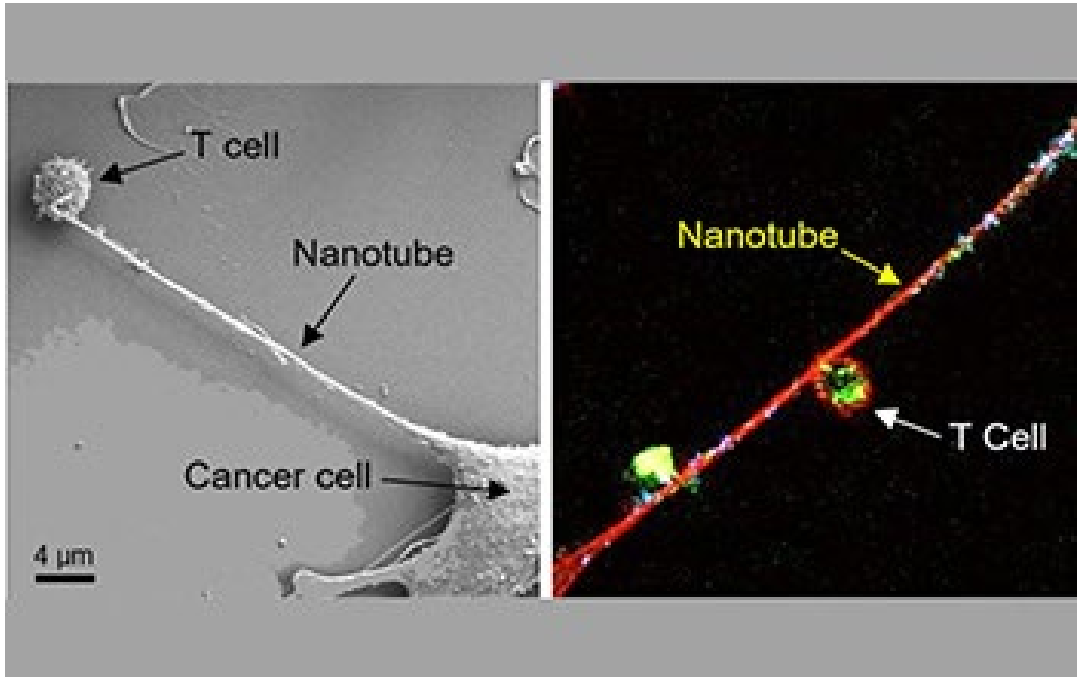
Developing a system for predicting how the functions of live cells will be altered by changes to their genomes, living conditions or physical characteristics.

Ex: Cell, 2022; University of Illinois Urbana-Champaign

Ex.: Defense mechanism: Cancer cells use nanotube tentacles to defend against T-cells

Nanotubes generated by cancer cell are stealing the immune cells' energy source, mitochondria. This is a mechanism by which cancer cells evade the immune system.

Shiladitya Sengupta, Brigham and Women's Hospital
Credit: *Nature Nanotechnology*
https://doi.org/10.1038/s41565-021-01000-4

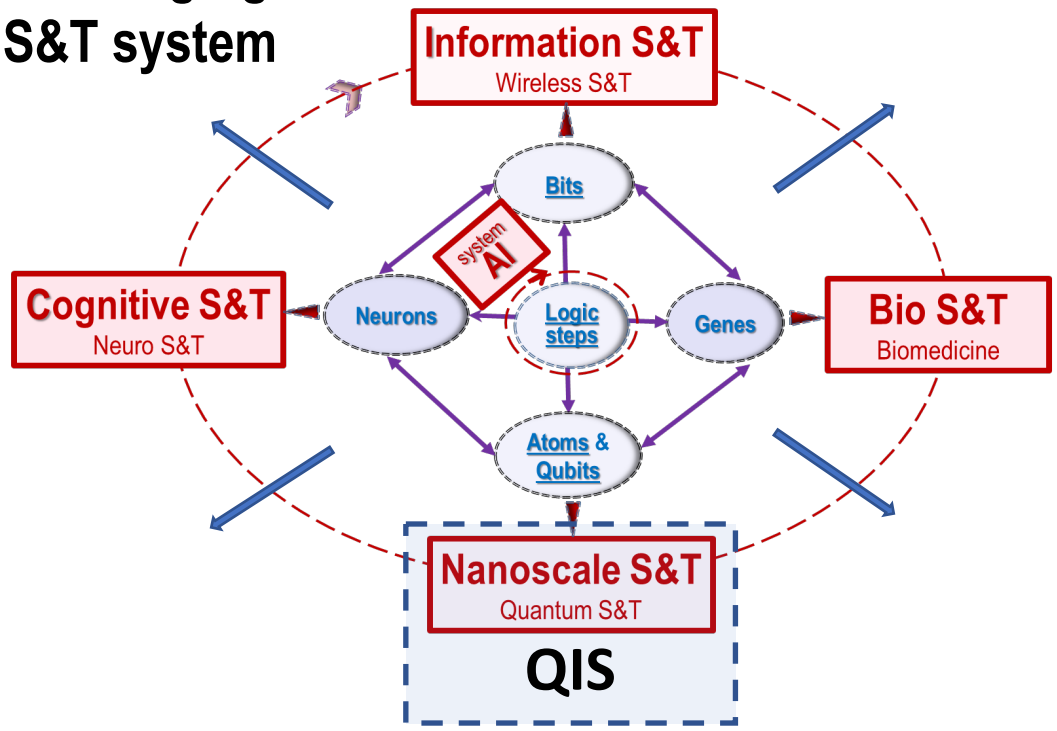


Ex.: Mechanisms of transport through specialized nanochannels (plasmodesmata) for RNA and protein signals between neighboring plant cells

Nanotechnology provides a foundation for the emerging S&T system

About 50% NSF's NNI awards are part of converging technologies
from advanced semiconductor and synthetic biology to AI systems, quantum information systems, and advanced wireless ...

Converging S&T system



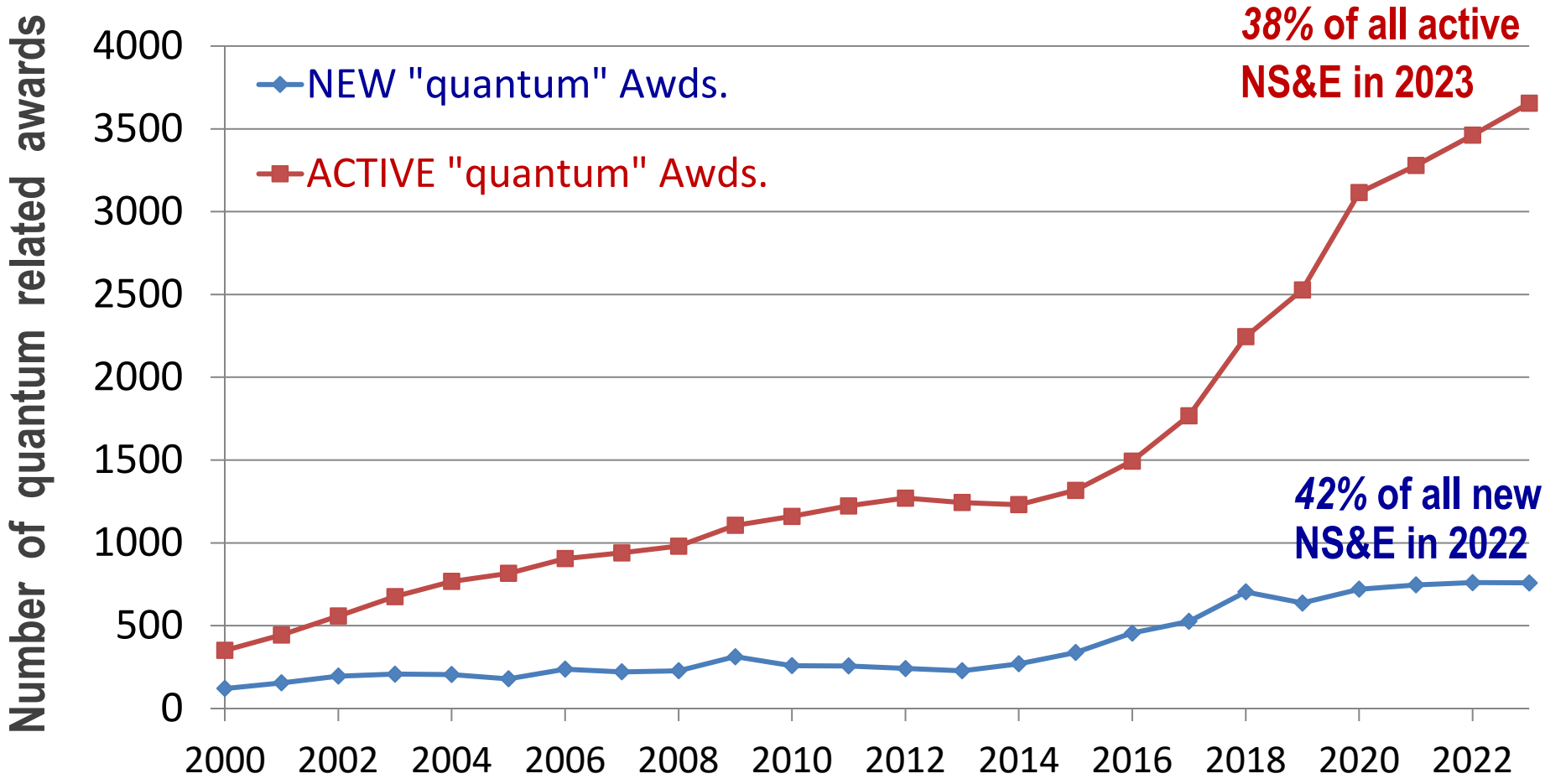
Nanotechnology supporting **quantum information systems**

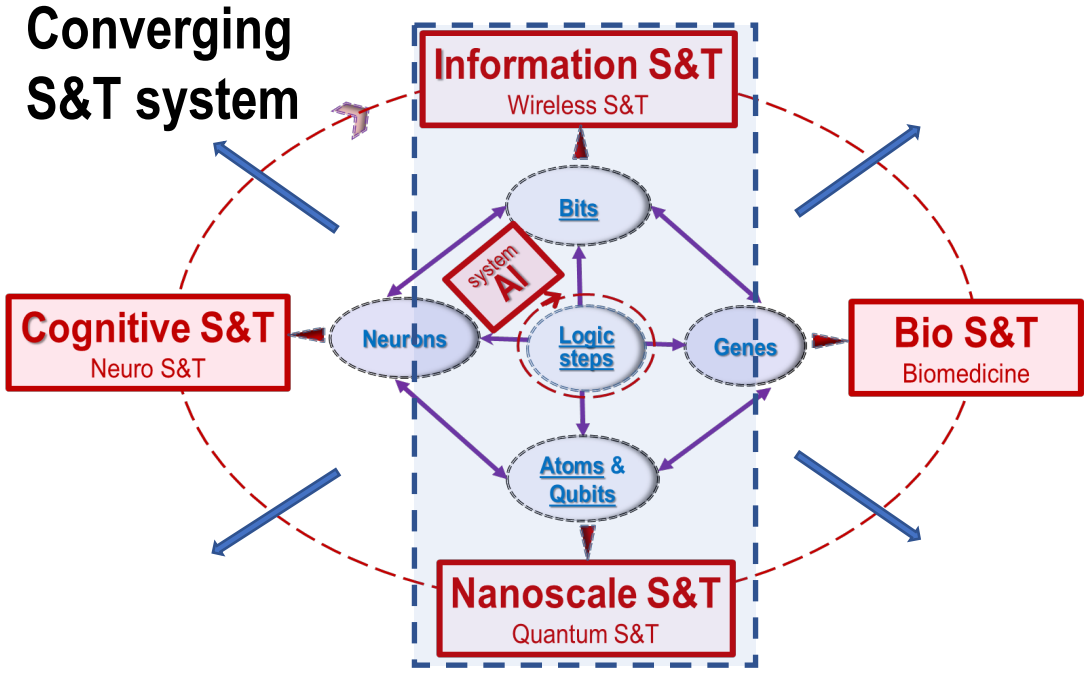
"Quantum National Initiative" (QIS)
is an outgrowth of NNI

- ***Ex. Topics***: Quantum materials, Quantum communication, Quantum computing, Quantum biology, Quantum sensors
- ***Ex. Outcomes***: First quantum device in 2010; Quantum internet; IBM and Google quantum computer systems, highly efficient
- ***Ex. NSF programs***: in core programs; *Network of Quantum Centers; Convergence Accelerators on Quantum Systems*

Confluence NS&E with QIS

Number of quantum in the NS&E portfolio in 2000-2023



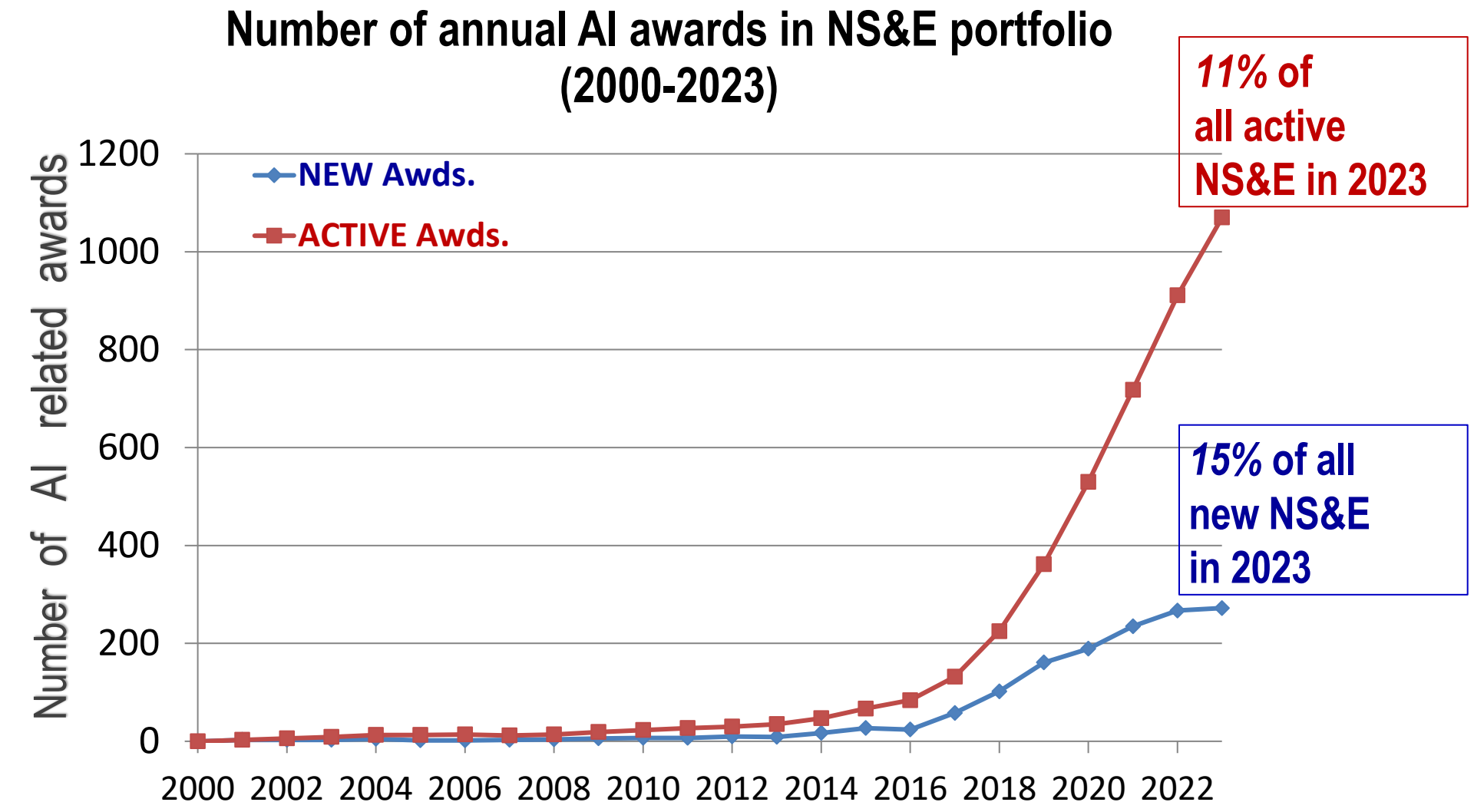


Nano - Info – AI :

Advanced computing;
AI systems;
Robotics; and
Wireless (5G,6G)

- ***Ex. Topics***: 3D nanosystems; Nanorobots; Soft robots; Nano-sensors; Natural language –AI; Semiconductors; Advanced materials; Neural networks; Neuromorphic engineering
- ***Ex. Outcomes***: AI designed nanoarchitectures; Superconductors; AI for Sustainable Nanomanufacturing
- ***Ex. NSF programs***: Energy efficient Components - Devices - Architectures (NSF-SRC); National AI Res. Institutes (18, $360M)

Confluence NS&E with artificial intelligence (AI)

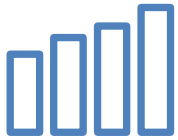


"CHIPS and Science" U.S. Congressional Act (8/2022)

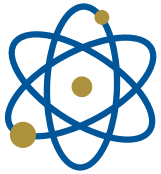
$280 B over ten years to NSF, DOE, DOC/NIST, industry, of which:

- **In 2023: $52.7B for domestic semiconductor industry:**
  $39B in semiconductor incentives new fabs,
  $13B in R&D and workforce development, ….

- **Provides support for key research and education areas (new + continuations)**



Authorizes a doubling of the NSF budget over 5 yrs.



Strengthens fundamental research (SEMI, BIO, others)

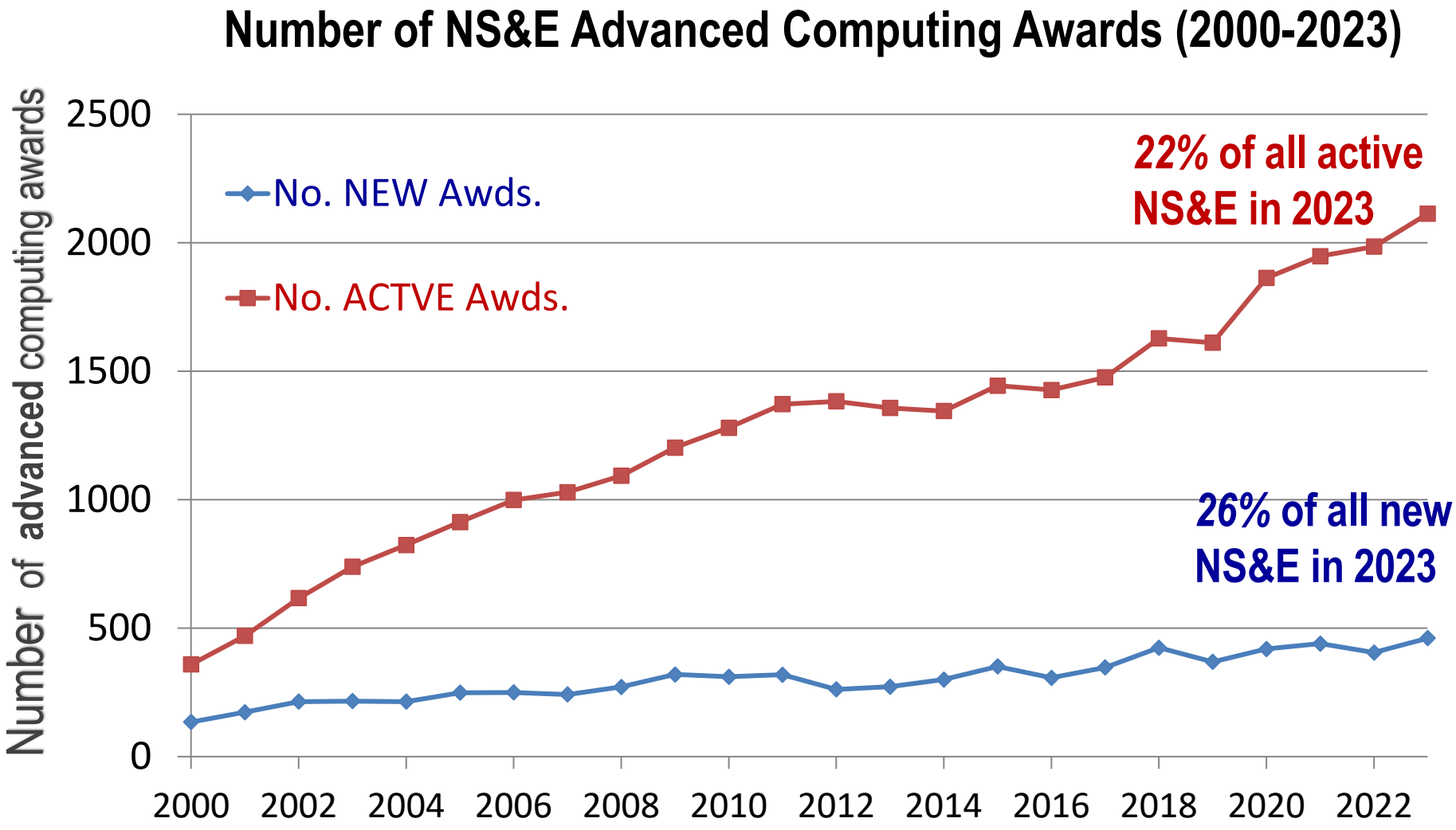
"Technology, Innovation & Partnerships (TIP)" - new

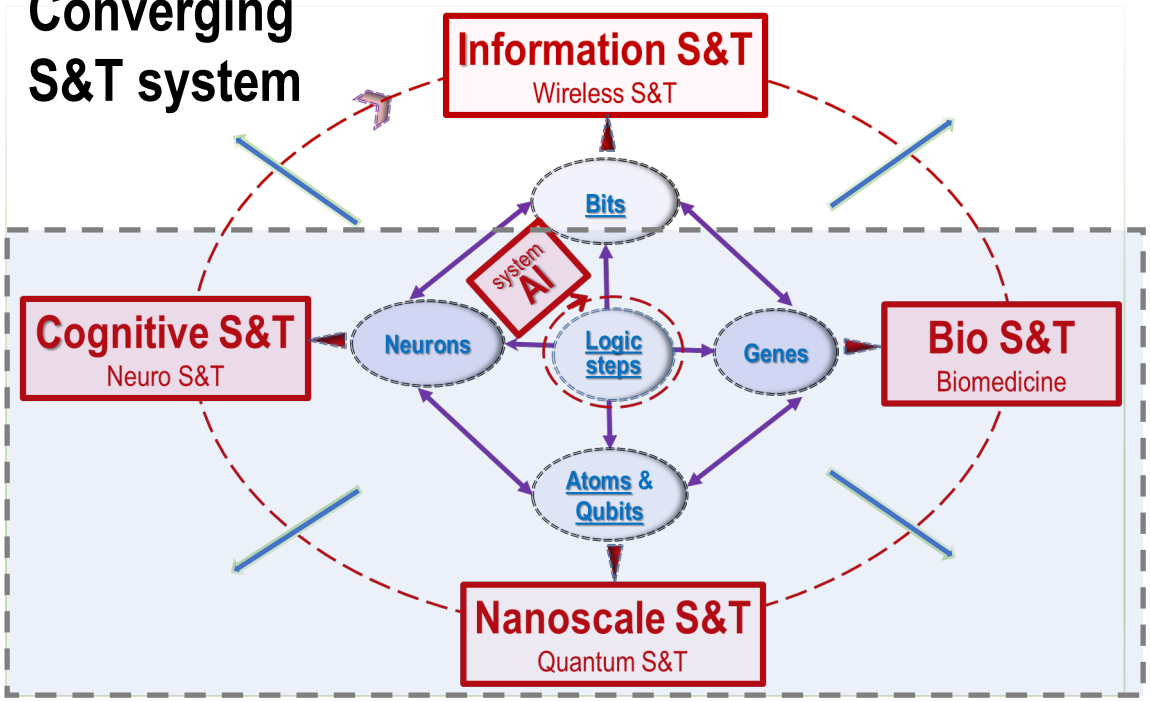
Invests in STEM Education

Advances diversity in STEM

Addresses research security

Confluence NS&E with advanced computing

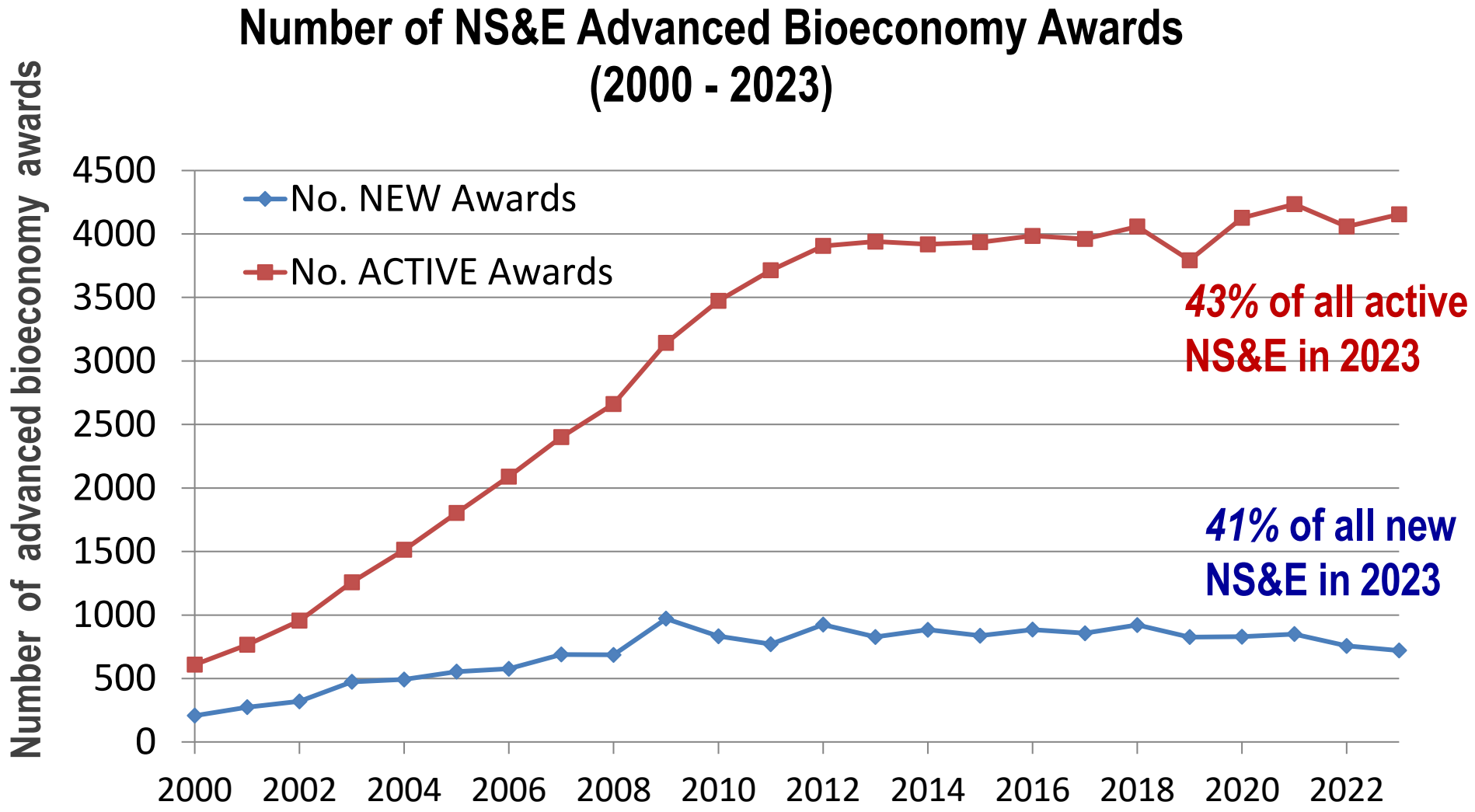




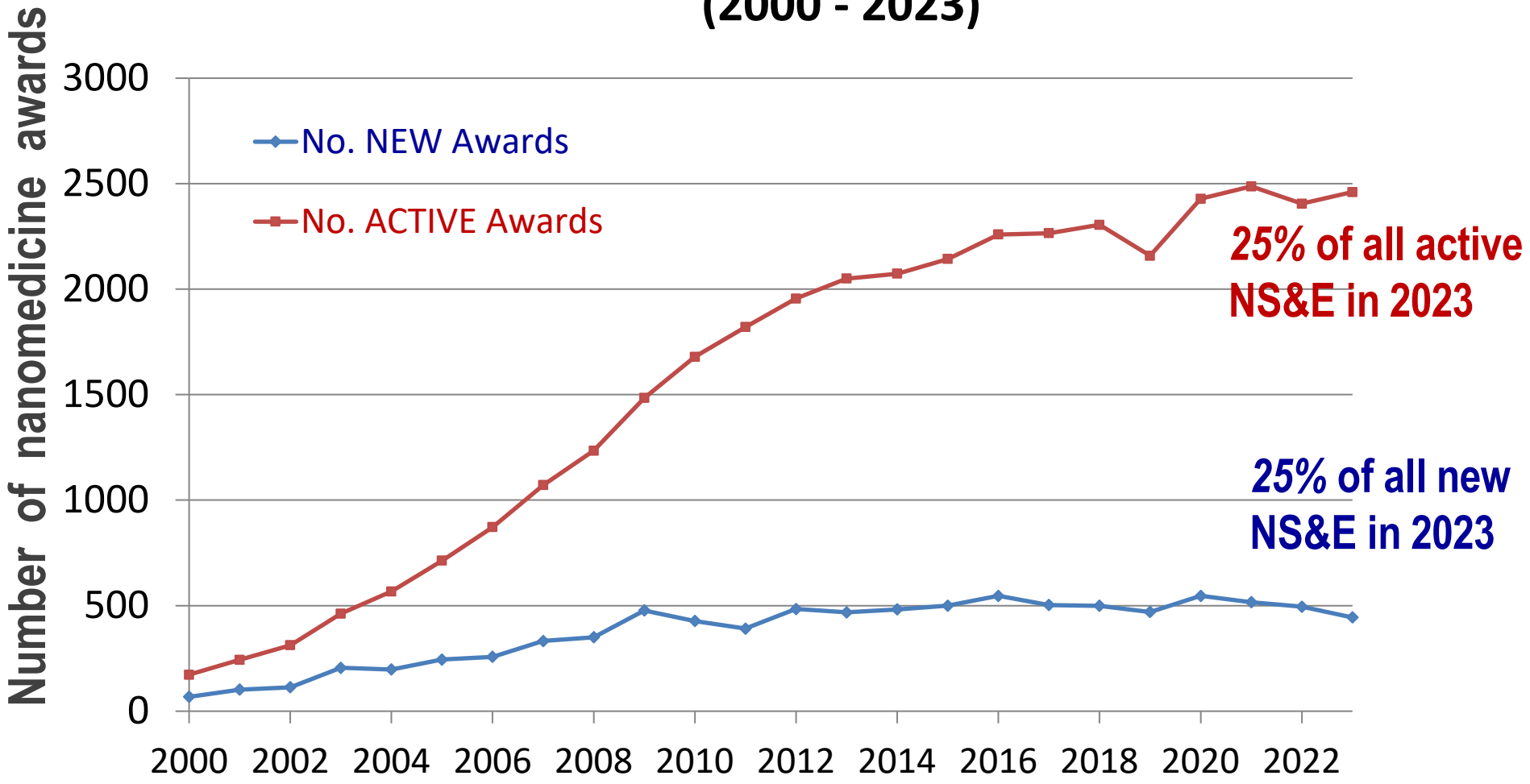
Nano-Bio-AI-Cogno convergence

- ***Ex. Topics***: Nanobiotechnology; Nano-neurotechnology; Synthetic biology (convergence Nano, Bio, Cogno and AI); Nanobiomedicine, Nano-neuro-brain, Nano-bioinformatics.
- ***Ex. Outcomes***: Evolution enzymes; Nanoscale understanding of brain architecture; Nanomedicine; COVID19 vaccines & al.
- ***Ex. NSF Programs***: Advanced biotechnology and bioeconomy; Molecular foundations for biotechnology; Designing synthetic cells; Nano-neuro technology; Nano-sensors in plants

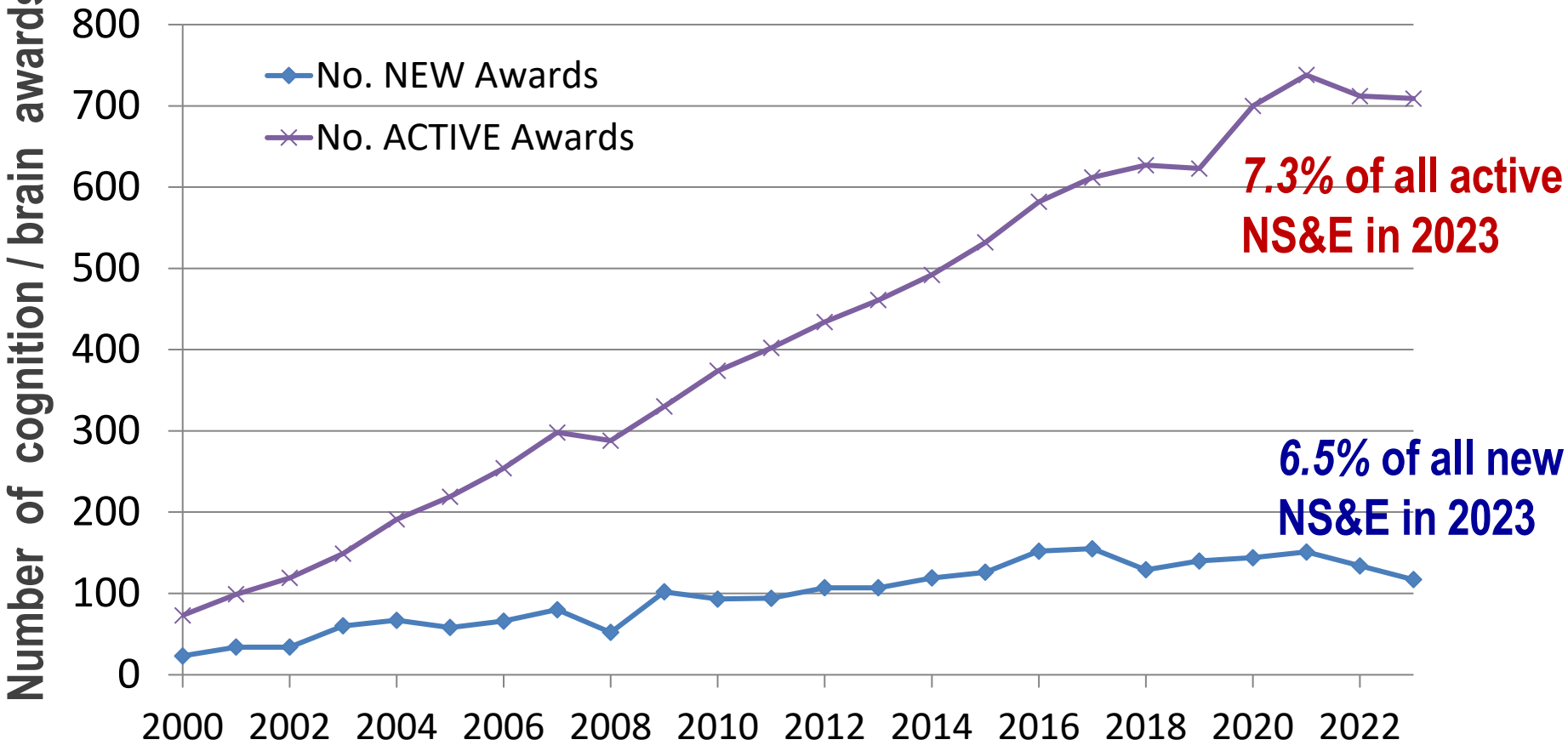
Confluence NS&E for Advanced Bioeconomy

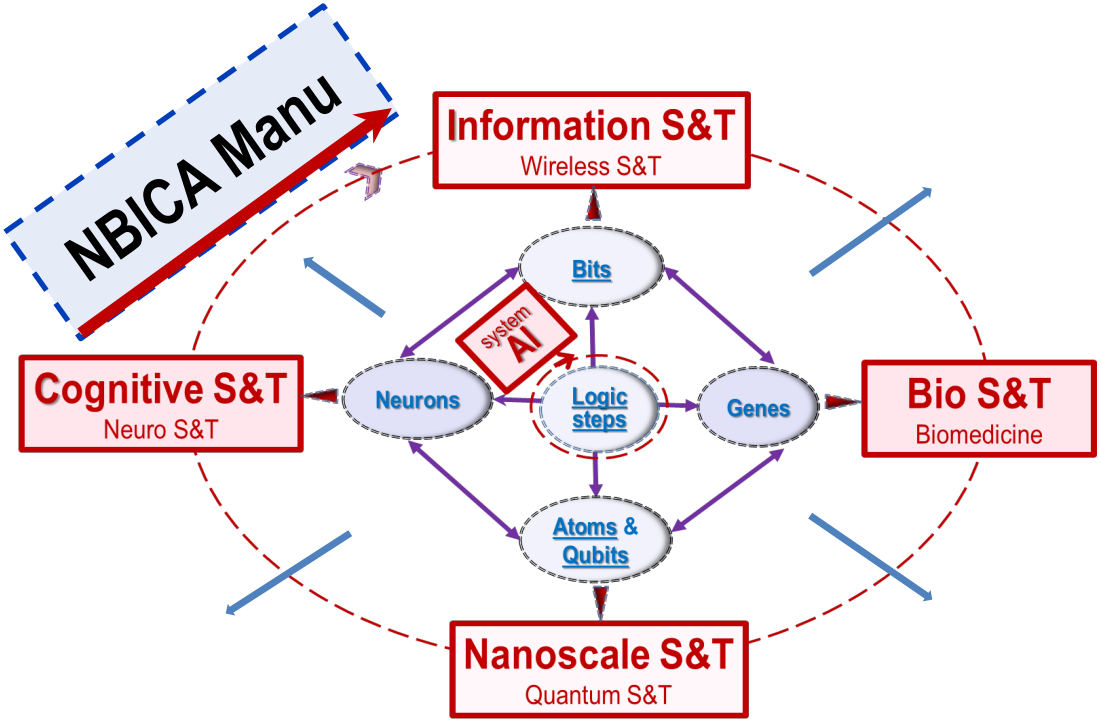


Number of NS&E Nanomedicine Awards (2000 - 2023)



Numbers of NS&E Cognition / Brain Awards (2000 - 2023)

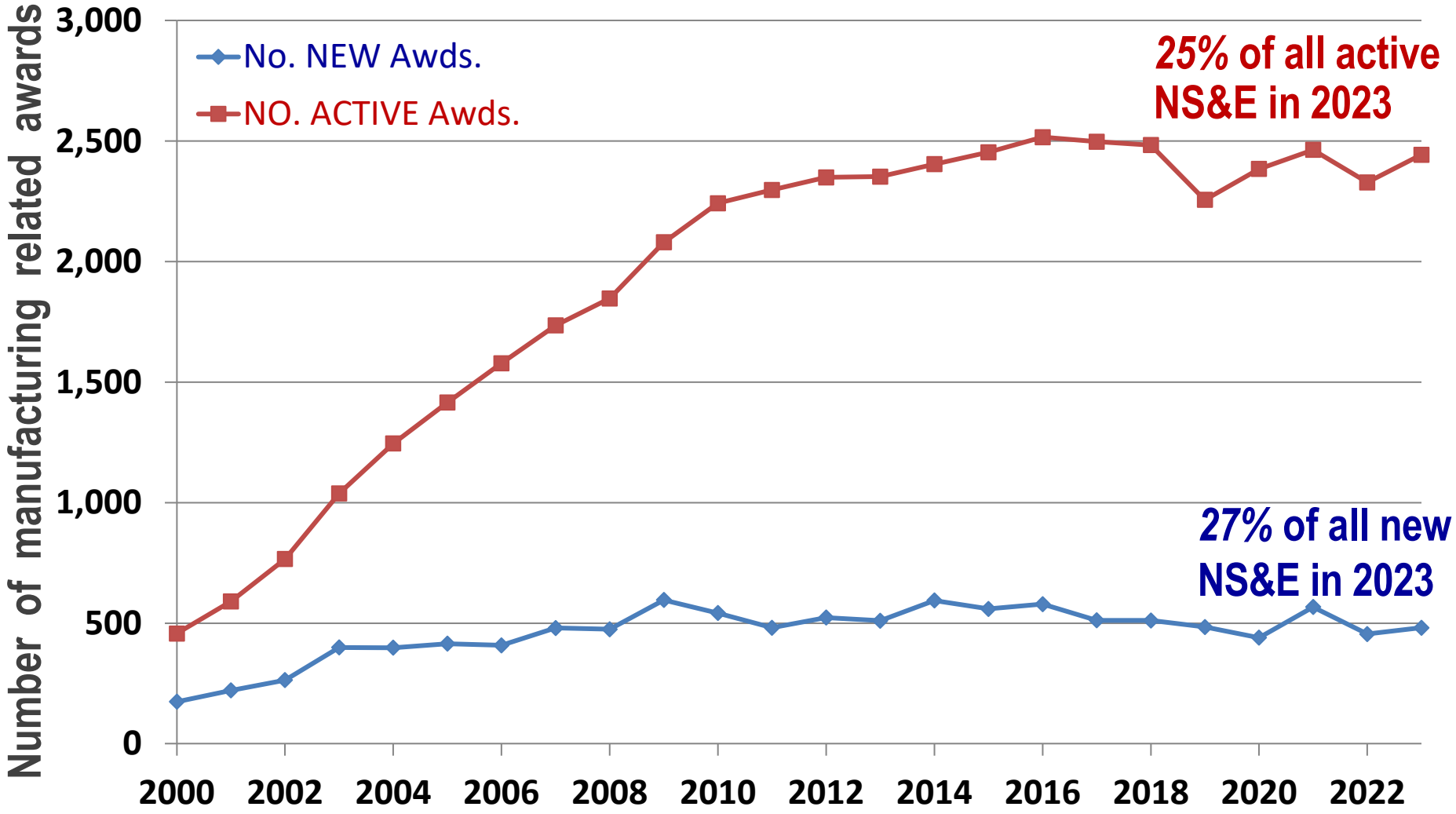


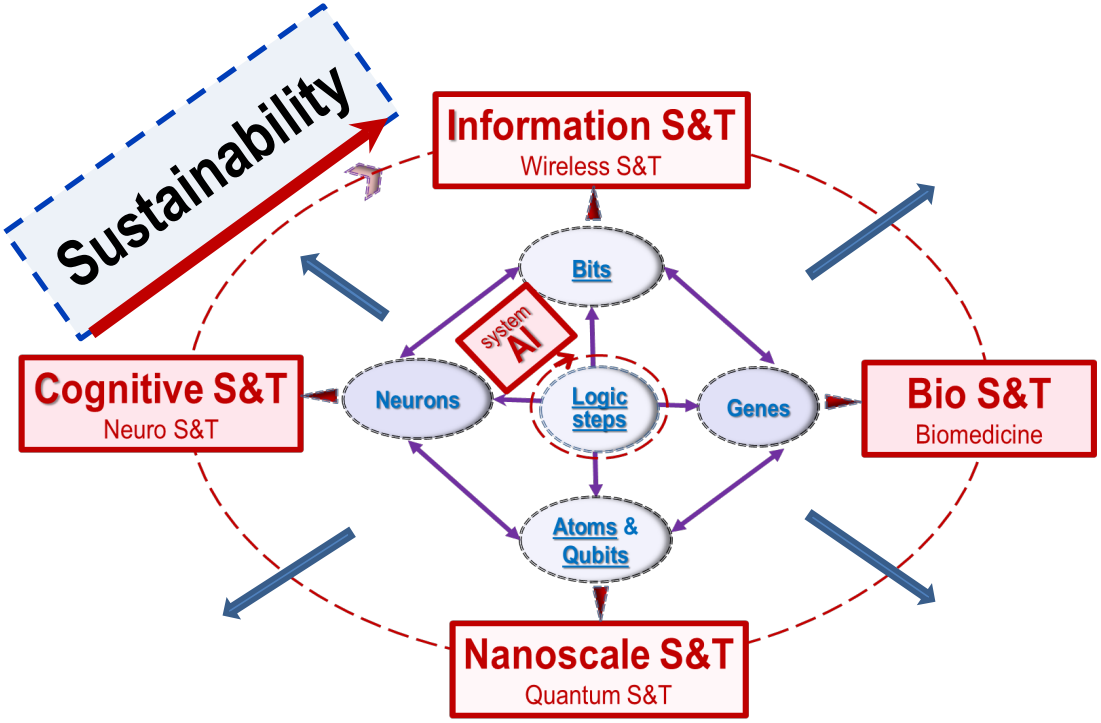


Convergence NBICA *manufacturing*

- ***Ex. Topics:*** Nanomanufacturing convergence with Bio, remote IT, AI, neuro, other fields; Cellular manufacturing
- ***Ex. outcomes:*** Hierarchical design; Additive manufacturing of 3D nanoarchitectures; Vaccine microneedles; 2-D nanomanufacturing; DNA and RNA manuf.; Self-healing mat.
- ***Ex. Programs:*** "Manufacturing for the Future"; "Hierarchical nanomanufacturing" node of Network for Comput. Nanotech.

Number of NS&E NBICA Manufacturing Awards (2020-2023)



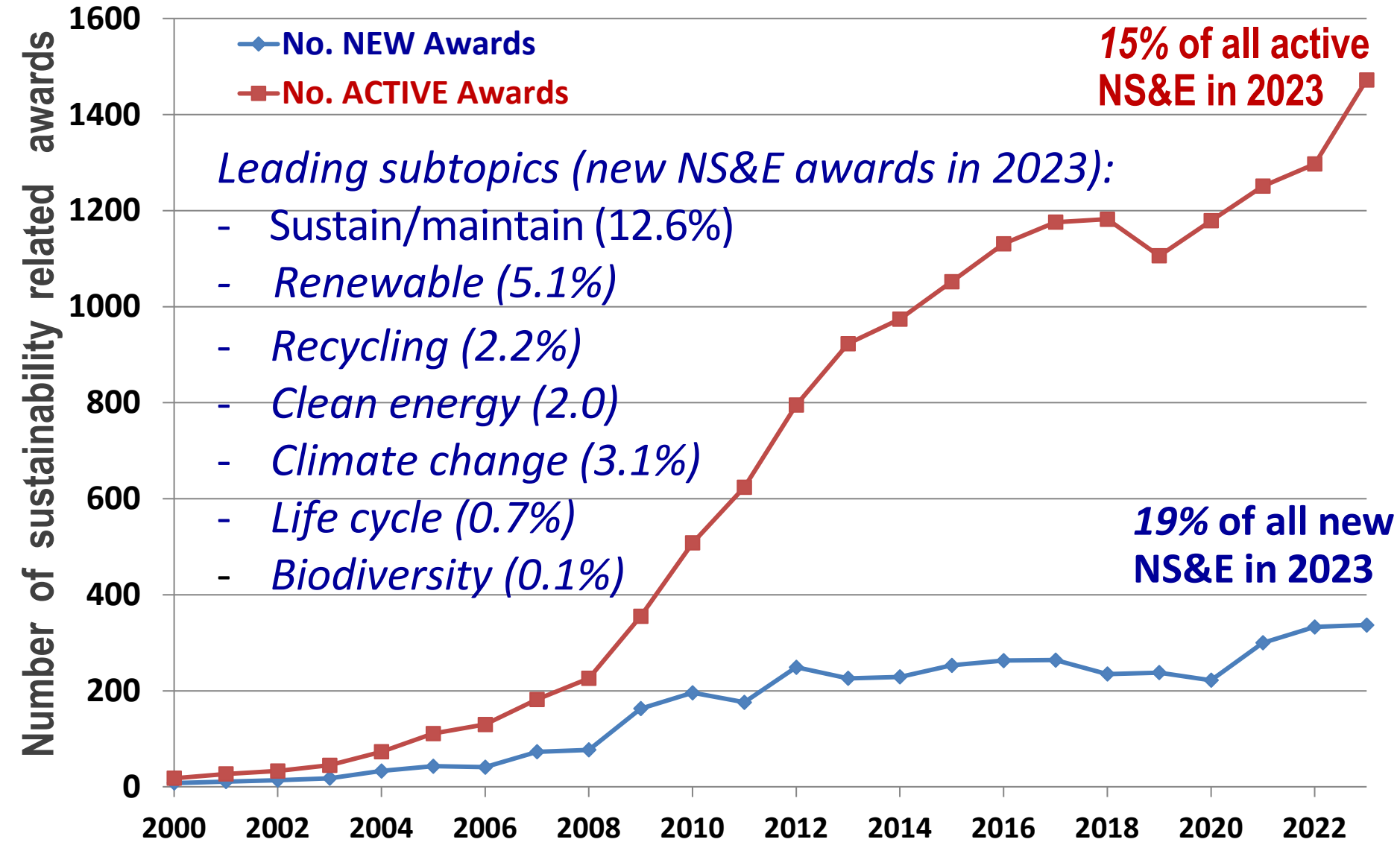


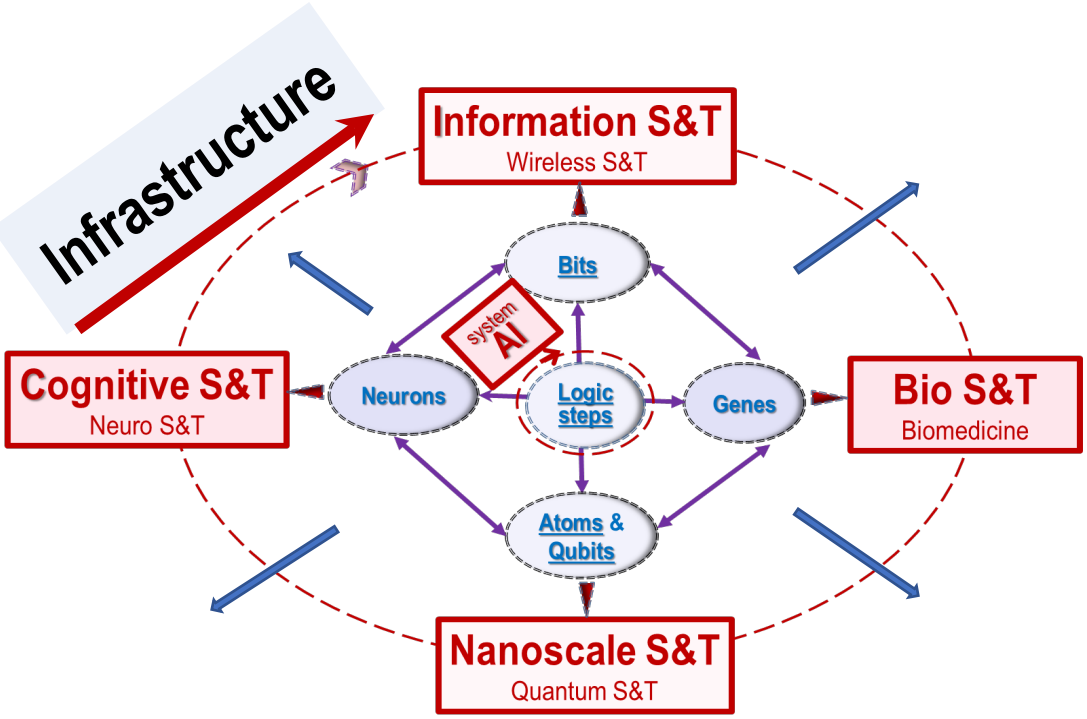
Using converging NBICA technologies ***for societal sustainability***

NNI's Nano4EARTH

- ***Ex. Topics:*** Transport phenomena and nano-EHS issues; PFAS Nanostructures for energy conversion and storage; Water filtration;
- ***Ex. Outcomes:*** Sustainable communities; Renewable resources; Recyclable materials; Supporting biodiversity; Circular economy, Life cycle performance and assessment; Nanostructured batteries
- ***Ex. Programs:*** Critical Aspects of Sustainability (CAS, NSF 21124): Micro- and Nanoplastics (MNP, DCL NSF 20-050); NEWT; Sustainable Regional Systems Research Networks.

Number of NS&E sustainable society awards (2020-2023)

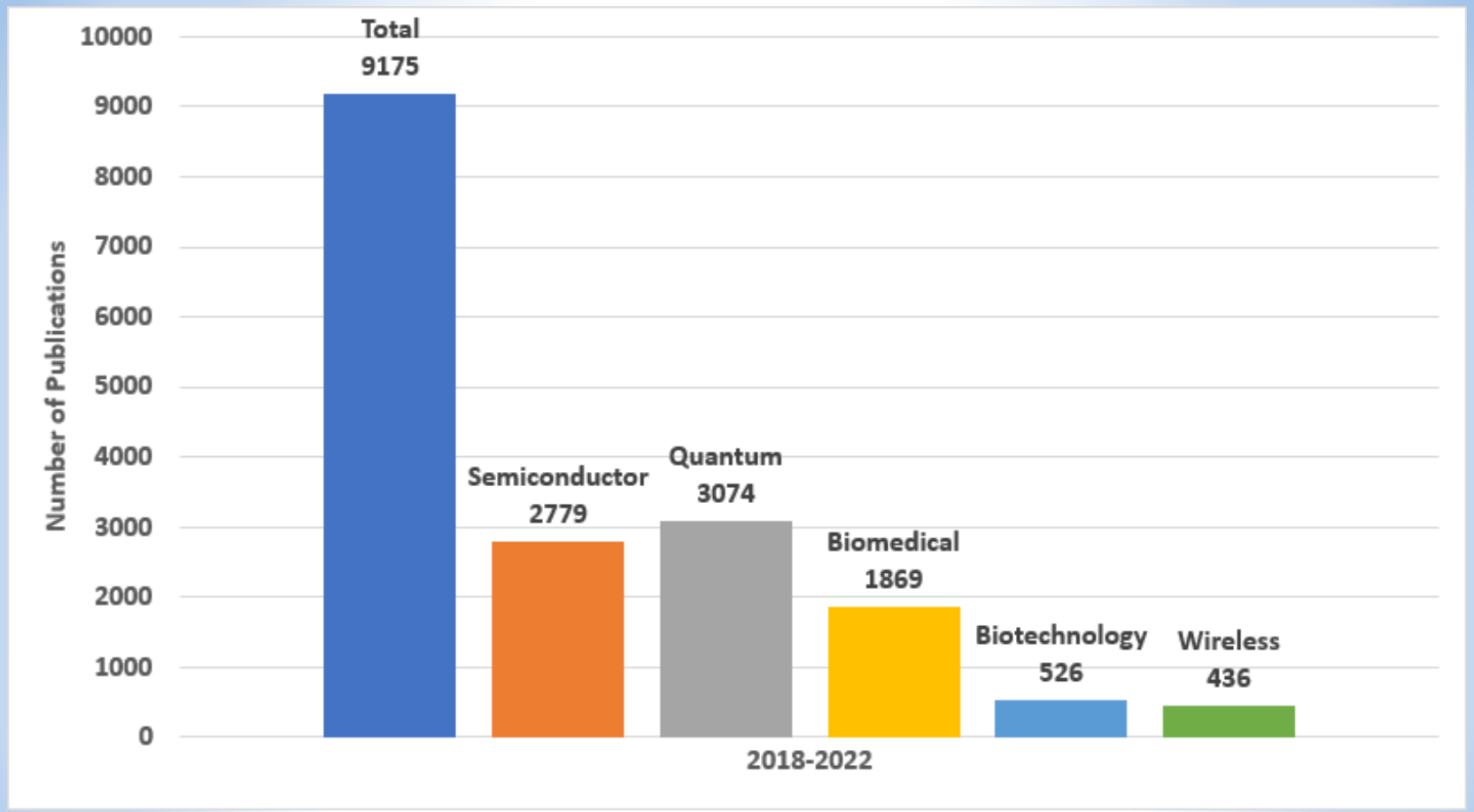




Using Nano-inspired solutions for ***convergence infrastructure***

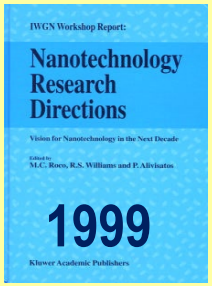
- ***Ex. Topics:*** Flexible infrastructure; Integrated centers for more efficient, responsible transition from fundaments to technology platforms & applications
- ***Ex. Outcomes:*** High Magnetic Field Beamline at Cornell U.; Micro-Nano Technology Education Center
- ***Ex. Programs:*** Mid-scale (I, II) infrastructure investments; User facilities (NNCI, nanoHUB, Cyber-ecosystem; distributed)

NNI: NNCI supports industries of tomorrow



9,175 journal articles published 2018-2022 that acknowledge the NNCI award numbers: (i) "Quantum" is mentioned by 3,074 (*34%*) ;
(ii) "Semiconductor" is found in 2,779 (*30%*) ;
(iii) "Biomedical" is included in 1,869 (*20%*) (keyword search)

MC Roco,
Dec 7 2023



nano3

2020-2030

Horizon: Nano solutions for economy of the future

- **Artificial intelligence (AI)** – use and design nanosystems
- **Quantum Information S&T** - a part of nanoscale S&T
- **Wireless Connectivity (5G, IoT)** – incl. use nanosystems
- **Advanced Manufacturing -** a focus on nanomanufacturing
- **The Bioeconomy -** a focus on nanobiotechnology, gene edit.

- **Computing systems** – semiconductors, neuromorphic, data
- **Sustainable society** – for materials/water/energy/food/env/climate
- **Flight and space exploration –** for fuel, light loads, bio-loop
- **Reshaping education** – unifying concepts, virtual learning
- **Independent aging** – includes nano-medicine and robotics
- **Increase human capacity** – physical, mental, group
- **Enhancing life** – co-evolution of S&T and human development

Related publications

1. ***"Nanotechnology: Convergence with Modern Biology and Medicine",*** (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, report 2002, book 2003)
5. ***CKTS**: "Convergence of knowledge, technology and society: Beyond NBIC"* (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)
6. ***"Long View of Nanotechnology Development: the NNI at 10 Years"****(JNR, 2011 13:2)*
7. ***"Overview: Affirmation of Nanotechnology between 2000 and 2030"*** (Ch.1 in Nanotech. Commercialization, Wiley, Ed. T. Mensah et al., 2018)
8. ***Proc. NSF NSE Grantees*** *Dec. 2020, available on www.nseresearch.org/2020/*
9. ***"Principles of convergence in nature and society and their application: from nanoscale, digits, and logic steps to global progress*** *(JNR, 2020 22:321)*
10. ***"NNI at 20 years: enabling new horizons"*** (JNR, 2023 25:197)

Enabling the Nanotechnology Revolution:

Celebrating the 20th Anniversary of the 21st Century Nanotechnology Research and Development Act

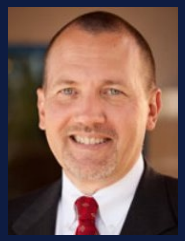
March 5, 9-5, National Academies

www.nano.gov/anniversarysymposium

Ilke Arslan
Argonne National Laboratory

Theresa Dankovich
Folia Materials

Ali Beskok
Southern Methodist University



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Chief Science Advisor to President Biden; OSTP Director

Neal Lane
Rice University; Former Science Advisor to President Clinton and OSTP Director

Ron Wyden
U.S. Senator from Oregon

Chad Mirkin
Northwestern University

Kate Rubins
NASA Astronaut (tentative)

Maxx Arguilla
University of California, Irvine

Jennifer Dionne
Stanford University

Thomas Epps, III
University of Delaware

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