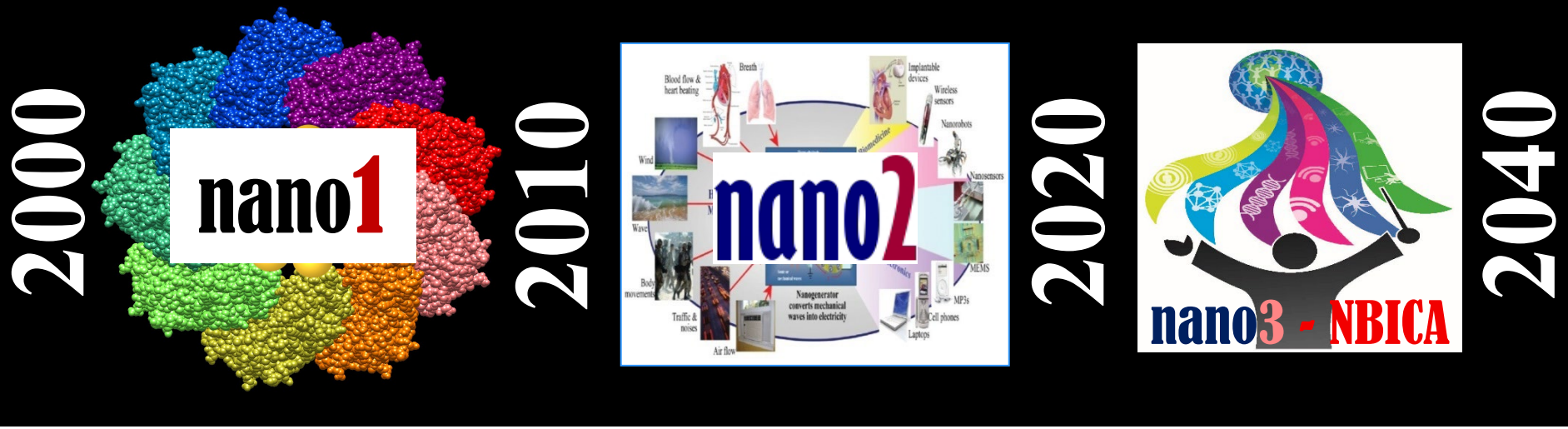


NANOTECHNOLOGY SOLUTIONS for Sustainable Society

Mike Roco
National Science Foundation and National Nanotechnology Initiative

11th Sustainable Nanotechnology Organization annual conference
November 11, 2022, 9-9:50 am, http://www.susnano.org/index.html

Outline

- **Context for sustainable society**
- **Converging S&T from nanoscale**
- **Role of nanotechnology as an inspiration and enabler for sustainability**
- **Several trends**

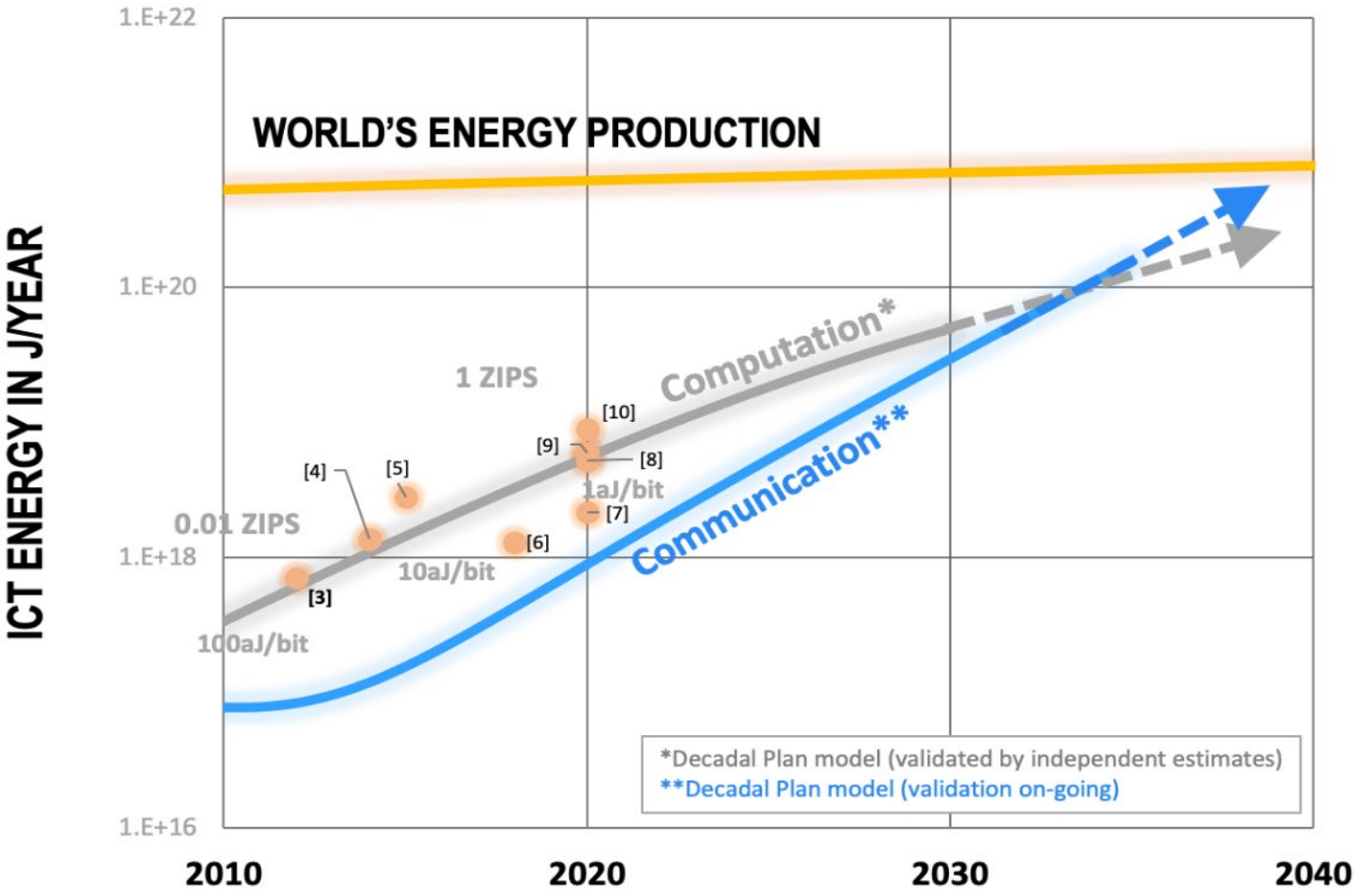
Sustainable society

Has several interconnected dimensions *(Nano2020 report, 2011, Ref 3)*

http://www.cnhlcms.org/uploads/hands_earth_many2_280x240.JPG

- **Environmental sustainability within the planetary boundaries -** clean, stable, biodiverse, renewable resources
- **Economic prosperity -** "more with less": knowledge, technology, materials, water, energy, land, food, climate
- **Resilience of habitat and its infrastructure**, emergency response, advance life cycle
- **Social factors -** population growth and needs, health, safety, governance, enduring democracy
- **Maintaining quality of life and expectations of progress** for current and future generations

Considering long-term trends (*example*):
Energy needs for computation and communication



Seismic shift in the **SRC 2030 Decadal Plan for Semiconductors**

https://www.src.org/about/decadal-plan/

(using mostly nanoscale devices)

There is an increased recognition of sustainability

- *International context* -

- **United Nations General Assembly resolutions:**
  - "The right to a clean, healthy and sustainable environment" **declared an essential human right** , Aug 2022
  - **End plastic pollution**: Towards an international legally binding instrument (Mar 2022)
  - **UN Climate Change Summit**, Egypt, Nov 2022

- **OECD** Series on the Safety of Manufactured Nanomaterials: "**Sustainability and Safe and Sustainable by Design"** (Sep 22)

- **EU**: **Sustainable European Economy** framework & activities

- **APEC and its member states activities** on plastic particles

Increased recognition of sustainability:
- *Hierarchical context at all levels in U.S.* -

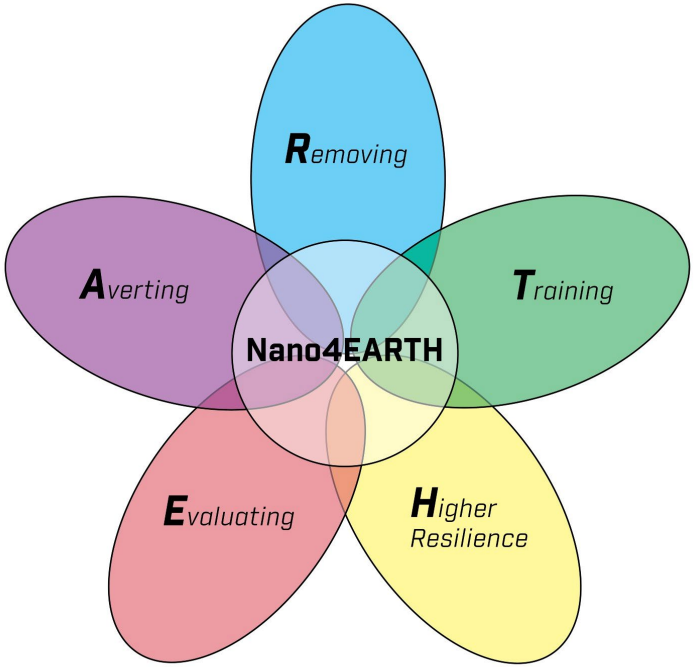
- **US Congressional legislations**
  supporting various sustainable development investments

- **WH/ OSTP**: **National Climate Task Force** , and
  Federal Ocean Climate Action Plan (Sep 2022)

- **NNI: Nano4EARTH** - National Nanotechnology Challenge
  Sustainability - a key motivation of NNI
  2001: workshop-GC; 2005: WGs on NEHI, 2011: NSI sustainable nanomanufacturing in 2011; Now: WG on water, sensors, databases

- **Other activities** of Federal Agencies, states, local governments, industry, professional societies, and NGOs

NNI: National Nanotechnology Challenge



Nano4EARTH: vision & partnerships

Evaluating, monitoring and detecting climate change status and trends;

Averting future greenhouse gas emissions

Removing existing greenhouse gasses;

Training and educating a highly skilled workforce to harness nanotechnology solutions; and

Higher resilience

Research areas: (1) decarbonize electricity, (2) electrify end uses and switch to other clean fuels, (3) cut energy waste, (4) reduce methane and other non-carbon dioxide emissions, (5) scale up carbon dioxide removal

nano.gov/nano4EARTH

Increased recognition of sustainability:

- *Research and education support* ***at NSF*** -

- **New NSF programs for sustainable society in 2022:**
  - Climate Change Coordinating Committee
  - NSF's Convergence Accelerator $30 M for *Blue Economy...*

- **New areas of research focus**: nano/micro single-use plastics, crypto currency computing needs, efficient computation...

- ***Indigenous people holistic knowledge and strategy*** on sustainability in land and Artic

- ***Sustainable Nanotechnology Organization*** stayed its course since its inception, co-sponsored by NSF

CHIPS and Science Act of 2022

www.chips.gov

$54.2 billion

For industry
in appropriations over 5 years
for the creating incentives
to produce semiconductors
(~ 30% investment cost)

$200 million

For Federal agencies,
in authorizations over 5 years,
of which $81 B for NSF
CHIPS for America Workforce
and Education Fund

Increase recognition of sustainability
- *in society,* ***beyond R&D*** -

Supreme Court shapes climate doctrine

The US Supreme Court in *West Virginia v. EPA*, found that the federal government's broad regulation of a leading source of carbon pollution violated the "major questions" doctrine, which says *Congress must speak clearly if it wants agencies to act on important political and economic issues.*

NASEM Report on

Managed Retreat in the U.S. Gulf Coast Region

Economist Impact Events

Sustainability Week (10/2022), World Ocean (10&11/2022), et al.

Nanotechnology has three-pathways to influence sustainable society

- **By direct applications of nanoscale processes, materials, devices and systems** - via control at the nanoscale and precise manufacturing

- **By mitigating pollution from other sources & technologies**, and reducing secondary nano-EHS&ELSI effects

- **By enabling other emerging technologies**, **and acting with them**: via advanced manufacturing, AI – systems, semiconductors, quantum systems, synthetic biology…

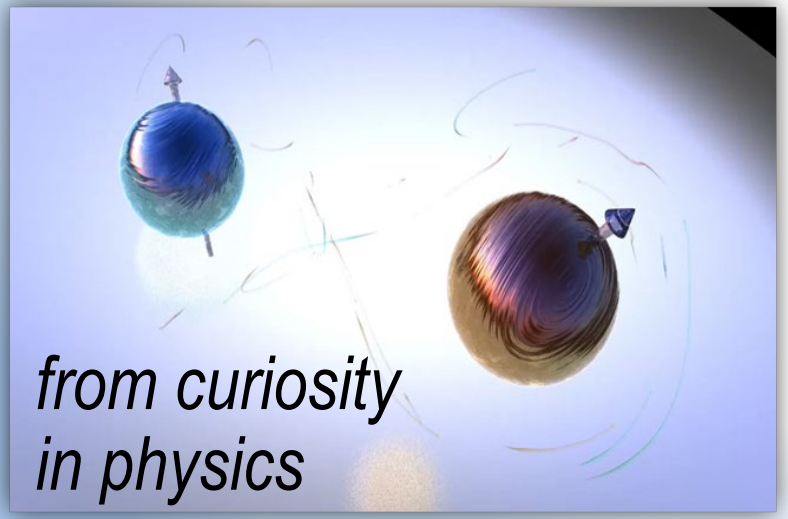
Several characteristics of

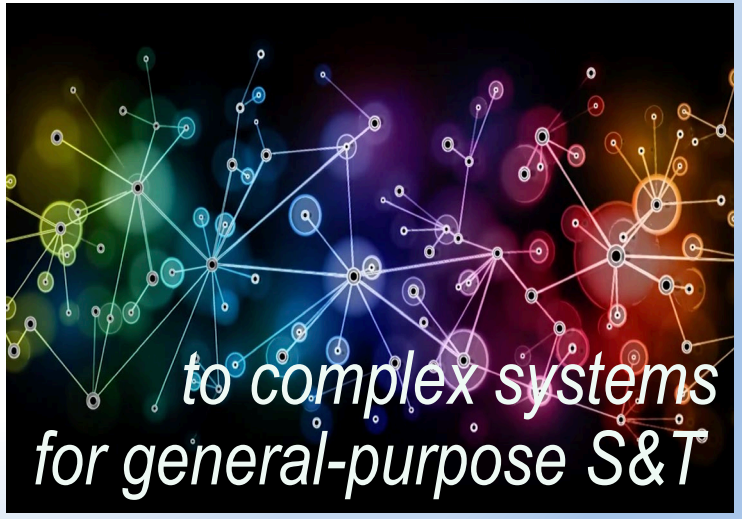
Nanotechnology progress

2000 – 2040

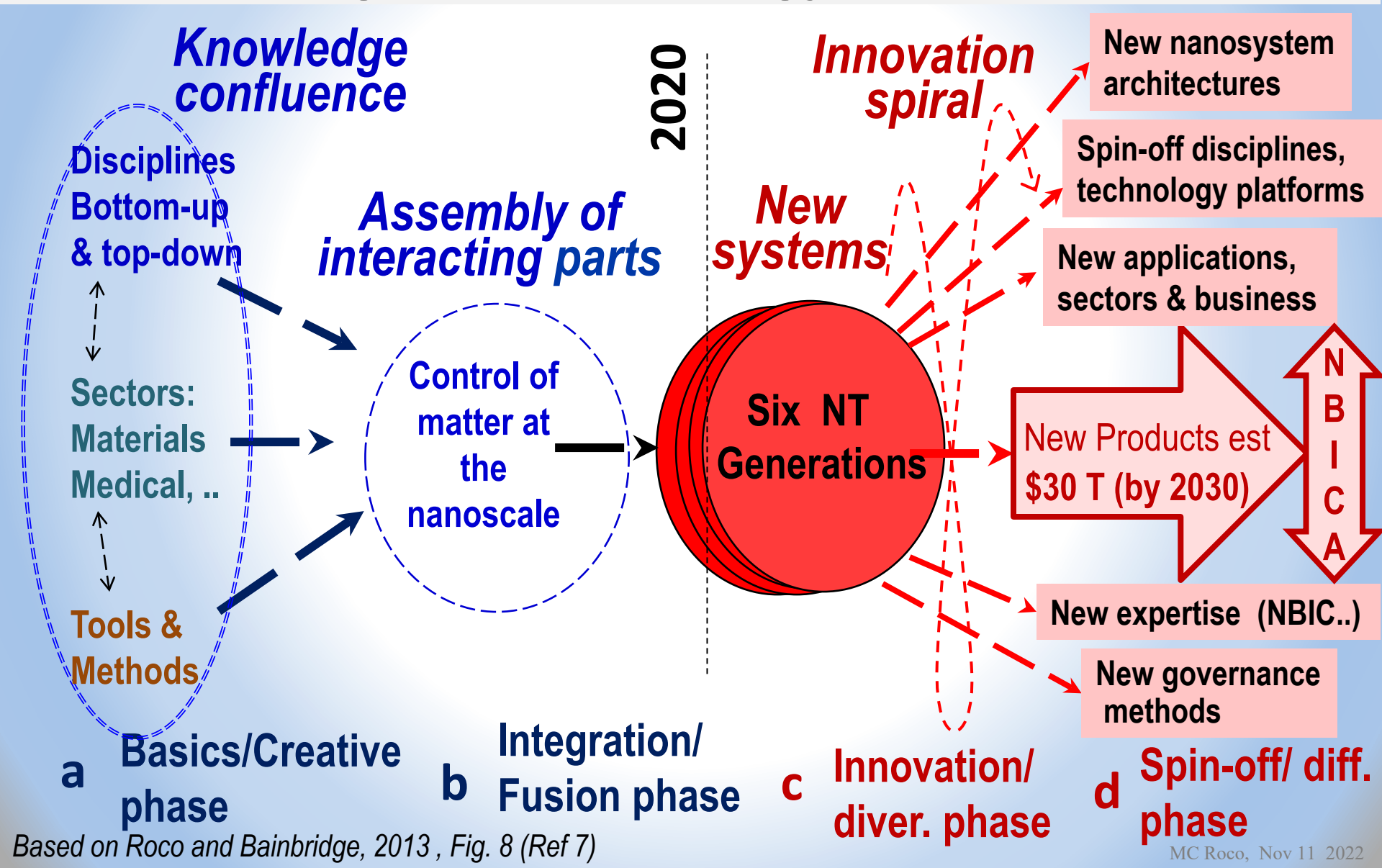
See: ***NNI Retrospective video at 20 years***

https://www.tvworldwide.net/NNI-Retrospective/VideoId/1903/UseHtml5/True





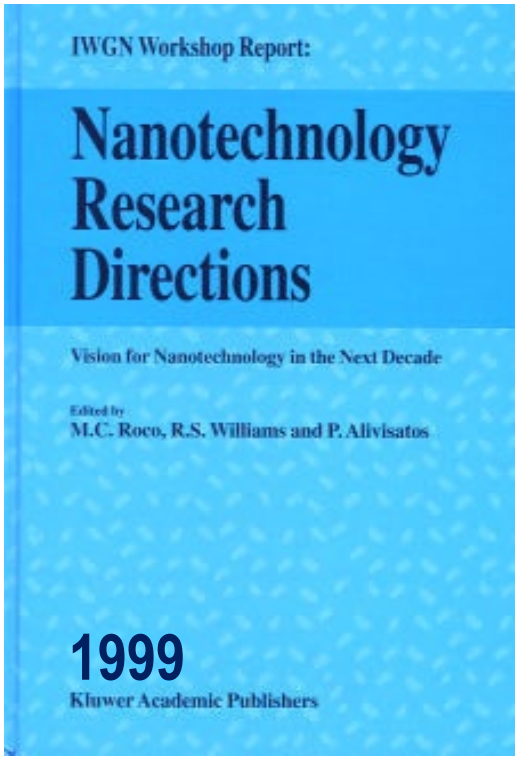
Convergence-Divergence cycle for establishing nanotechnology from 2000 to 2040



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

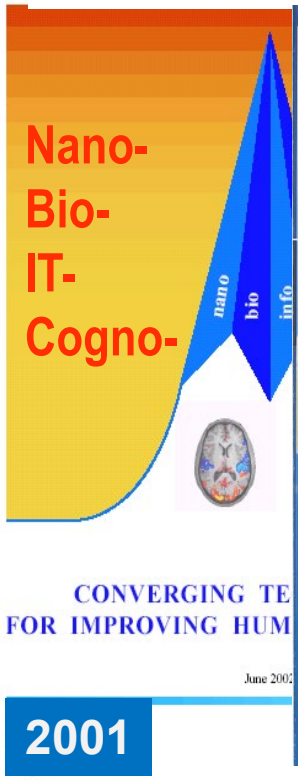
Nanotechnology: four vision-setting reports

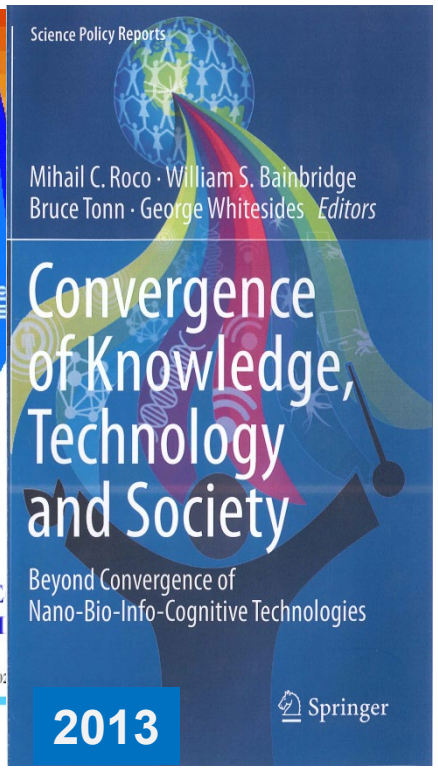
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1&2 (2011-2040)





40-year vision: changing focus and priorities in 4 stages

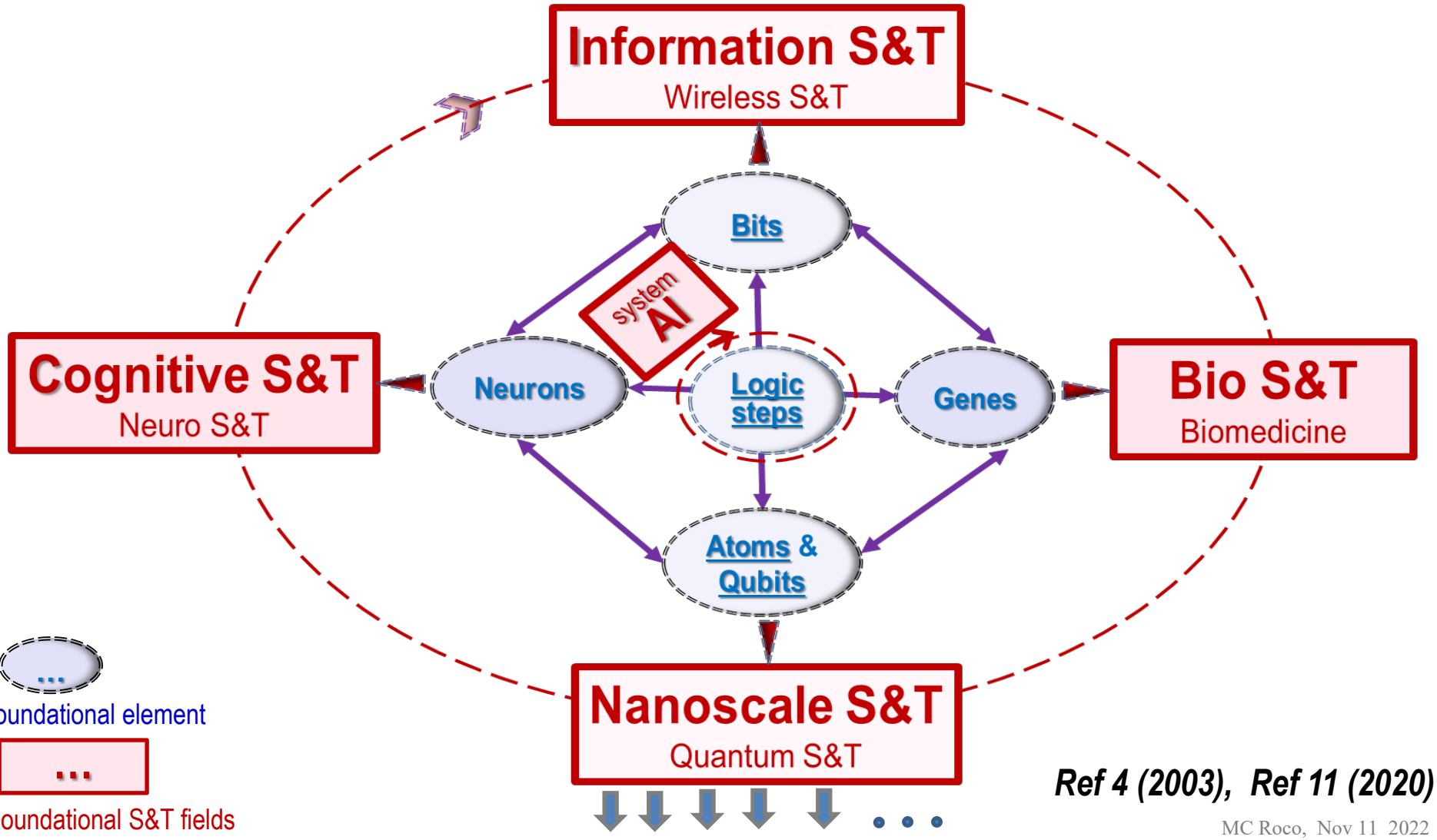
a. basics, b. system integration, c. divergence, d. diffusion

Input from >40 countries, Used in > ***80 countries****; Reports on scienceus.org/wtec/ (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*



Ref 4 (2003), Ref 11 (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 activities, 2005 NNI WG
- **Metamaterials** – 2004
- **Plasmonics** – 2004
- **Nanomedicine –** 2004 (NIH focused program)

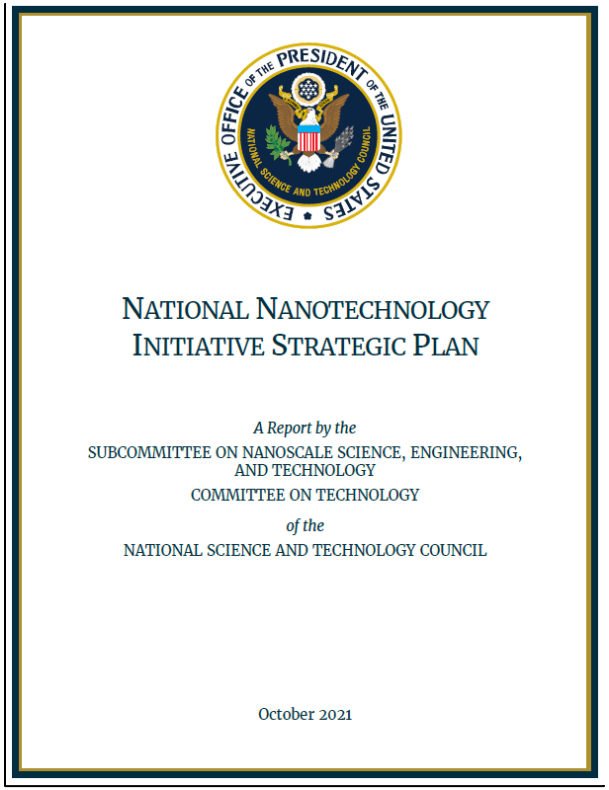
- **Synthetic biology** – 2004 (NSF increase of awards)
- **Nanoelectronics Research Initiative** 2005; expansion 2015;
- **Nano antennas and devices for wireless,** 2006
- **Modeling / simulation** - *Materials Genome Initiative 2011*
- **Nanophotonics** - *National Photonics Initiative 2012*

Nanotechnology spin-off areas

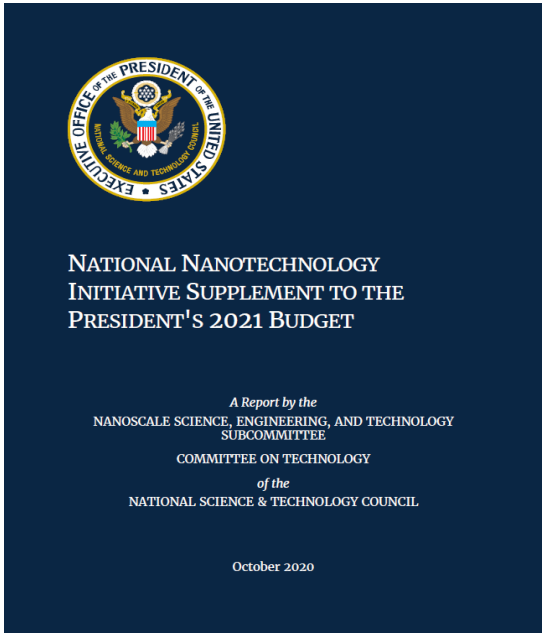
2000-2020 (top 20 topics) *(ii)*

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

National Nanotechnology Initiative in 2022



2021 NNI Strategic Plan



PCAST report on NNI

NAS/NRC report on NNI

Annual NNI Supplements to the President's Budget (each year since FY2001, in five administrations)

The actual NNI investment by 2022 **~ $38 billion**

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

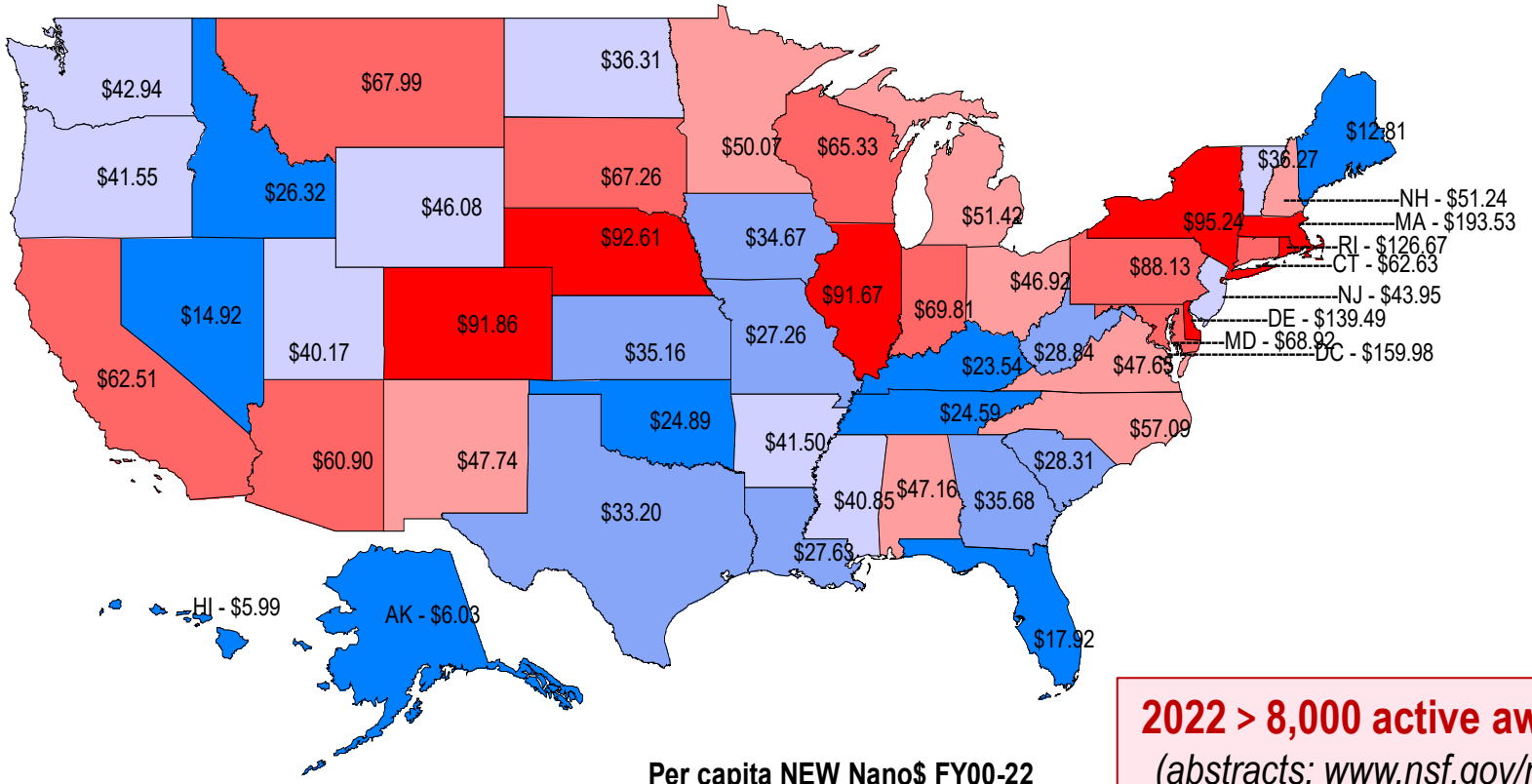
Networks, Comunities of research, Webinars, Videos, …

Signature Initiatives (2011~2022) ; National Nanotechnology Challenges

NSF's NS&E amount new awards per capita

FYs 2000 - 2022: U.S. average ~ $54 /capita

FYs 2012-2022 number of new NS&E awards / NSF total: **13-14%**

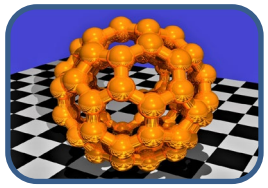
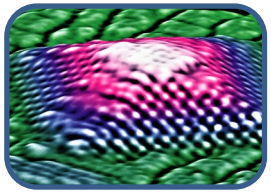
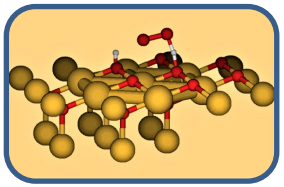
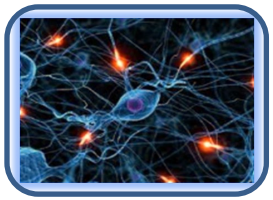
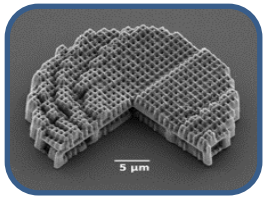
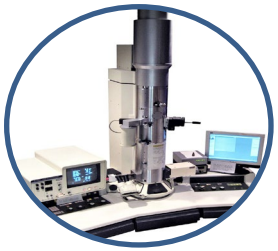
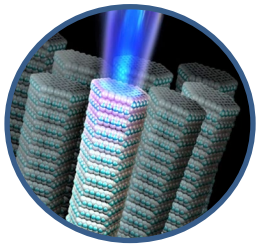


2022 > 8,000 active awards
(abstracts: www.nsf.gov/nano)

Total 2000-2022 ~ 36,000 NSF NS&E awards

#1 MA $193 / capita (2000-2022)

Significant investment impact (pervasive in economy):
Examples of discovery-innovation in nanotechnology

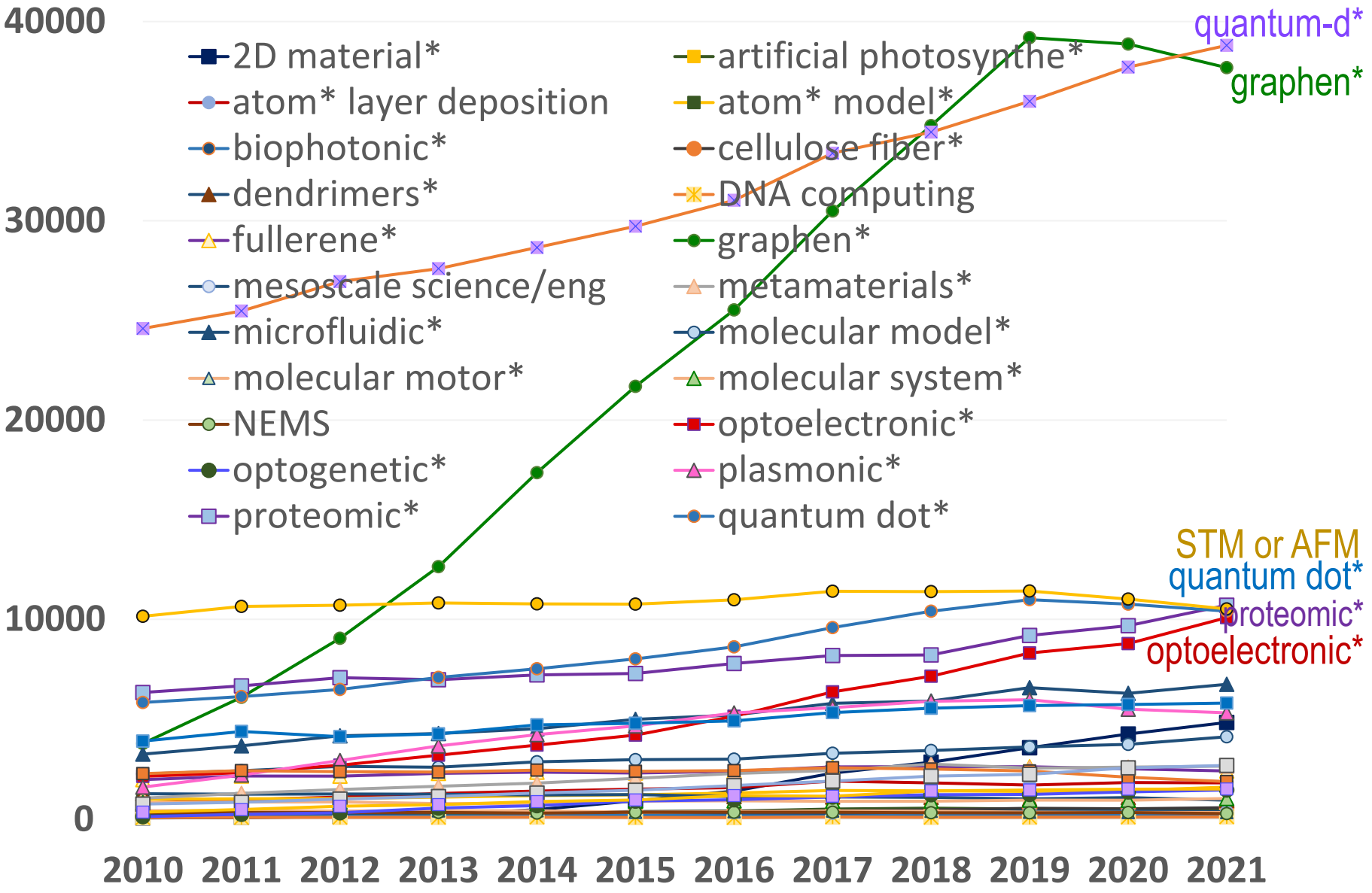
	1970-1980s: ATOMIC CLUSTERS, SUPTRAMOLECULES	1990s: CERAMIC, METAL & POLYMER NANO STRUCTURES; NANOPARTICLES	2000s: NNI – NSEC, NIRT, NRI, NSEE, NANO-BIO, QUANTUM, MANUFACTURING, ENVIRONMENT, ETHICS	2010s: NNI – INTEGRATION AT NANO, NSF-SRC SEMICONDUCTORS, NEUROMORPHICS	2020s: NNI – NANO FOUNDATION, NEW 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/2022

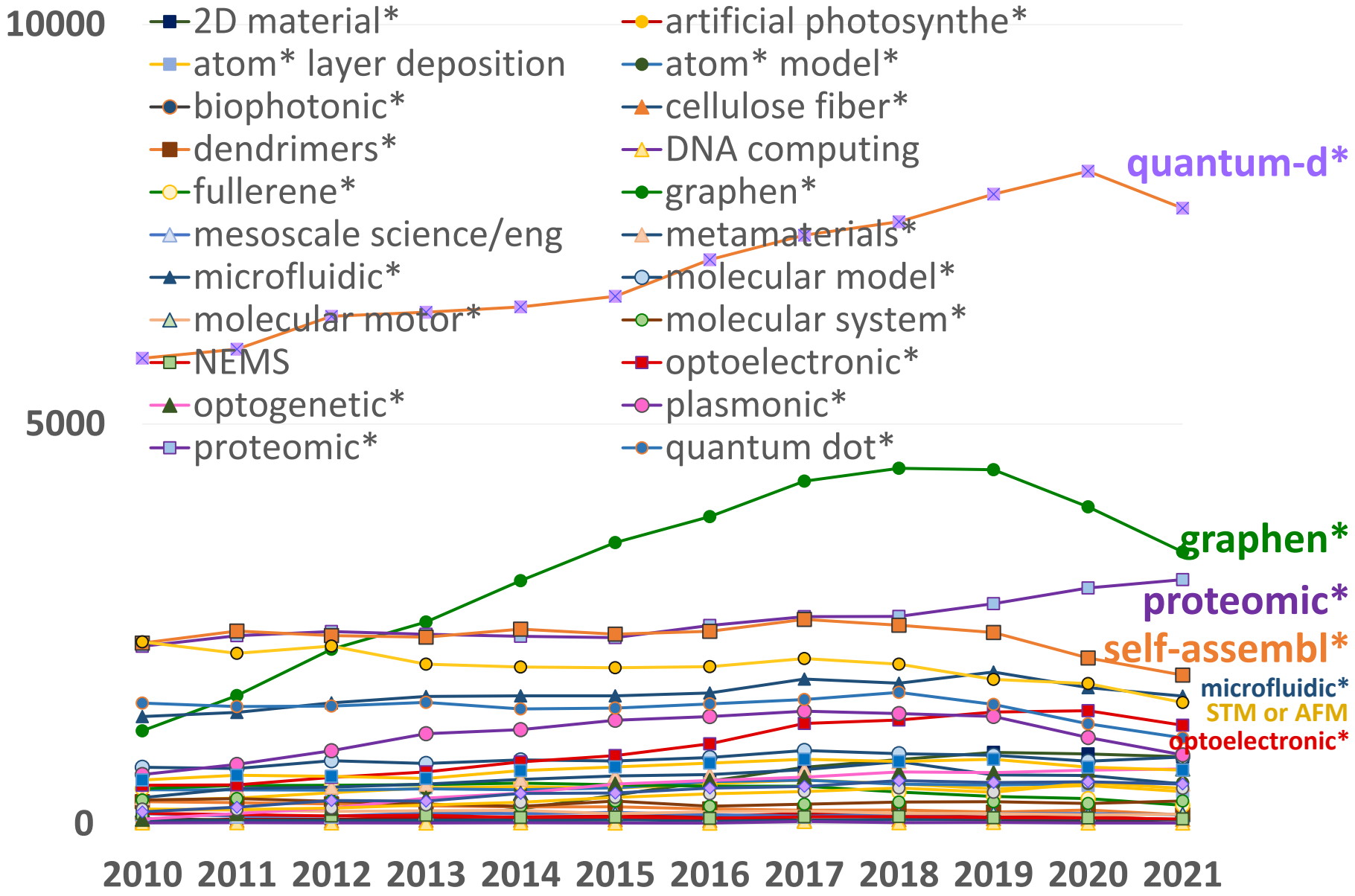
MC Roco

International dimension

Nanotechnology topics in WoS from authors WORLD (2010-2021)



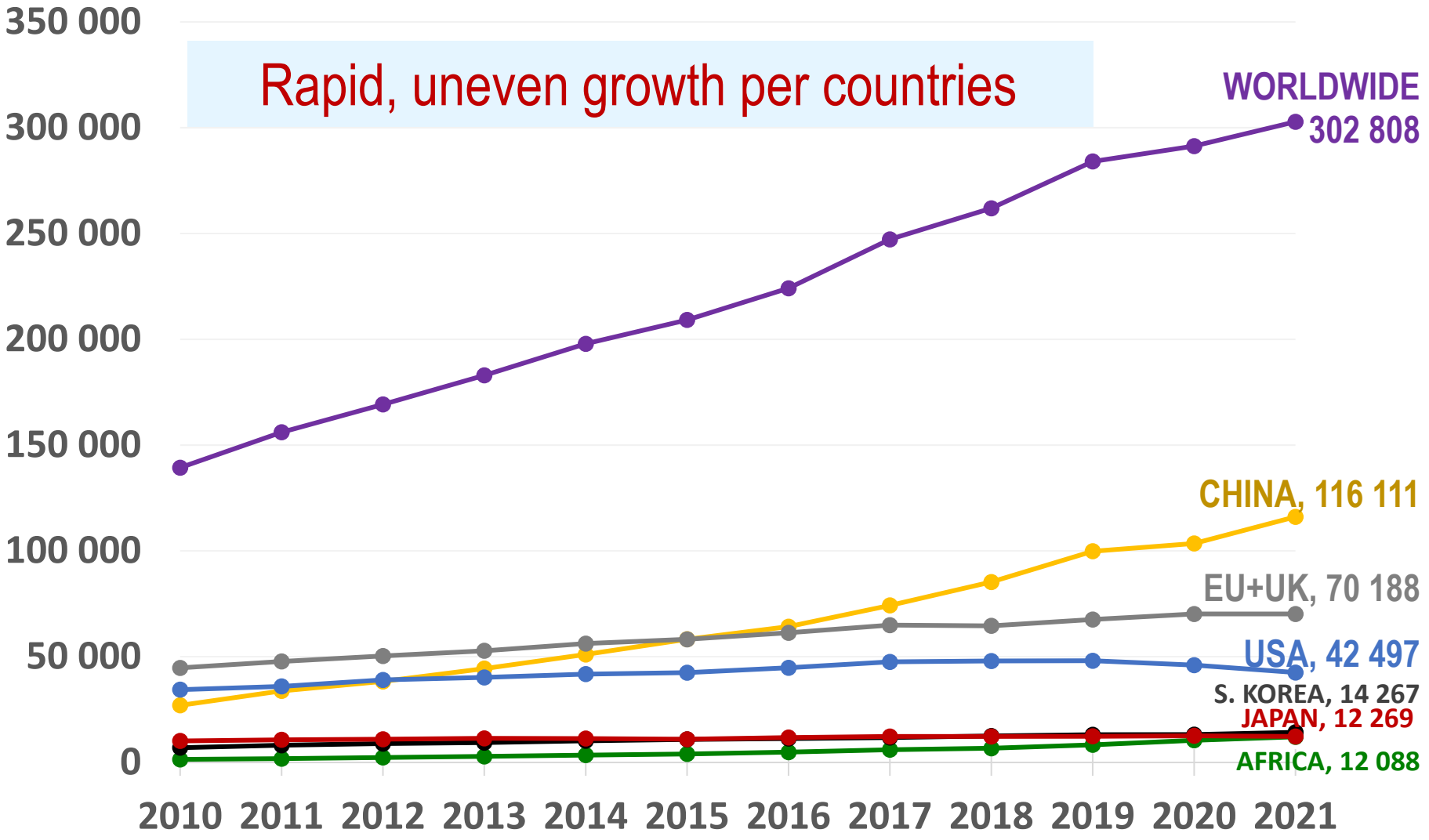
Nanotechnology topics in WoS from authors US (2010-2021)



MC Roco, Nov 11 2022

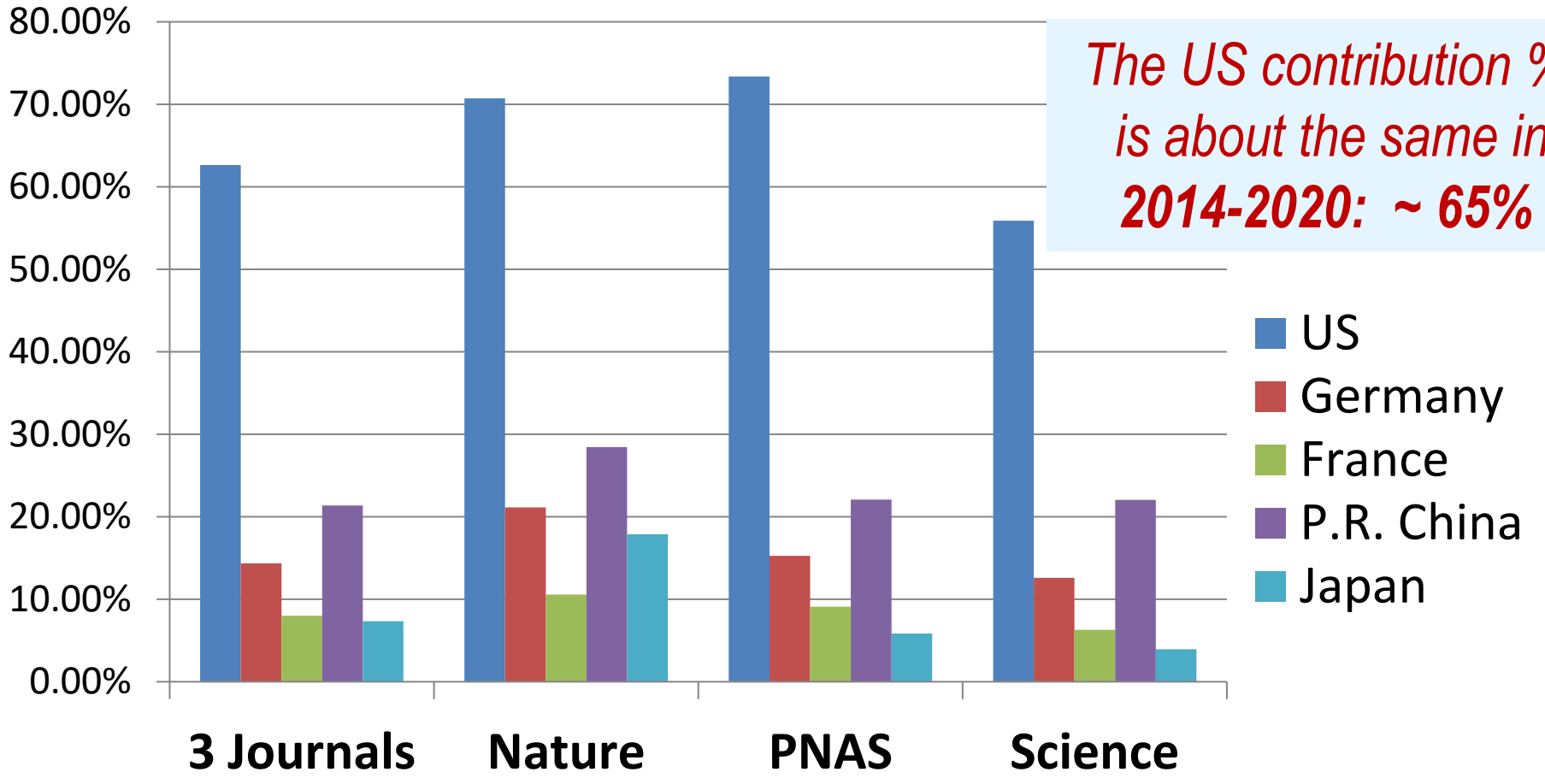
Nanotechnology papers in the WoS: 1990 - 2021

"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%.

Nanotechnology research has a direct impact on sustainable society

(a) by precise nano manufacturing with less materials, energy, water, waste; (b) by solutions not possible before

2022 Nobel Prize in chemistry
Carolyn Bertozzi, Morten Meldal and K. Barry Sharpless

Assembling of macromolecules based on shape, surface and molecular recognition ("click chemistry", "biorthogonal" chemistry). Creating novel molecules, including in the cells of living organisms; *where unwanted manufacturing by-products are minimized.*

2022 Nobel Prize in physics
John F. Clauser, Alain Aspect and Anton Zeilinger

Pioneering experiments i**n quantum information science on entangled quantum states in photons**. Creating a foundation for quantum information systems; *for smart and economic communication*.

Remediation of PFAS, not possible before
(Northwestern University, 2022)

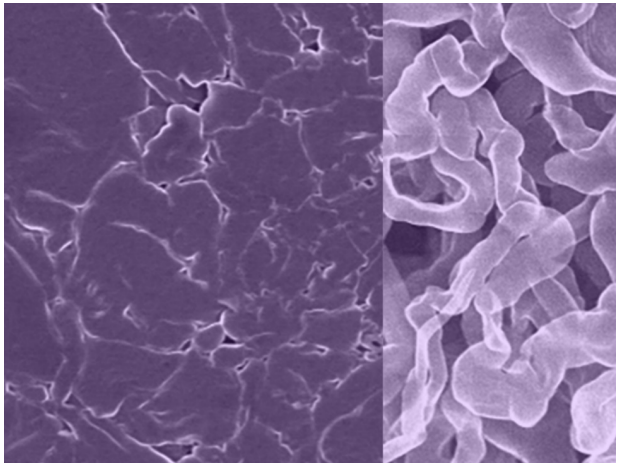
Per- and polyfluoroalkyl substances (PFAS) are anthropogenic substances containing multiple C–F bonds.

Using nanocharaterization tools at low temperatures where the specific bonds of PFAS compounds were broken leaving behind only benign end products

Ref: “Low-temperature mineralization of perfluoro carboxylic acids”, Brittany Trang Science, 18 Aug 2022. Support from NSF, NIH and State of Illinois, incl. from Soft and Hybrid Nanotechnology Experimental (SHyNE) Resource

Nanostructured sodium anodes for stable battery technology

In sodium-based batteries, anodes can develop filaments that could cause electrical shorts and raise the risks of a fire or explosion



- New anode material made by rolling a thin sheet of sodium metal onto an antimony telluride powder and folding the sheet repeatedly, resulting in **a uniform distribution of sodium atoms that resist formation of dendrites and corrosion**. It recharges as quickly as a lithium-ion battery.

Ref: D. Mitlin et al., UT Austin, Jan 2018; Advanced Materials, https://doi.org/10.1002/adma.202106005; https://beta.nsf.gov/news/scientists-develop-stable-sodium-battery-technology

Nanotechnology provides a foundation for other emerging S&T

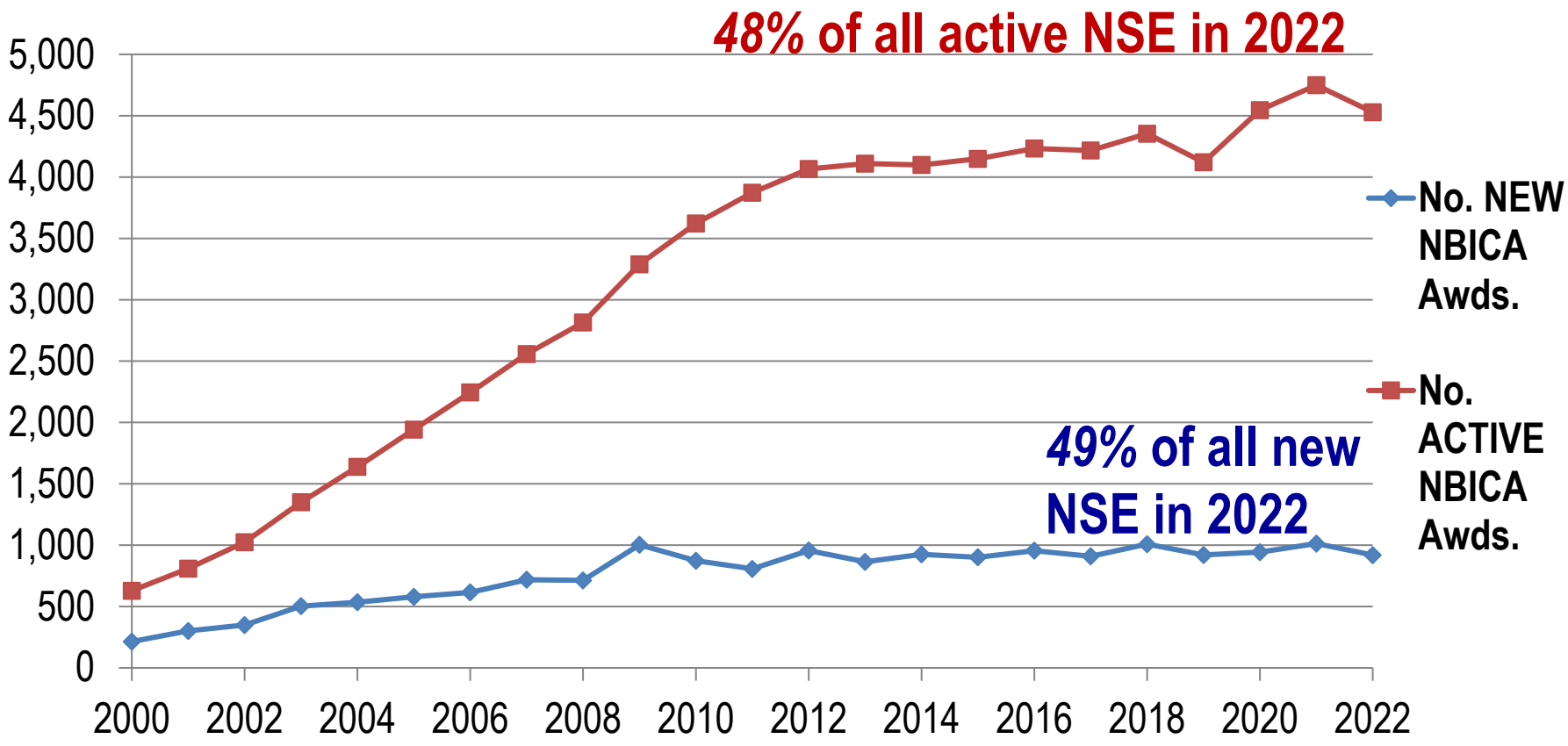
that at its turn provides opportunities for sustainability

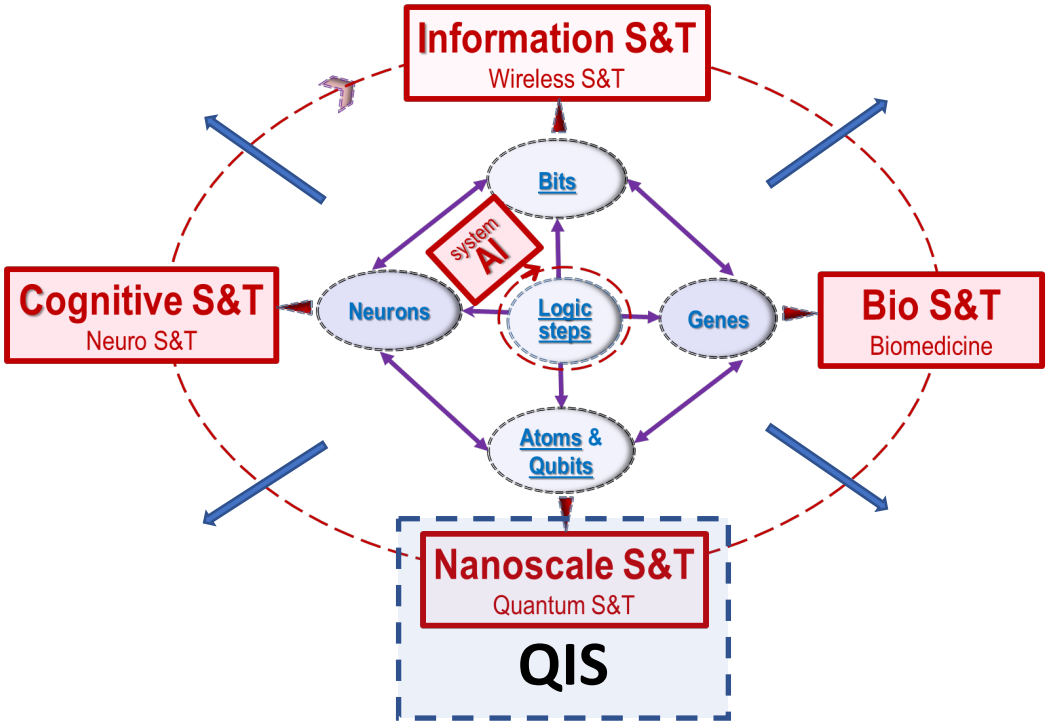
About ½ NSF's NNI awards are part of converging technologies

Convergence of foundational S&T fields

Number of NBICA awards at NSF in FYs 2000-2022

(searched by keywords)





Nanotechnology supporting **quantum information systems**

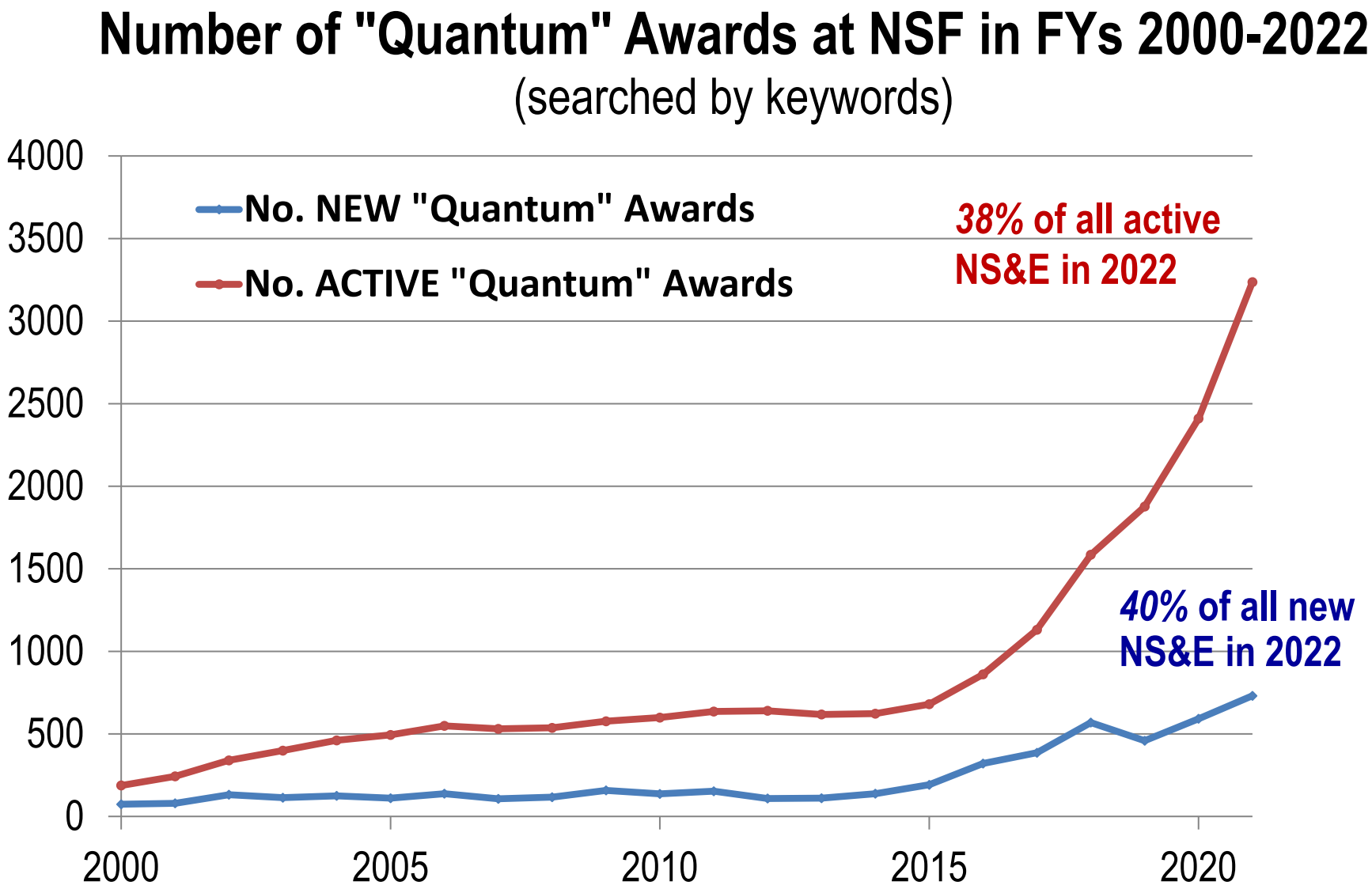
*Quantum National Initiative (**QIS**) is an outgrowth of NNI*

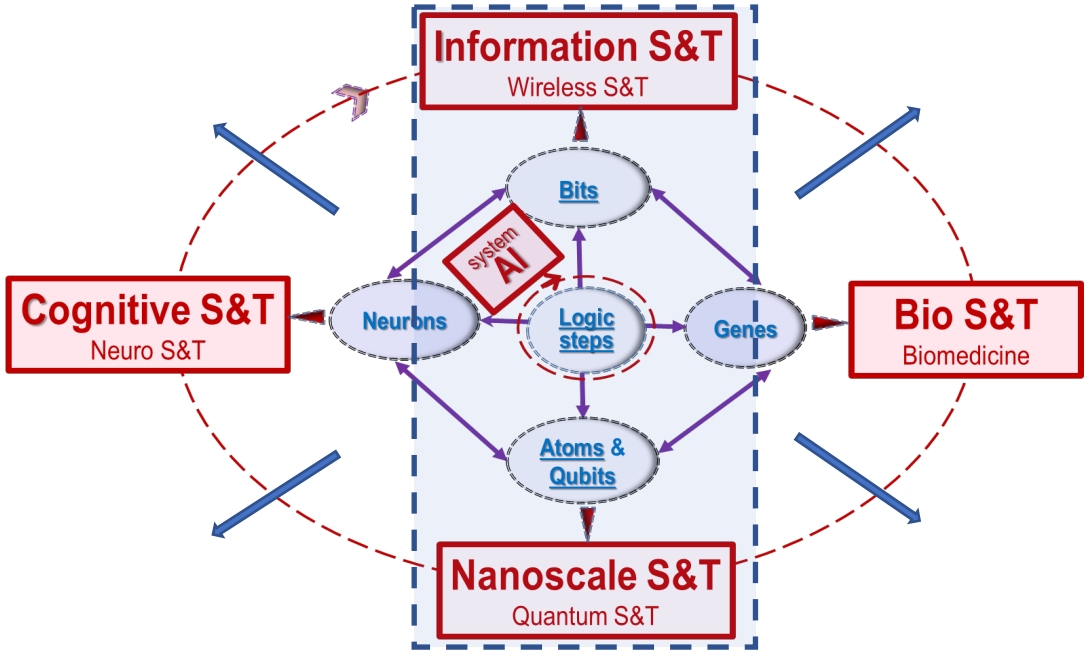
- ***Ex. Topics***: Quantum materials, Quantum sensors, Quantum communication, Quantum computing, Quantum biology
- ***Ex. Outcomes***: First quantum device in 2010; Quantum internet; IBM and Google quantum computer systems
- ***Ex. NSF programs***: in core programs; *Network of Quantum Centers; Convergence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

Illustration of quantum effects relevant to sustainability

- Use quantum biology in energy conversion, health, plant biology
- Use quantum sensors in environment
- Efficient quantum communication and computing
- Functional quantum devices in electronic, photonic, and mechanical systems

Confluence NS&E with QIS





Nano - Info - AI

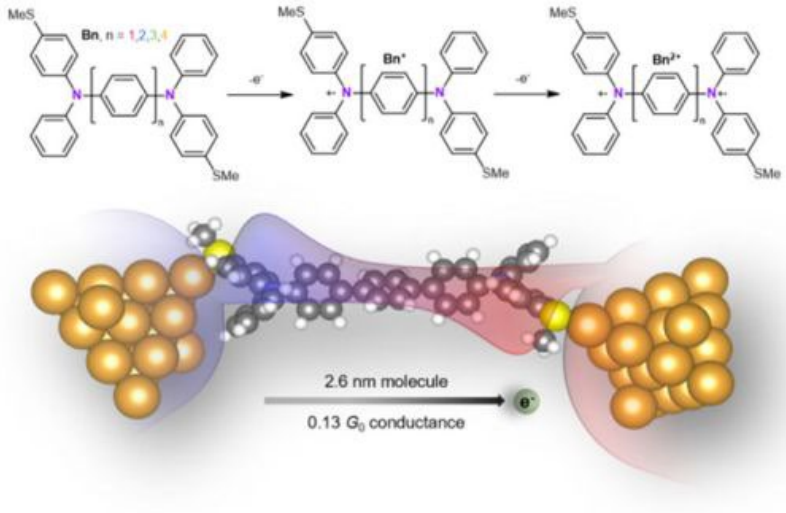
for advanced sensors, computing, AI systems, robotics & communication

- ***Ex. Topics***: 3D nanosystems; Advanced semiconductors; Neural networks; Neuromorphic engineering; Nanorobots; Soft robots; Nano-sensors; Natural language –AI, Wireless S&T (5G)
- ***Ex. Outcomes***: AI design nanoarchitectures; Quantum sensorial systems; Superconductors; AI for nanomanufacturing
- ***Ex. NSF programs***: Energy efficient Components - Devices - Architectures (NSF-SRC); National AI Res. Institutes (18, $360M)

Longest highly conductive molecular nanowire

(L. Venkataraman et al., Columbia U., July 2022)

- Organic molecules that behave like metals at the single-molecule level, in contrast to what had been done in the past where they were primarily weakly conducting.



- Discovering the longer molecules with higher conductance until the length of the wire exceeded 2.5 nanometers.

(https://www.nature.com/articles/s41557-022-00978-1)

CHIPS and Science Act of 2022

for NSF

- ***Authorizes*** **for next five years $81 B for NSF:**
  - **+$36 B for the agency**
  - **of that, +$20 B for TIP**

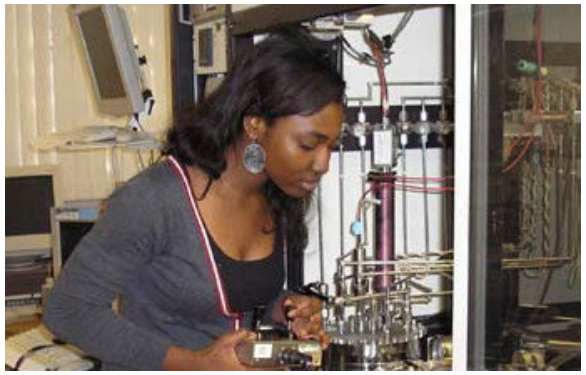
  of which $11.89 B in FY 2023
- ***Authorizes*** **a new NSF's Directorate for Technology, Innovation and Partnerships**

Advanced semiconductors

- example NSF research programs in 2022 -

- "**Future of Semiconductors**" (FuSe) program solicitation (NSF 22-589)
- "**Research Coordination Networks for Semiconductors** (RCN-SC)" (NSF DCL 22-116)
- "**Supplements for Access to Semiconductor Fabrication** (ASF)" (NSF DCL 22-113)
- "**Partnership for Prototyping of CMOS+X Systems**" (NSF DCL 22-076)
- **Semiconductors (S) topic SBIR-STTR Program**

NSF – student training in semiconductors in 2022

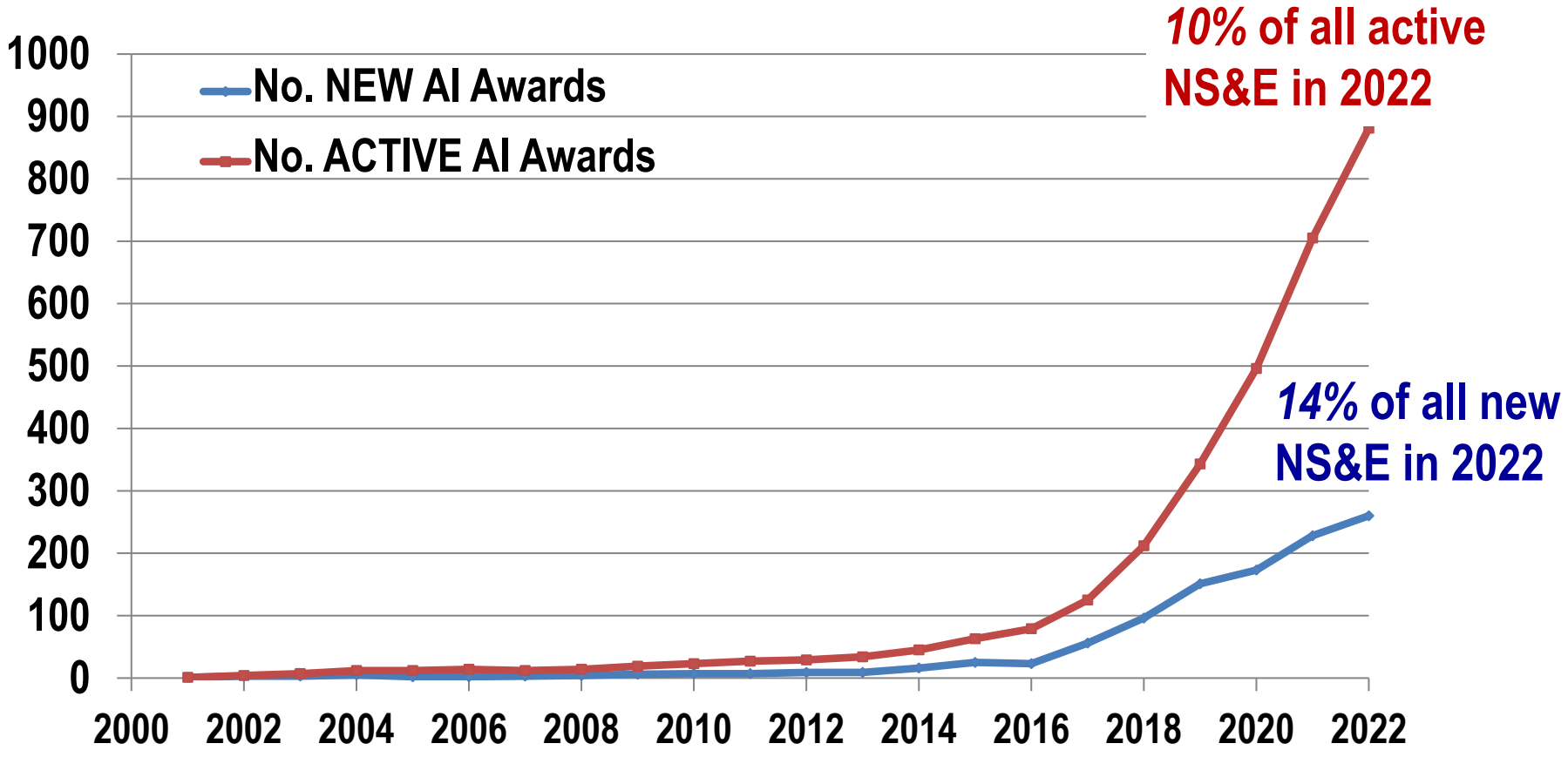


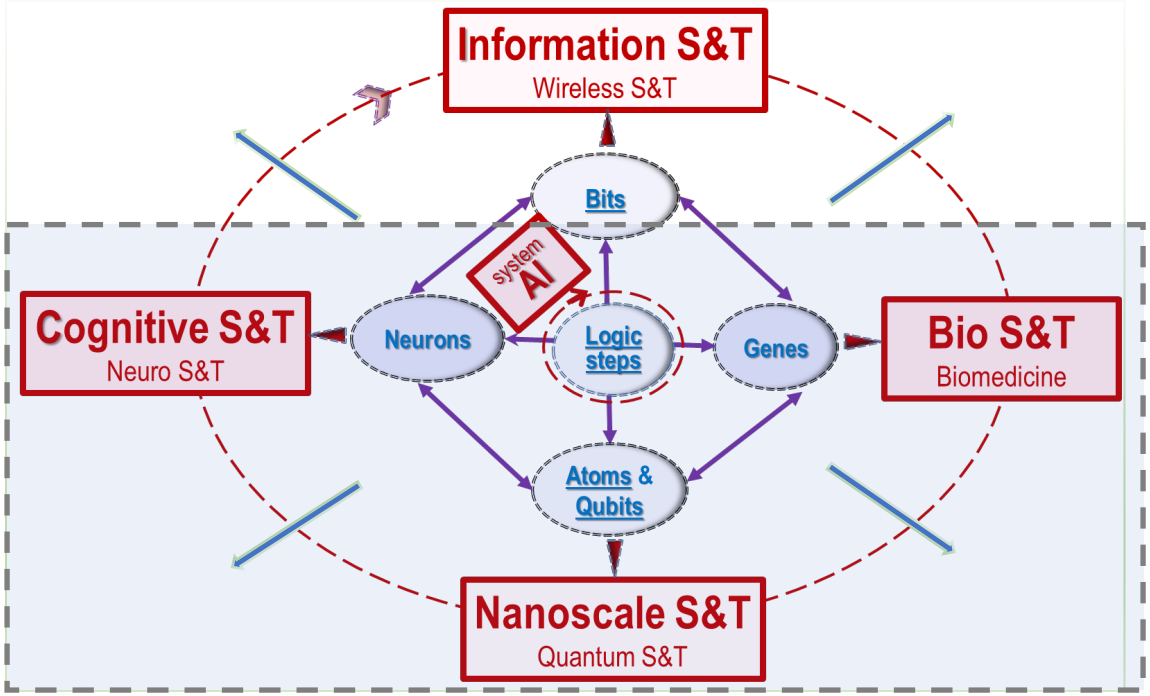
- **NSF and SRC** to support semiconductor research experiences for undergraduates, NSF 19-582 (5 years agreement)
- **EDU DCL**: Enhancing Engineering Technology and Advanced **Semiconductor Manufacturing Technician Educ.,** NSF 22-120
- Micro Nano Technology Education Center and National Institute for Technology and Innovation**: National Talent Hub for semi - nano**
- **NSF-Intel** ($10M) and **NSF-Micron** ($10M) for Semi Research & Education
- **NSF and MOST-Taiwan** co-funding for Semi Research & Education (NSF funds and MOST funds for 80% of the TSMF fab cost)
- **INTERN** – for graduate students in industry

Confluence NS&E with artificial intelligence (AI)

Number of annual AI awards at NSF in FYs 2000-2022

(searched by keywords)





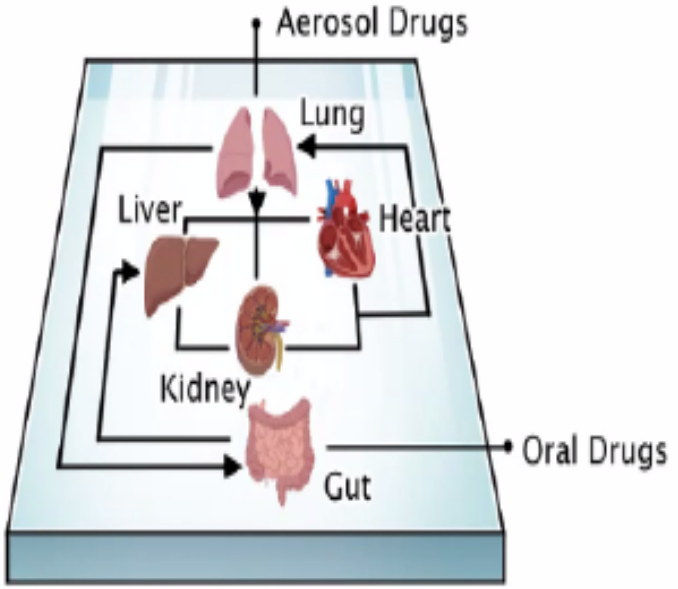
Nano-Bio-AI-Cogno convergence

- ***Ex. Topics***: Nanobiotechnology; Nano-neurotechnology; Synthetic biology (convergence Nano, Bio, Cogno and AI); Nanobiomedicine, 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

BRITE Fellow: Intelligent Nanoscale 3D Biomanufacturing Towards Human-on-a-Chip (UCSD)/ 2135720/$1,000,000

(E,E,E/V,V,V), PC1

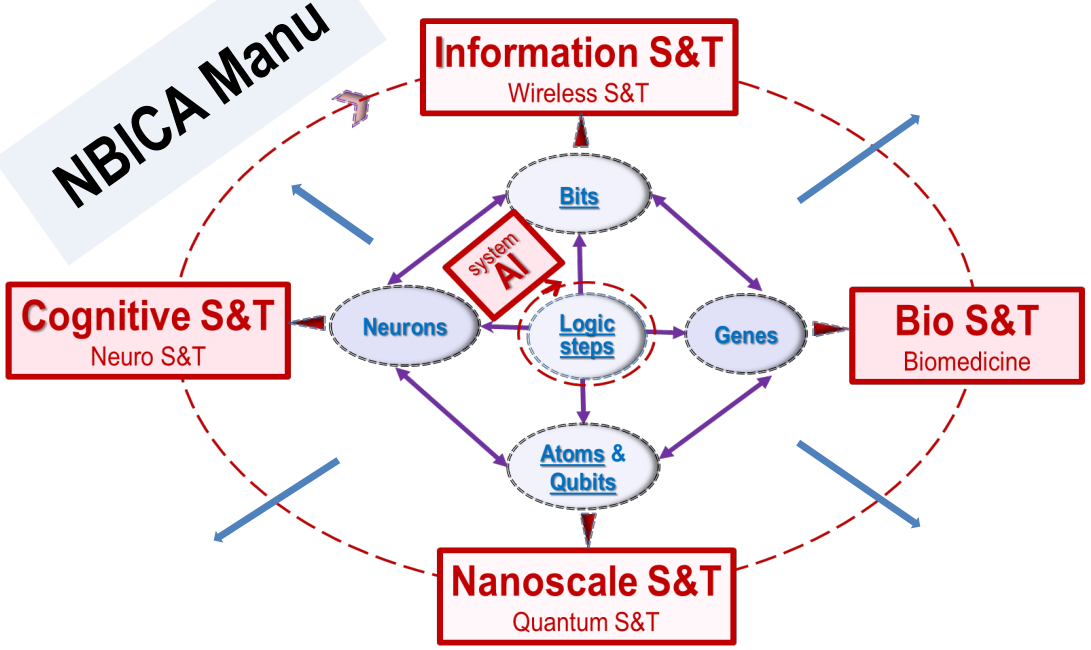
- Primary CMMI Program(s): AM
- Blue Sky Idea - Bioprinted microscale human organs.
- Intellectual Merit: Transformative research to break-through the 3D printing limit of 100 microns. Bioprinting at 100 nm in x-y-z directions
- Broader Impact: Early drug testing, disease modeling, toxicity studies, space exploration.
- PI Past Impact: Chair of first Nanoengineering dept in the US. Leader in Advanced Manufacturing. Initiated or inspired several startups. Leadership engagement in significant DEI efforts.



Nanostructured enzyme that increases tissue regeneration

Shashank Kosuri et al. Machine-Assisted Discovery of Chondroitinase ABC Complexes toward Sustained Neural Regeneration, Advanced Healthcare Materials, Feb 2022 https://doi.org/10.1002/adhm.202102101

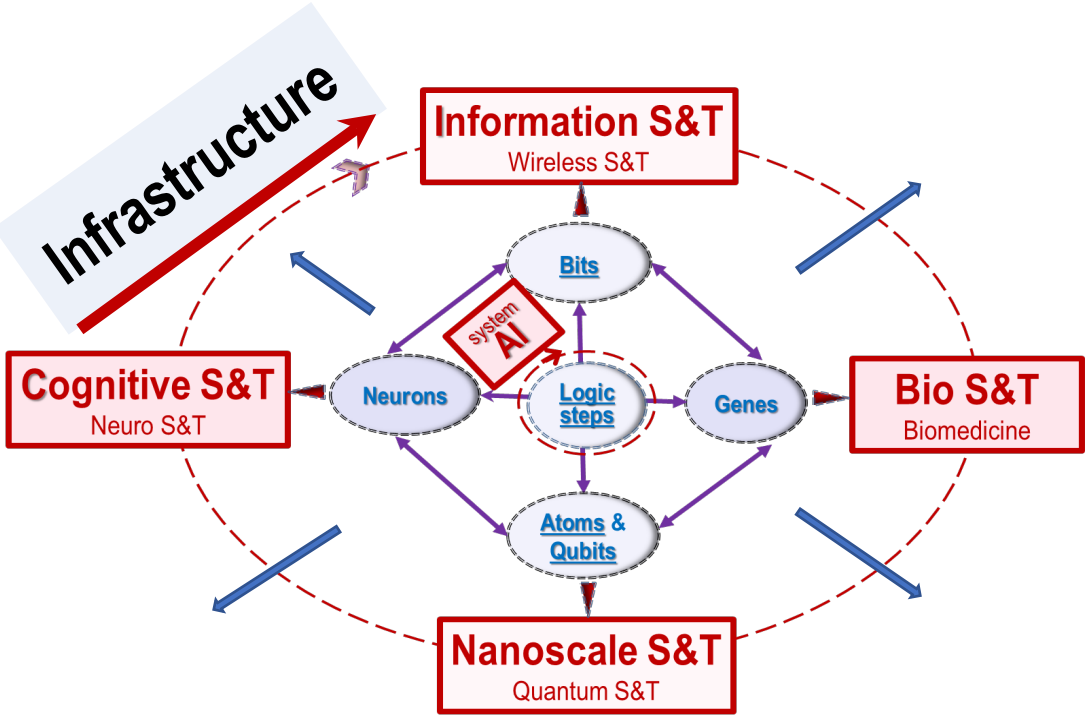
- **Using artificial intelligence and robotics, one has formulated therapeutic proteins that help repair damaged spinal cord tissue and increase tissue regeneration.**
- The treatments developed could mitigate the primary and secondary effects of spinal cord trauma



Convergence NBICA *Manufacturing*

NATIONAL STRATEGY FOR ADVANCED MANUFACTURING WH/NSTC, Oct 2022

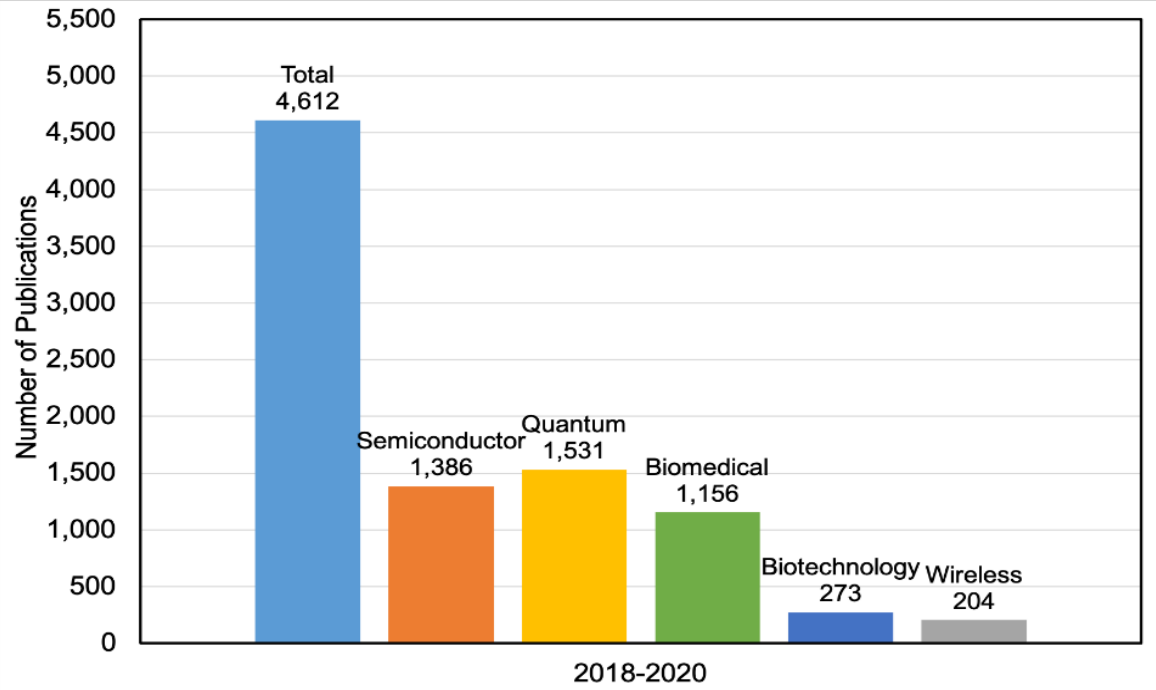
- ***Ex. Topics:*** Nanomanufacturing convergence with Bio, remote IT, AI, neuro, other fields; Cellular manufacturing
- ***Ex. outcomes:*** Hierarchical design; Additive manufacturing of 3D nanoarchitectures; Vaccine microneedles; 2-D nanomanufacturing; DNA and RNA manuf.; Self-healing mat.
- ***Ex.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



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

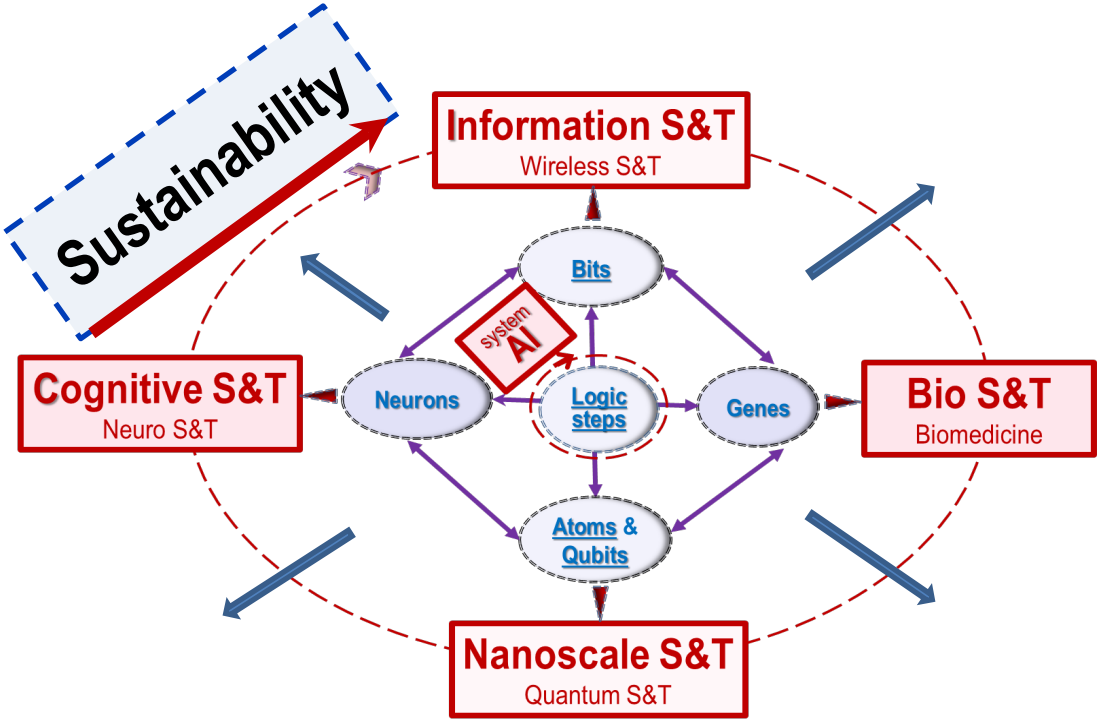
- ***Ex. Topics:*** Flexible infrastructure; Integrated centers for more efficient, responsible transition from fundaments to technology platforms & applications
- ***Ex. Outcomes:*** High Magnetic Field Beamline at Cornell U.; Micro-Nano Technology Education Center
- ***Ex. Programs:*** Mid-scale (I,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

NNI illustration:
NNCI supports industries of tomorrow



4,600 journal articles published 2018-2020 that acknowledge the NNCI award numbers: (i) "**Quantum**" is mentioned by 1,531 (**33%**) ;
(ii) "**Semiconductor**" is found in 1,386 (**30%**) ; and
(iii) **"Biomedical"** is included in 1,156 (**25%**) (keyword search)

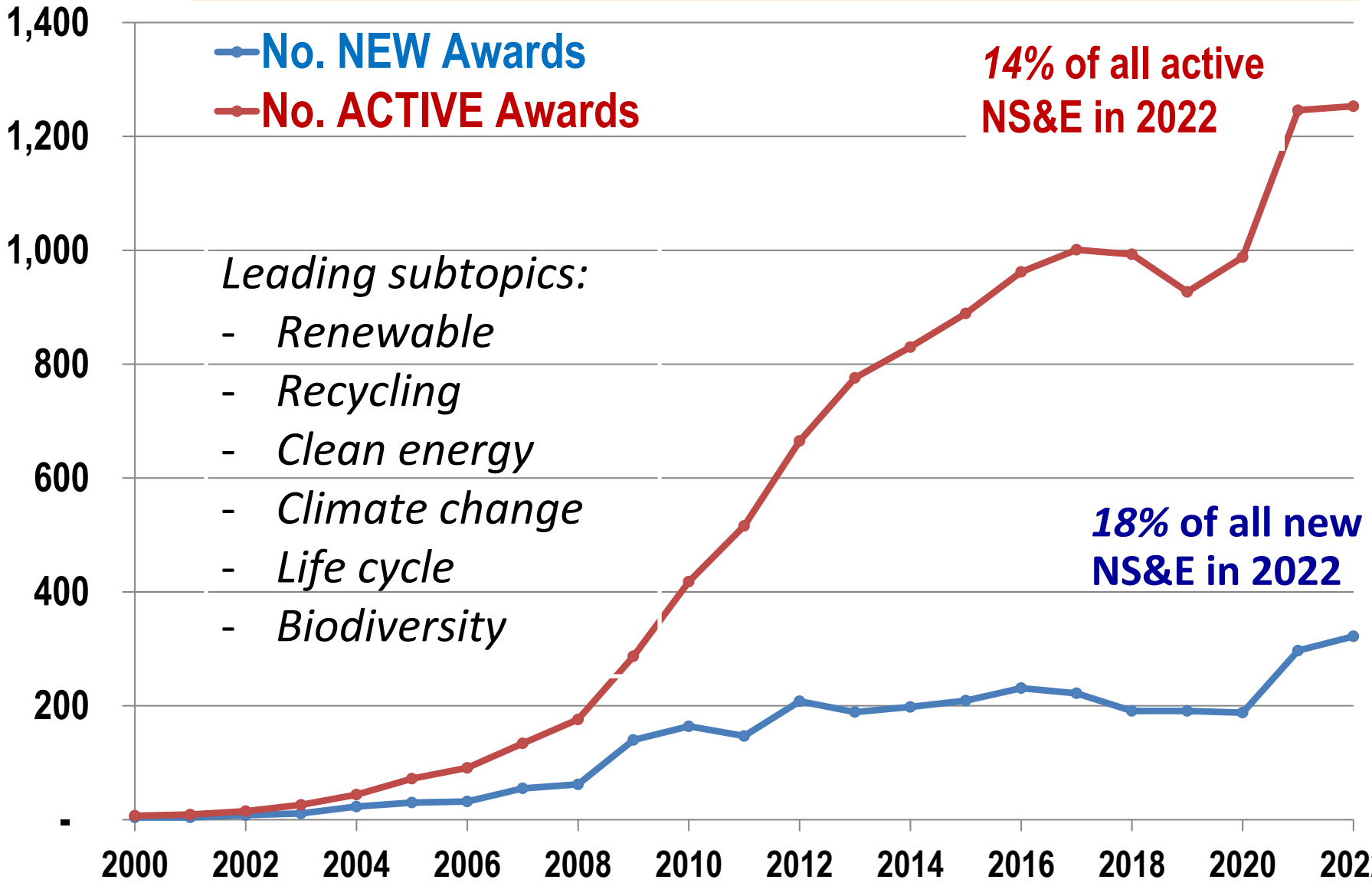
National Nanotechnology Coordinated Infrastructure



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

- ***Ex. Topics:*** Transport phenomena and nano-EHS issues; 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 FY 2000-2022 is about 1/8 of all NS&E awards



NSF-wide activities

Critical Aspects of Sustainability (CAS)

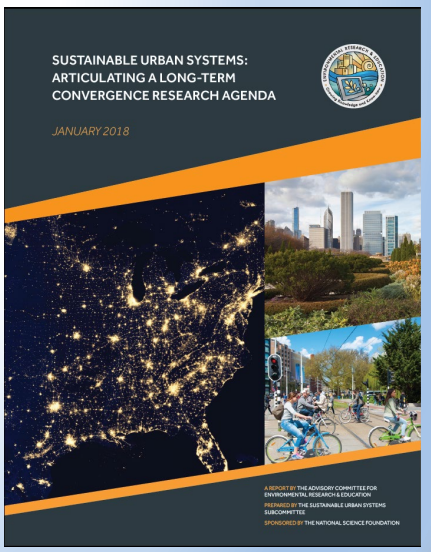
FY 2021-2023: rolling submissions via NSF 21124

This program seeks to support basic research through core disciplinary programs aimed at

- **Reducing greenhouse gas emissions and energy use**
- **Energy innovations for climate change mitigation**
- **Enhance carbon sequestration**
- **Strategies for climate change adaptation**

Urban Systems and Communities in the 21st Century

- **Smart and Connected Communities** (2016-)
- **Sustainable Urban Systems** (2019-)
- **Coastlines and People** (2019-)
- **Long Term Ecological Research - Urban Ecology** (network since 1980 with 24 sites)
- **Core programs**: Civil infrastructure systems, Cultural anthropology, Environmental Sustain.



https://www.nsf.gov/ere/ereweb/urbansystems/

Growing Convergence Research (GCR): a main theme is sustainable society

Examples "**Growing Convergence Research**" awards

1934824	GCR: **Convergence Around the Circular Economy**	University of Pittsburgh	Melissa M Bilec
1934887	GCR: **Life Cycle Management of Materials: Sustainable Biomass to Designer Polymer Systems**	University of Delaware	Thomas H Epps, III

Part of NSF's ***Convergence Accelerators***

Open Knowledge Networks on Sustainability

Creating and deploying Open Knowledge Networks which specify needs and requirements **to serve various stakeholder interests, including for climate change**

https://nsf-gov-resources.nsf.gov/2022-09/OKN%20Roadmap%20-%20Report_v03.pdf?utm_medium=email&utm_source=govdelivery

CIVIC INNOVATION CHALLENGE

POWERING SMART & CONNECTED COMMUNITIES

Partnership between NSF, DOE, and DHS

- Foster collaboration for smart and connected communities
- *Finds community-based solutions*

FY 2023 NSF 22-565 competition underway

- Living in a changing climate
- *Bridging the gap between essential resources and services & community needs.*

Examples of other recent NSF programs

at the levels of directorates and divisions

- **Environmental Convergence Opportunities in Chemical, Bioengineering, Environmental, and Transport Systems (ECO-CBET)** : NSF 21-596, 2021
- **Predictive Intelligence for Pandemic Prevention Phase I: Development Grants (PIPP Phase I)** 2021, NSF 21-590
- **Climate and Large-Scale Dynamics**
- **Climate Change Education**
- **Biodiversity on a Changing Planet**
- **Life on a Warming Planet Research**
- **Organismal Response to Climate Change**

Partnerships for International Res. and Educ., PIRE

2022 focus on global societal challenges related to climate change & clean energy

Examples awards re nanotechnology in 2022

- Center **All-Solid-State Batteries** for Clean Energy Society: IIT
- US-Japan Partnership in **Excitonic Soft Materials** for Clean Energy: U. of Vermont
- JUNCTION, Japan-US Network for Clean Energy Technologies Involving **Oriented Nanotubes**: Rice U.
- Advancing International Partnerships in Research for Decoupling **Concrete Manufacturing** and Global Greenhouse Gas Emissions: U. Texas at Arlington
- Networks for **Geologic Hydrogen Storage**: UC Berkeley

NSF/OISE networks for sustainability

FY2022 AccelNet – Sample Awards

US-Africa Sustainable Food Systems through Water-Energy-Food Nexus

Transformation to Sustainability across the World's Mountains

Study of Ocean Metabolism and Nutrient Cycles on a Changing Planet

Implementation of Quantum Materials

US — EU

Nanotechnology Communities of Research (CORs)

(https://us-eu.org/)

NNI: CORs - a platform for community-led activities: telecons, webinars, publications, and annual in-person meetings

- ***Seven CORs addressing potential environmental, health, and safety (EHS) implications of nanomaterials and nanodevices***
- ***COR on Nanomanufacturing***
- ***Topical bilateral workshops***

Several sustainability challenges

- **Are renewable water/energy/food/materials** sources sufficient?
- **Thermonuclear energy** will be controlled, economic, how soon?
- **Emerging technologies** will be sustainable?- For how long?
- **How "smart systems"** (incl. AI, NBIC) will help sustainability?
- **DNA control and hybrid nanobiodevices** will have safe regulations and suitable organizations for life security?
- **How to balance international collaboration and competition**: for convergent technologies, patenting, databases, labeling ?
- Ensure **holistic & time view** in nanotechnology risk governance?

Other challenges & solutions to be discussed in the SNO Panels

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. ***"Long View of Nanotechnology Development: the NNI at 10 Years"(JNR, 2011)***
7. ***"The new world of discovery, invention, and innovation: convergence of knowledge, technology and society"*** (Roco & Bainbridge, JNR 2013a, 15)
8. ***"International perspective on nanotechnology papers, patents, and NSF awards (2000–2016)"*** (Zhu, Jiang, Chen & Roco, JNR 2017, 19-370)
9. ***Proc. NSF NSE Grantees*** *Dec. 2020, available on www.nseresearch.org/2020/*
10. ***"Overview: Affirmation of Nanotechnology between 2000 and 2030"*** (MC Roco, Ch.1 in Nanotech. Commercialization, Wiley, Ed. T. Mensah et al., 2018)
11. ***"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)*