The Path of Nanotechnology past and present

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NSF and NNI

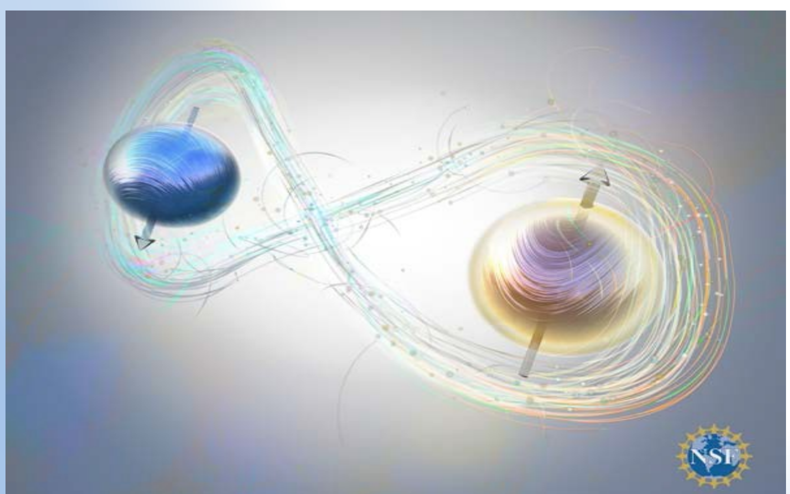
NNI Quadrennial Review by National Academies, Washington, D.C., Mar 14, 2019

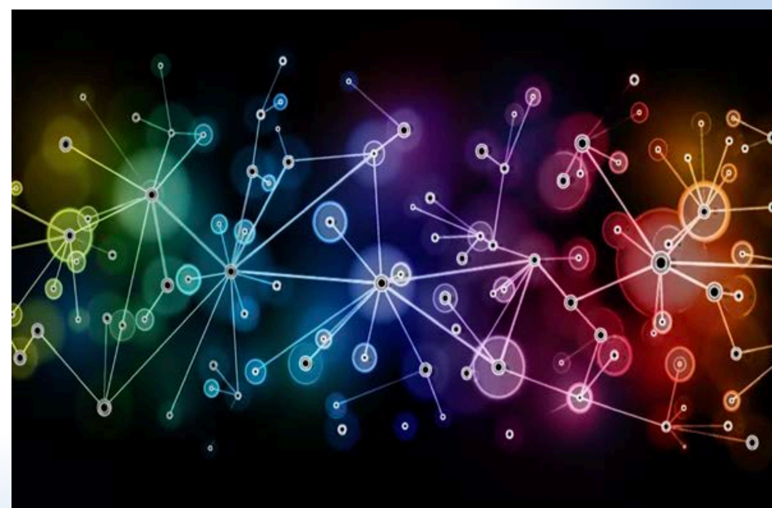
Topics

- Long-view of nanotechnology development
- Emergence and convergence from the nanoscale: three hierarchical stages
- NSE at NSF: 2019 perspective

A NNI drive: Long view of nanotechnology development

2000 - 2030





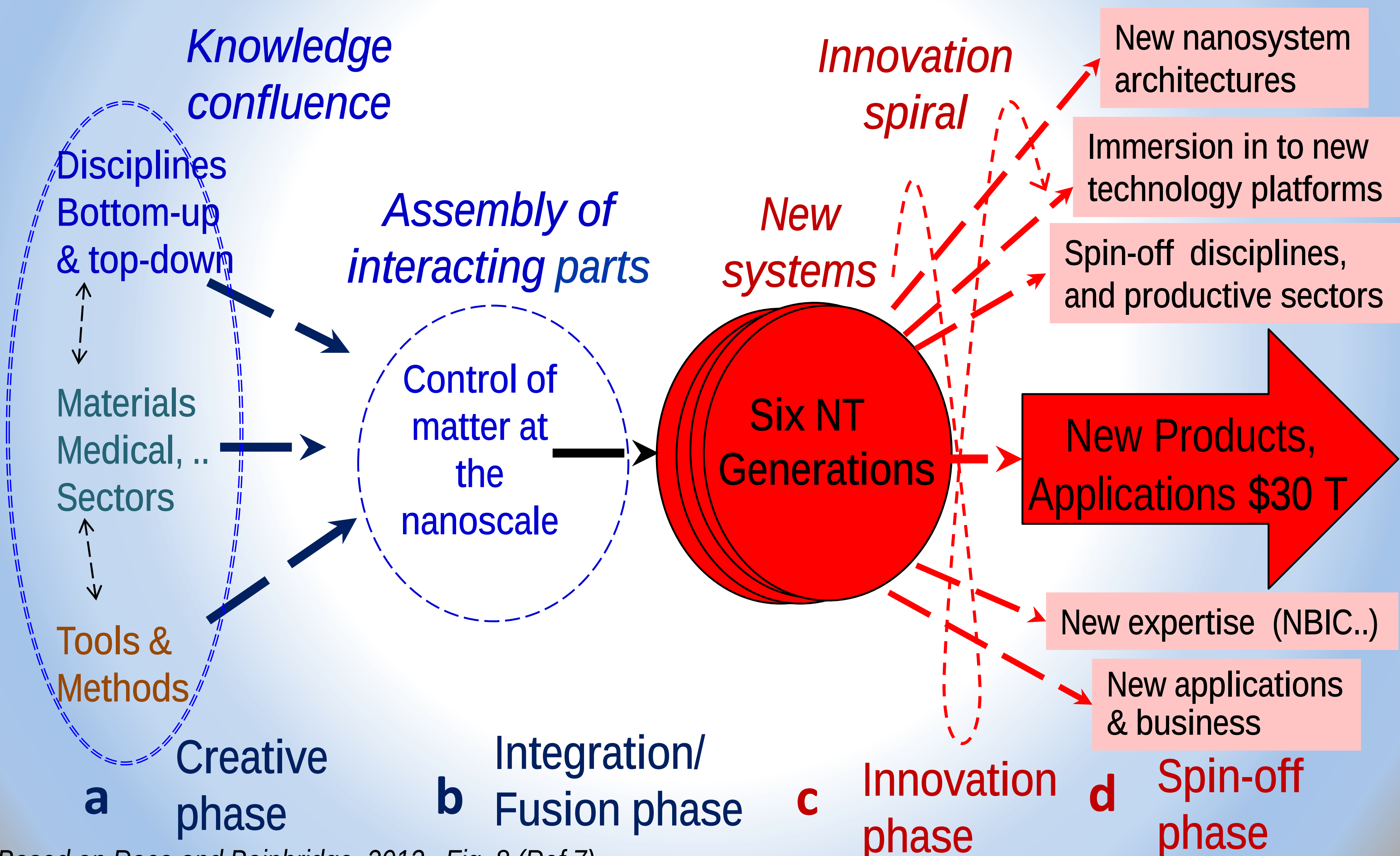
A foundational science and engineering field

- Nanotechnology is a foundational, general purpose S&E field, in development phase 2000-2030

- Nanotechnology continues quasi-exponential growth by penetrating in disciplinary platforms, vertical science-to-technology transition, horizontal expansion to areas as agriculture/ textiles/ cement, and spin-off areas (~20) as nanophotonics/ metamaterials/ spintronics/ nanosustain

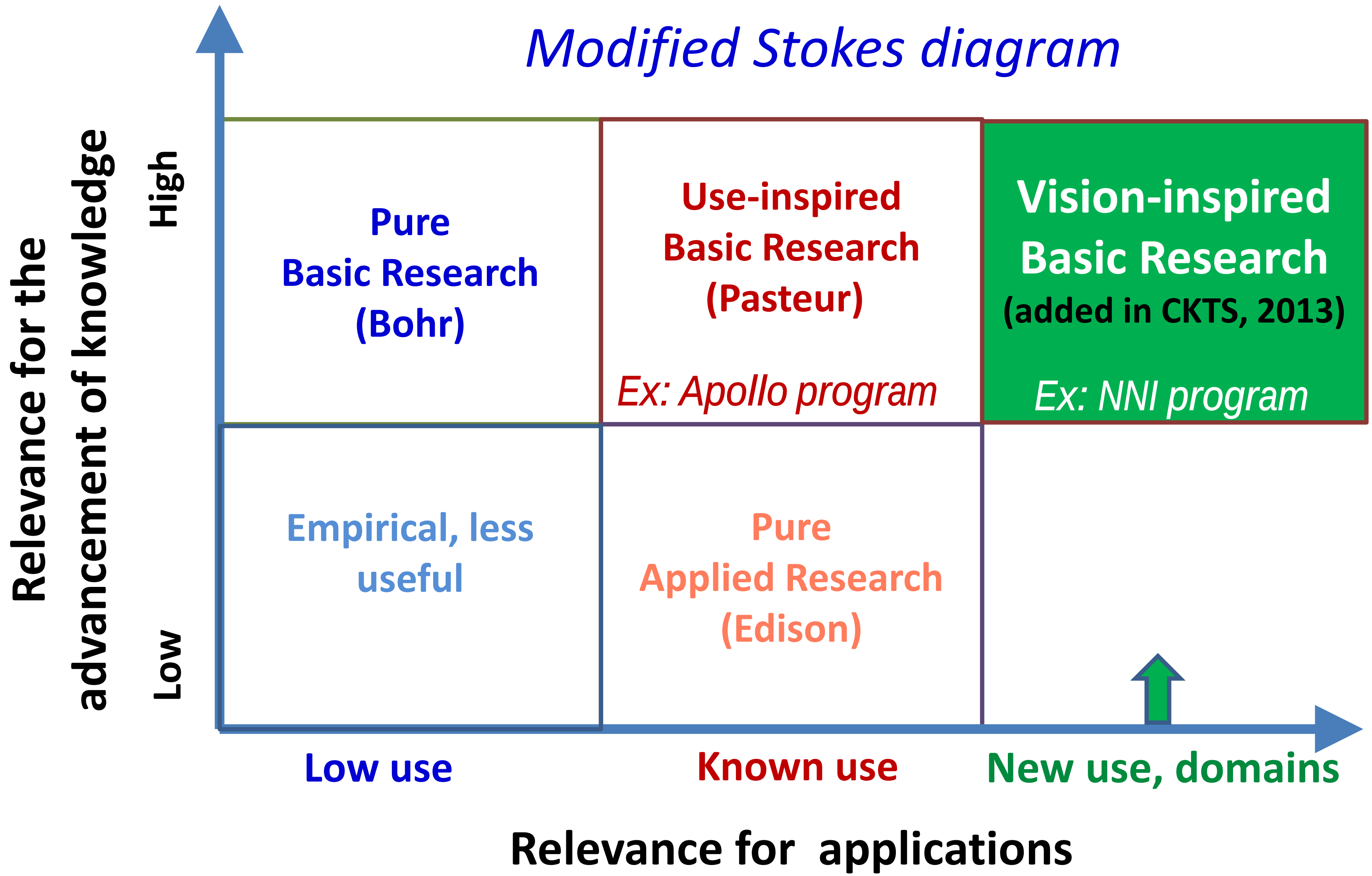
- Nanotechnology promises to become a primary S&T platform for investments and venture funds once efficient design & manufacturing methods are established

2000-2030 Convergence-Divergence cycle for global nanotechnology development

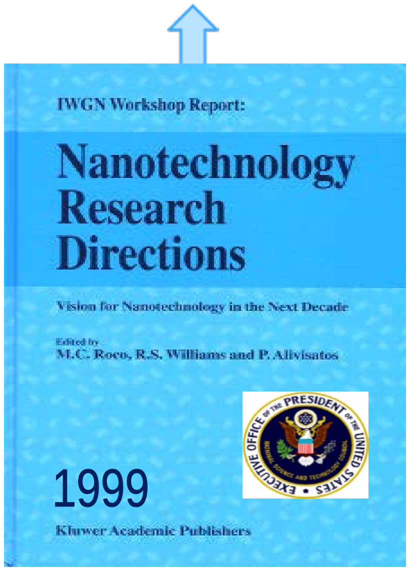


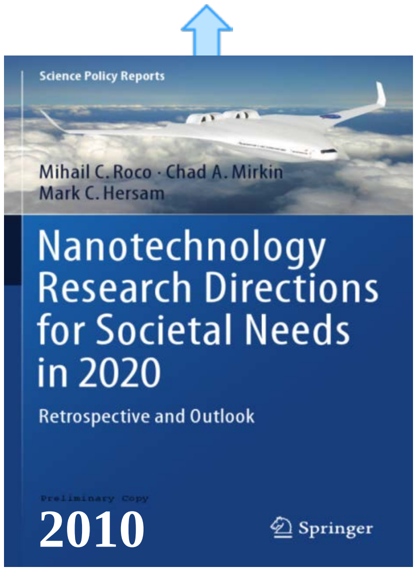
Based on Roco and Bainbridge, 2013 , Fig. 8 (Ref 7)

Vision inspired research has been essential for the long-term view of nanotechnology



Roco and Bainbridge, 2013 , Fig 9 (Ref. 7)





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)

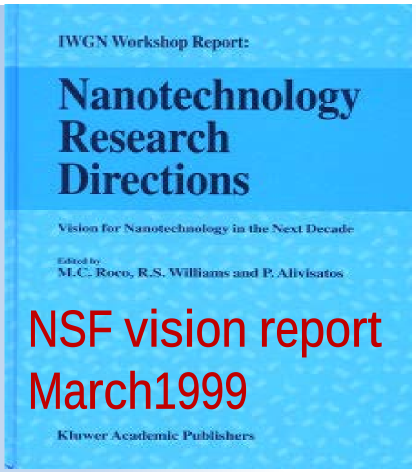
S&T breakthroughs underpin Grand Challenges

(examples of novel concepts targeted by NNI in 2000 "in 20-30 years")

- **Library of Congress in a "one cubic cm" memory device:** target 30-40 atoms (2000); Realized 12-atom structure (IBM, 2012), DNA structure (Harvard, 2012; in "one cubic mm"). "*Millions times smaller*"
- **Molecular cancer detection and treatment** (first gold-shells, Rice, 2002 - 2016 many other solutions in progress) "*Not possible before*"
- **Materials 10 times strength of steel, fraction of weight**; done
- **Exploit nano-photonics:** change direction and frequency of light (2004, then succession of solutions); negative diffraction of light / electrons in meta-metamaterials (2004) & 2D mat (2007). "*New phenomena and devices*"
- **Quasi-frictionless nanocomponents**: quantum fluctuations between selected material surfaces (first Harvard, 2008). "*Almost frictionless*"
- **Magnetic computing** close to the lowest Landauer fundamental limit of energy dissipation under the laws of thermodynamics (STC Berkeley, 2016). "*Millions times less energy consumption*"

The 30 year vision has sparked imagination in Congress and 4 Presidents

NNI in four administrations: Clinton, Bush, Obama, Trump



NSF vision report March1999

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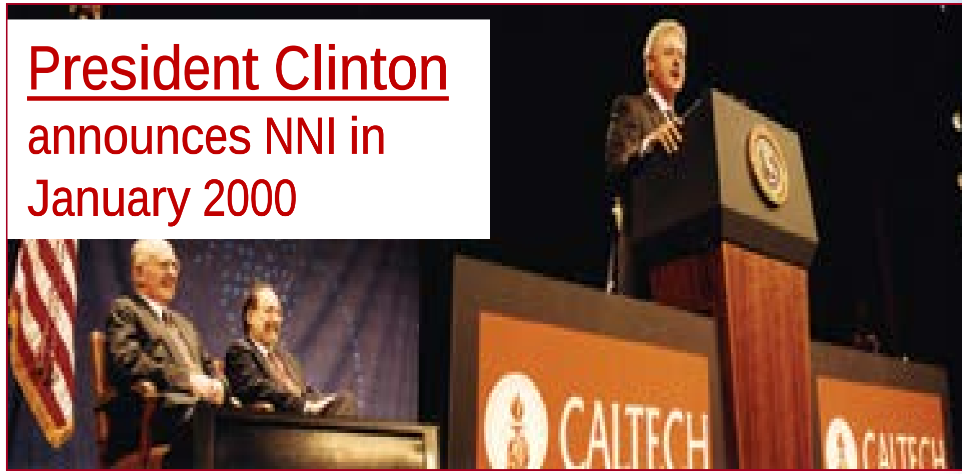
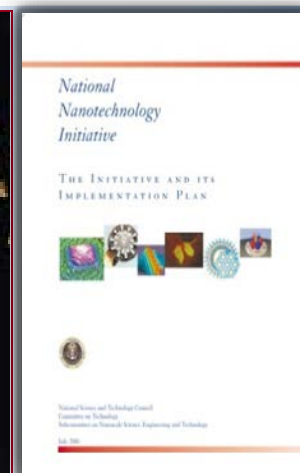
President Clinton announces NNI in January 2000





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President Bush

Signing 21st Century Nanotech. R&D Act – Dec. 2003

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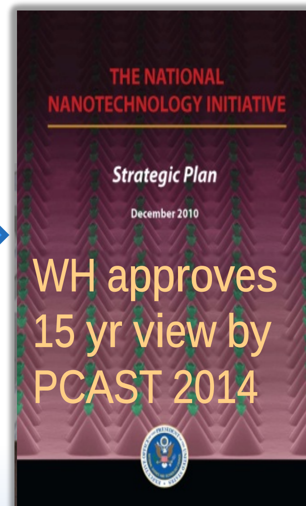


WH approves 15 yr view by PCAST 2014

President Obama

→

President Trump

Priority basic research

2017–2020 NNI budgets

CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES

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

2030

DIVERGENCE

CONVERGENCE

2000

New socio-economic capabilities

nano3 Technology divergence

2020-2030

To general purpose technology

nano2 System integration

2010-2020

Create library of nanocomponents

nano1 Component basics

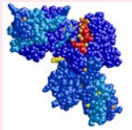
2000-2010

GENERATIONS OF NANOPRODUCTS

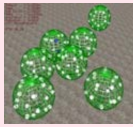
6. Nanosystem Conv. Networks

5. NBICA Technology Platforms

4. Molecular Nanosystems

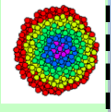


3. Systems of Nanosystems



2. Active Nanostructures

1. Passive Nanostructures



OVERVIEW: *CREATING A GENERAL PURPOSE NANOTECHNOLOGY IN 3 STAGES (2000 – 2030)*

Described in NANO1, NANO2020 (Fig. 5), NBIC reports [2-5]

Increase control at nano, integration, complexity

Higher uncertainty and risk

2030

Major changes in:

New convergence platforms & economy immersion

~ 2021 ← **nano3 divergence** → **~ 2030**

NBICA measurements; <u>Spin-off science-based systems in industry, medicine and services; New competencies, S&T areas, education</u>

Socioeconomic NBICA platforms, capabilities, and projects

NS&E integration for general purpose technology

~ 2011 ← **nano2 integration** → **~ 2020**

Direct measurements; <u>Science-based system design and processes</u>; Collective effects; Create nanosystems by technology integration

New disciplines

New industries

Societal impact

Foundational interdisciplinary research at nanoscale

~ 2001 ← **nano1 basics** → **~ 2010**

Indirect measurements, Empirical correlations; Single principles, phenomena, tools; <u>Create nanocomponents by semi-empirical design</u>

Infrastructure

Workforce

Partnerships

2000

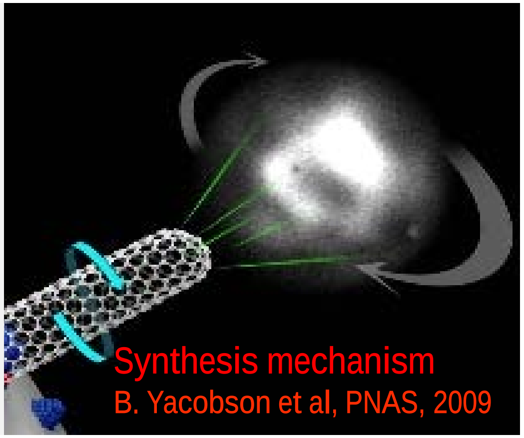
MC Roco, Mar 14 2019

nano1

Examples for Nano 1 (2001-2010)

- New individual phenomena, processes, structures

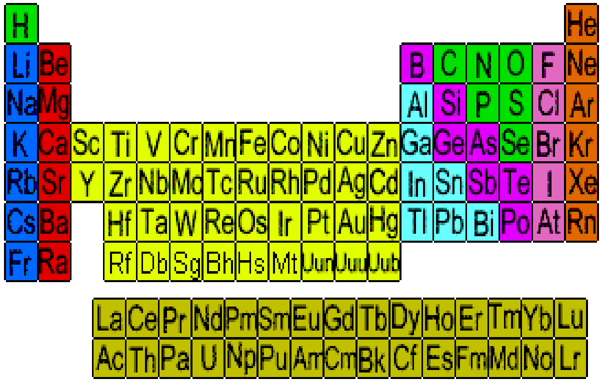
Quantum effect repulsion force
Federico Capasso, Harvard University



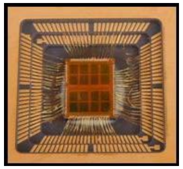
Synthesis mechanism
B. Yacobson et al, PNAS, 2009

First quantum device
Aaron O'Connell and Andrew Cleland, UCSB, 2010

- Semi-empirical synthesis of nanocomponents (particle, quantum dots, tubes, coatings,..) over all the periodic table



- Nanocomponents have extended semiconductor’s Moore’s law since 2000



MC Roco, Dec 1 2010

nano1

2000-2010 Outcomes

- **Remarkable scientific discoveries** than span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of 1D - 4D nanostructured **building blocks for devices and systems**
- **Methods and Tools:** Femtosecond measurements, sub-nanometer measurements, single-atom and single-molecule characterization methods..
- **New S&E fields have emerged** such as: spintronics, plasmonics, metamaterials, carbon nanoelectronics, molecules by design, nanobiomedicine, branches of nanomanufacturing, and nanosystems
- **Technological breakthroughs** in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; **expansion into** energy resources and water filtration, agriculture and forestry; and **integration of nanotechnology with other emerging areas** such as quantum info. systems, neuromorphic engineering, and synthetic and system nanobiology

Examples for Nano 2 (2011-2020)

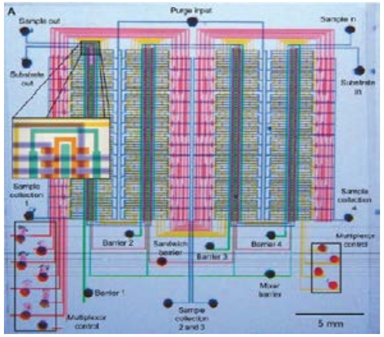
- Direct measurements & simulations (at femtosecond, N↑ interacting atoms) for domains of biological and engineering relevance

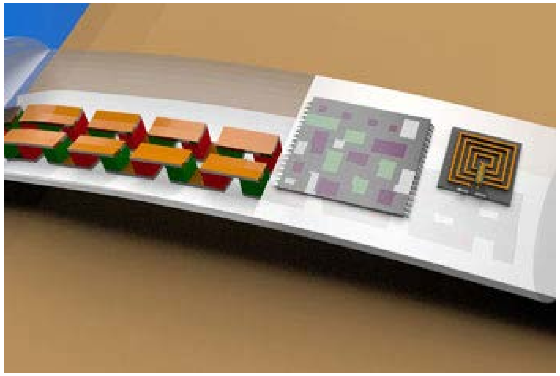
Atomic and femtosecond resolutions . A. Zewail, Caltech

- Science based integrated nanosystems by design

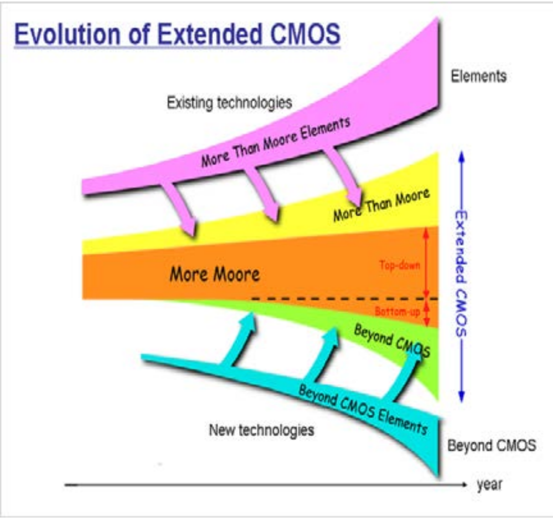
IBM: 12-atom structure (2012)

UIUC: Nanofluidics system (2011)





NCSU: Nanosystem for health and environmental monitoring (2014)



nano2

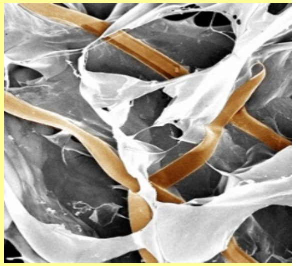
Twelve global nano trends to 2020

10 year perspective, www.wtec.org/nano2/ (Ref. 4)

- 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**

Examples for Nano 3 (2021-2030)

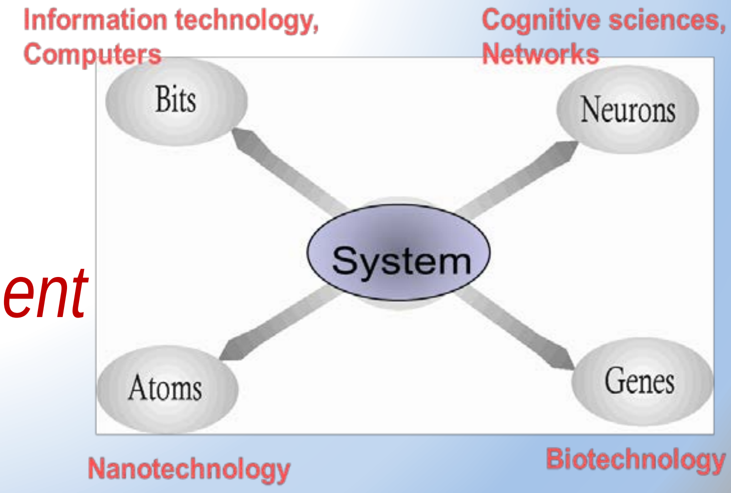
- **New system architectures**: guided self-assembling structures, evolutionary architectures, biomimetics--based, biorobotics-based, neuromorphic, adiabatic switching for IT, quantum systems… to be invented.
- Nano-Bio-Info-Cognition-AI technology platforms, such as for hierarchical modular nanomanu. and personalized nanomed.



- Genetic/single cell, neurotechnologies, robotics - .... **to improve human potential**
- High productivity - high return **new industry sectors**

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

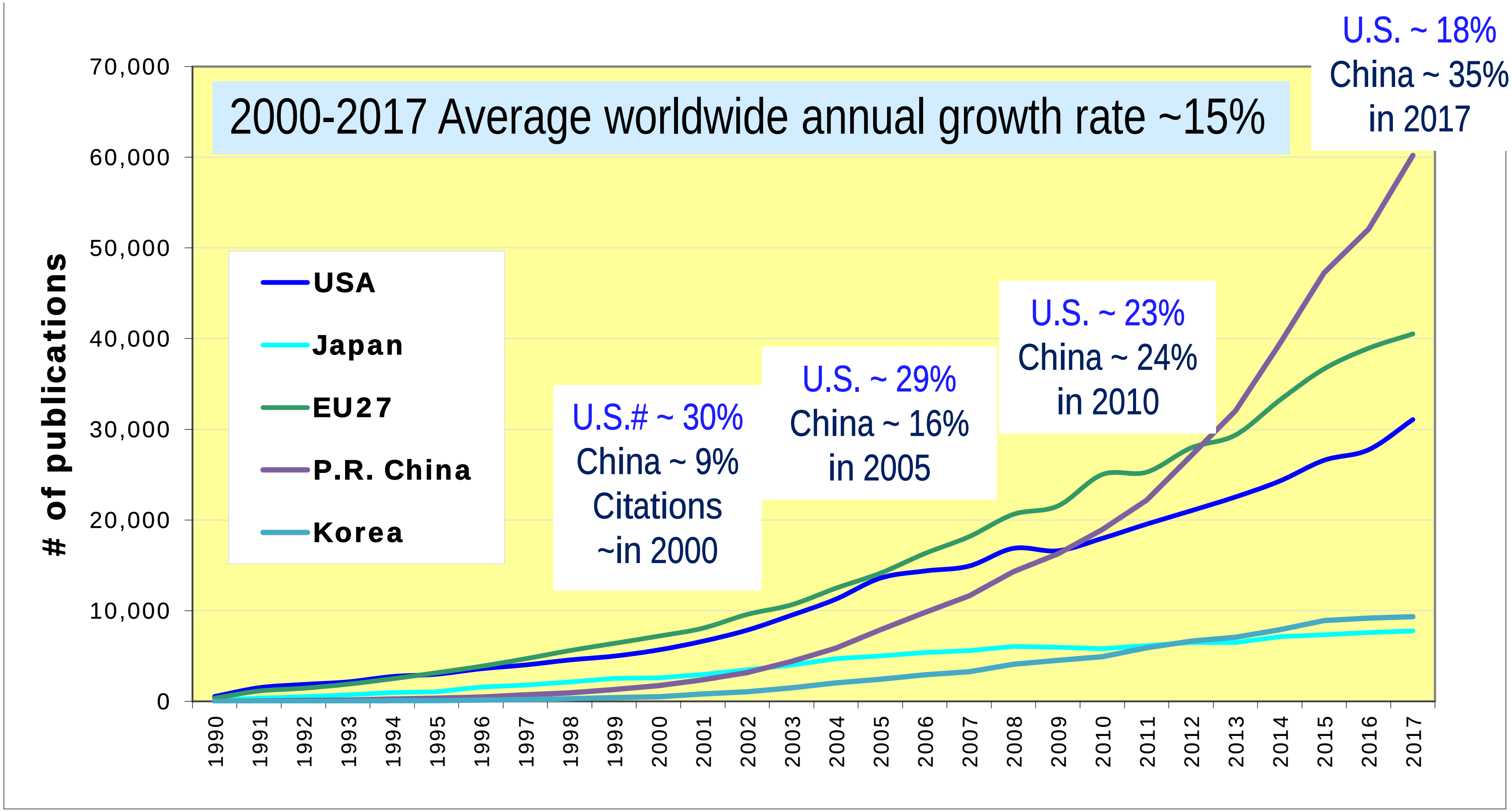
- Hierarchically interconnected world using nano-el. - *reality in 2015*
- Non intrusive brain-to-brain communication – *accepted*
- Computer Personal Advisor – Intel.Cogn.Assistant – *at beginning*
- Brain machine and brain robotics systems – in development
- From physics/chemistry to mind and education – 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*



Ref. 5: NBIC Report, 2003

Nanotechnology publications in the WoS: 1990 - 2017

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

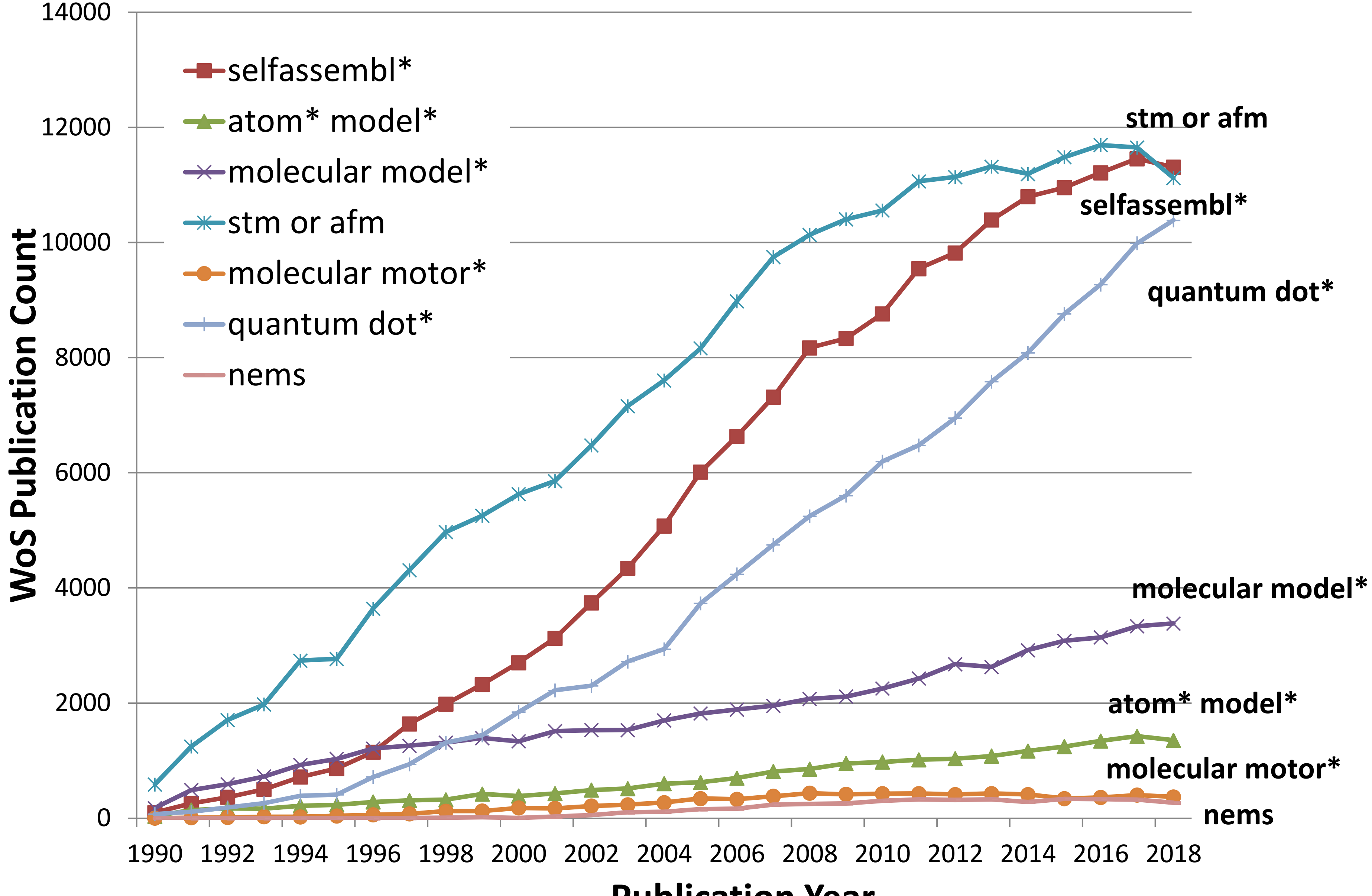


Rapid, uneven growth per countries

MC Roco, Mar 14 2019

U.S. contribution from ~29% in 2005 to ~18% in 2017 (about -1% per year)

WoS publications on seven terms (1990-2018)



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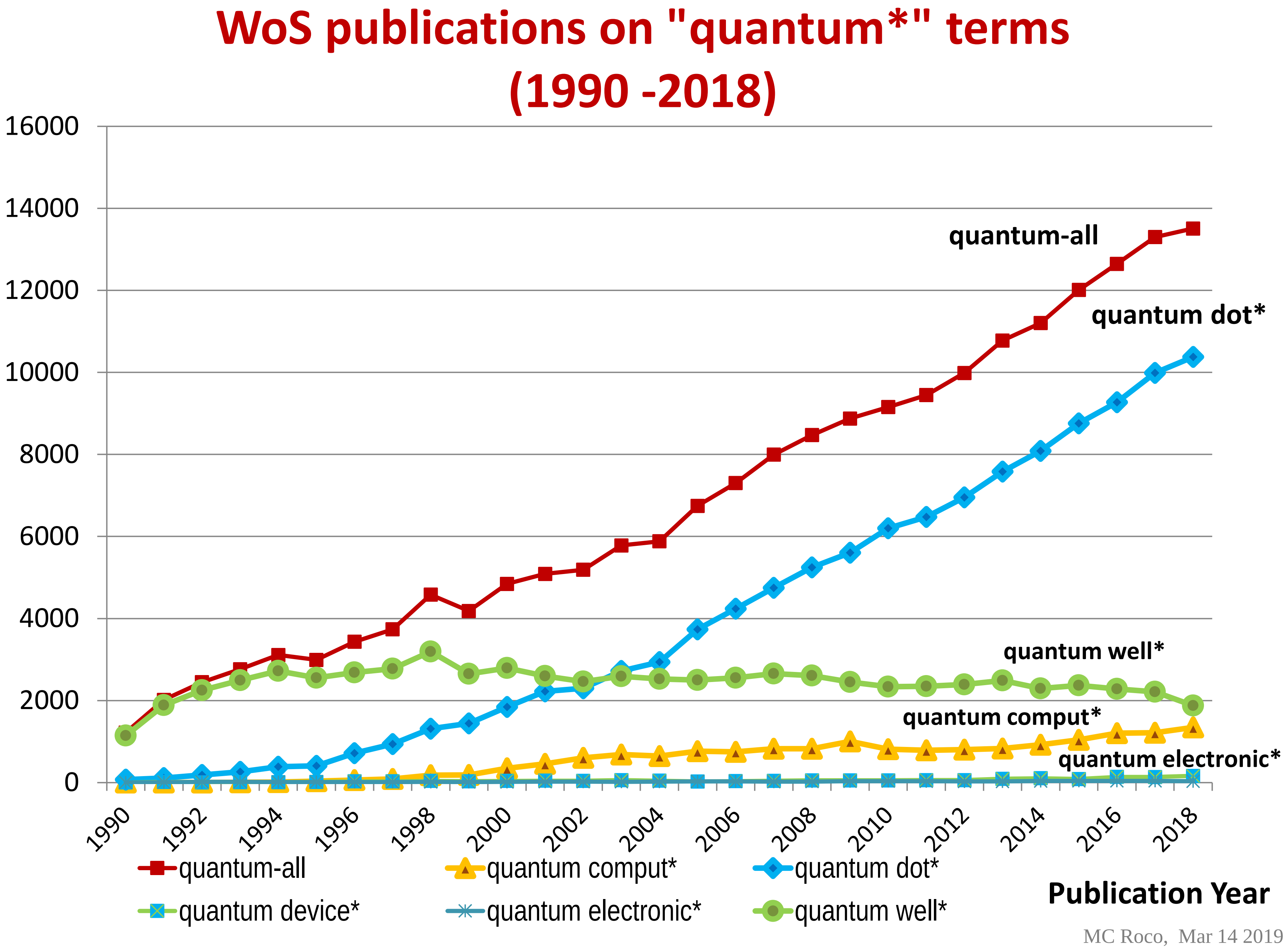
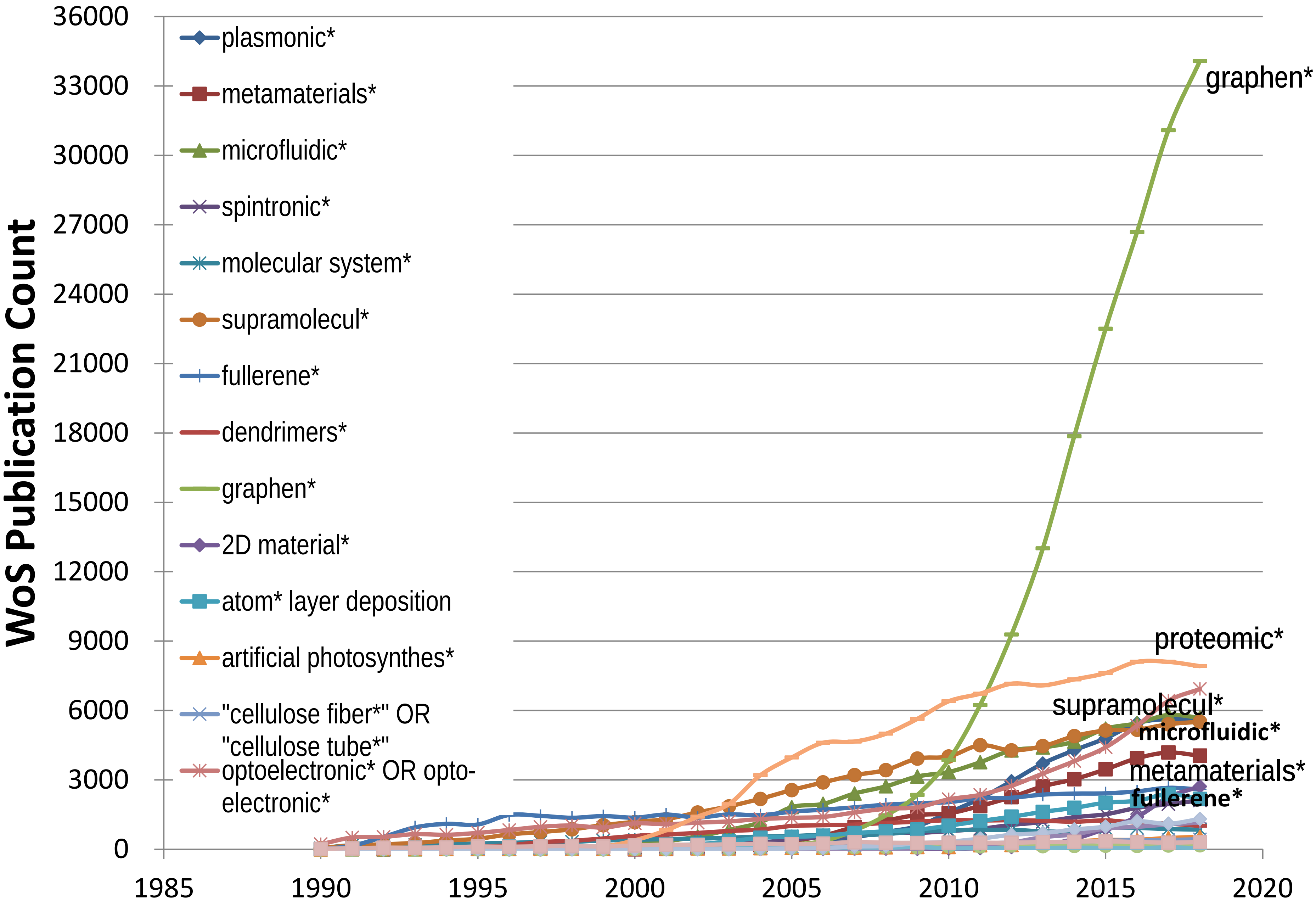

WoS publications on "quantum*" terms
(1990 -2018)
16000
14000
12000
10000
8000
6000
4000
2000
0
quantum-all
quantum dot*
quantum well*
quantum comput*
quantum electronic*
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
quantum-all
quantum comput*
quantum dot*
quantum device*
quantum electronic*
quantum well*
Publication Year
MC Roco, Mar 14 2019

WoS publications on nano-extended 20 new terms (1990-2018)



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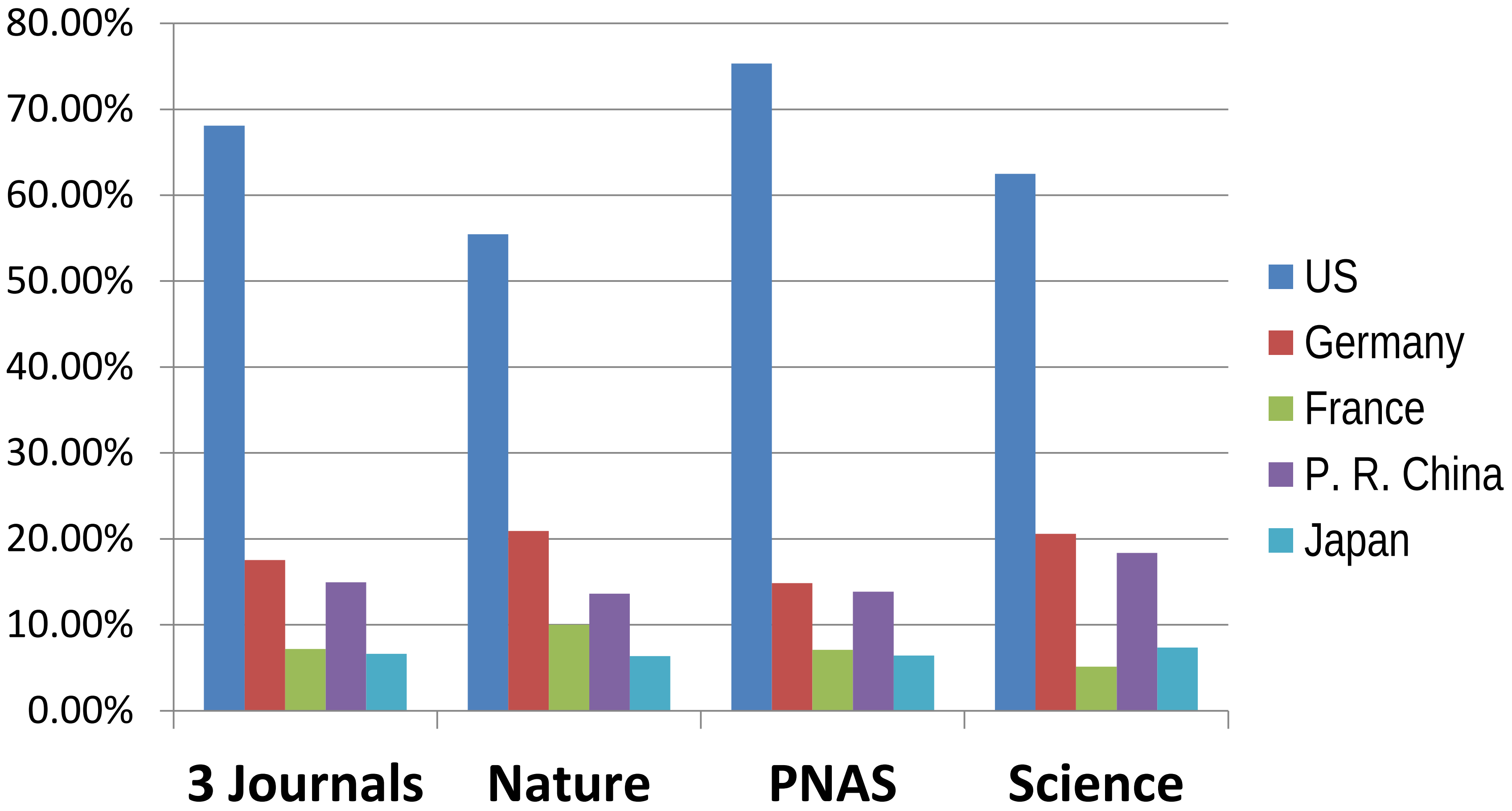
Five countries' contributions to Top 3 journals in 2017

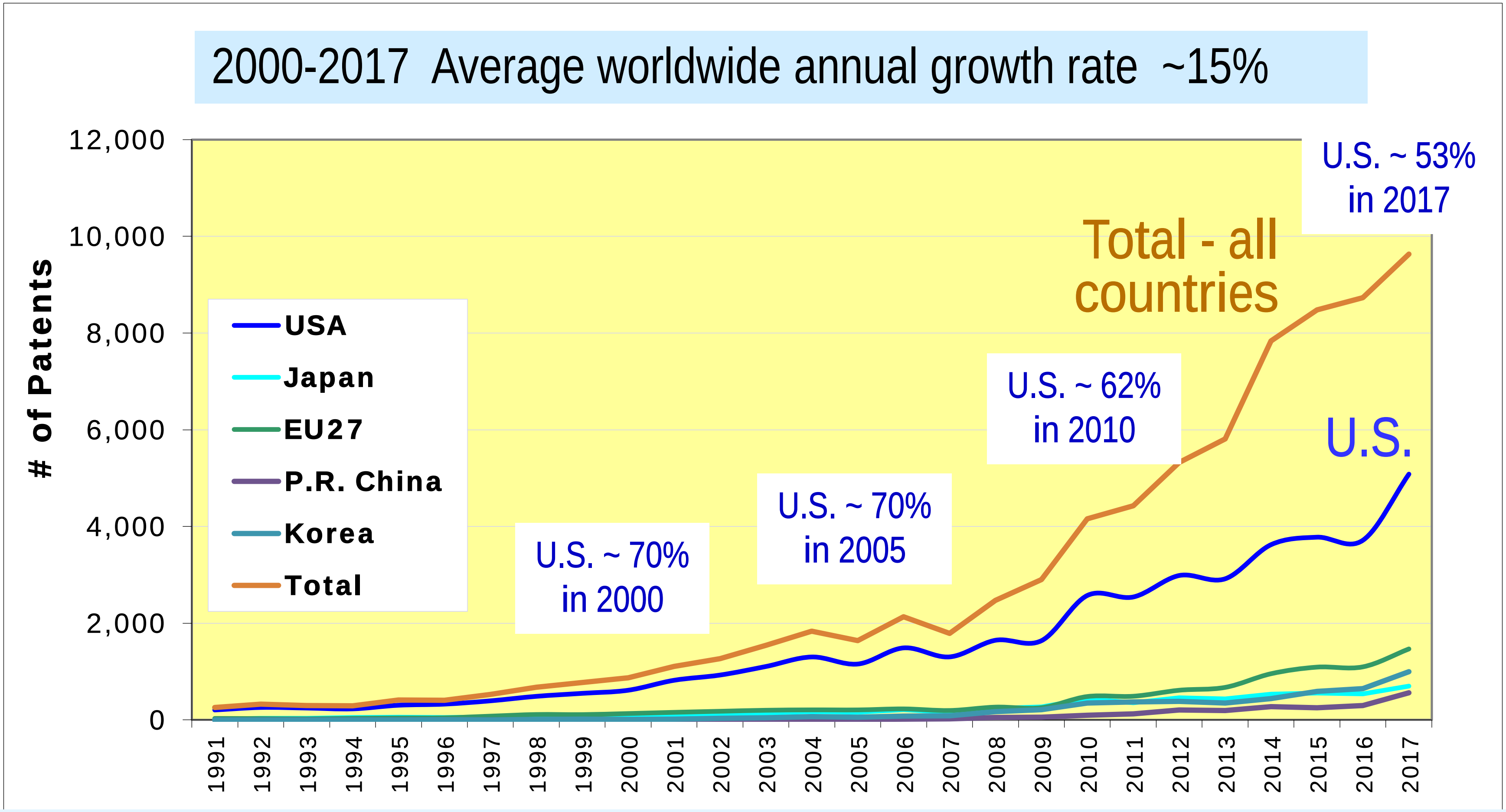
(about the average for last 4 years)



* 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: 1991-2017

"Title-abstract" search of nanotechnology by keywords (update Chen and Roco [7])

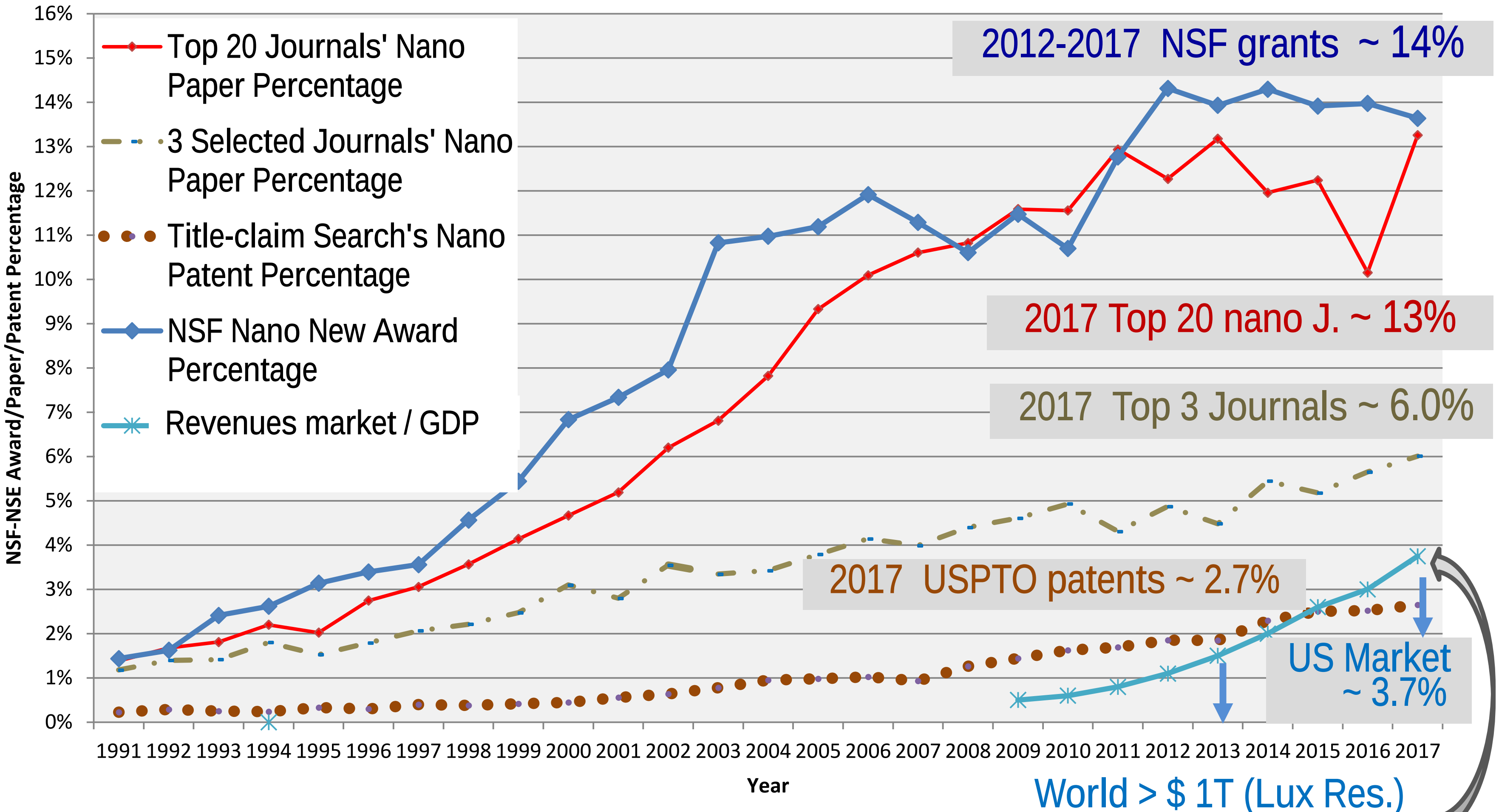


U.S. patent authors maintain the lead at USPTO in 2017

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 (1991-2017)

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



Est. US Market / US GDP: 2014 ~ 2%; 2017 ~ 3.7%; 2020 ~ 7% (if 25% market growth rate)

MC Roco, Mar 14 2019

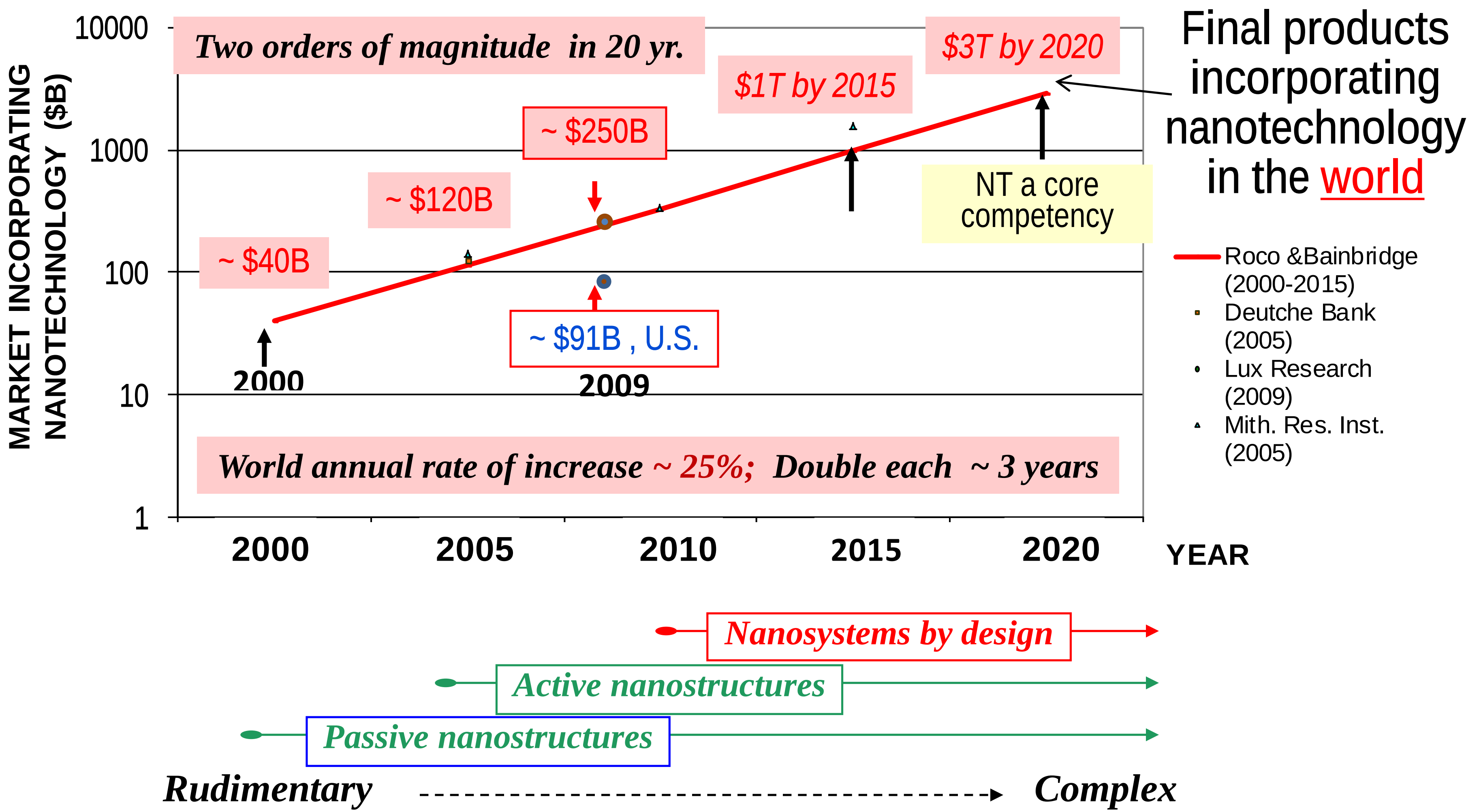
2000-2010
Estimates show an average growth rate of key nanotechnology indicators of 16% - 33%

World (US)	People -primary workforce	SCI papers	Patents applicat-ions	Final Products Market	R&D Funding public + private	Venture Capital
2000 *(actual)*	~ 60,000 (25,000)	18,085 (5,342)	1,197 (405)	~ $30 B ($13 B)	~ $1.2 B ($0.37 B)	~ $0.21 B ($0.17 B)
2010 *(actual)*	~ 600,000 (220,000)	78,842 (17,978)	~ 20,000 (5,000)	~ $300 B ($110 B)	~ $18 B ($4.1 B)	~ $1.3 B ($1.0 B)
2000 - 2010 average growth	~ 25% (~23%)	~ 16% (~13%)	~ 33% (~28%)	~ 25% (~24%)	~ 31% (~27%)	~ 30% (~35%)
2015 *(estimation in 2000)*	~ 2,000,000 (800,000)			~ $1,000B ($400B)		
2020 *(extrapolation)*	~ 6,000,000 (2,000,000)			~ $3,000B ($1,000B)		
Evolving Topics	*Research frontiers change from passive nanostructures in 2000-2005, to active nanostructures after 2006, and to nanosystems after 2010*					

updated Nano2 Report, 2010, p. XXXIII

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

- Estimation made in 2000 after international study in > 20 countries
- THE ESTIMATIONS ARE IN AGREEMENT WITH SURVEYS UNTIL 2010; then, LUX surveys larger in 2012 (world $731B, US $235B; ~40% annual increase)



Refs: Roco and Bainbridge, "Societal Implications.." 2001; and NANO2020, Fig 3

MC Roco, April 10 2014

Global revenue from nano-enabled products by sector

(Lux Research, updated in January 2016) (US / World ~ 32%)

Sector *(all in US$ Billion)*	**2012** (survey)	**2013** (survey)	**2014** (survey)
Building materials	$28.837	$44.564	$66.891
Materials & manufacturing	$457.936	$625.508	$826.704
Electronics & IT	$265.306	$377.631	$527.137
Healthcare & life sciences	$74.742	$103,350	$139,597
Energy & Environment	$25,668	$38.478	$55.737
Total (world)	**$853**	**$1,190**	**$1,616**
Annual Increase Rate (%)		*~ 35%*	*~35%*

Change in annual rates: from ~25% in 2001-2010 to 30-35% in 2011-2014

Papers and patent publications per million capita in the five regions

(Notations: M = million, /MC = per million capita)

Region	US	Japan	EU27	P.R. China	South Korea	Totals numbers
Population on July 1, 2017	*325M*	*128M*	*506M*	*1,410M*	*51M*	*(2,419 M)*
2016 papers /MC	84	60	78	37	185	19,003
2016 Top-three-papers /MC	1.04	0.25	0.40	0.04	0.35	516
2016 USPTO patents /MC	11.5	4.2	2.2	0.21	12.7	8,732
2015 WIPO patents /MC	20.7	23.1	4.2	18.8	53.3	42,822

Article citations by NSF Principal Investigators

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                                Individual 95% CIs For Mean Based on Pooled StDev
Level            N    Mean   StDev  -------+---------+---------+---------+--
NSF           3615   166.0   693.5                                     (*-)
IBM           1877    53.8   158.8               (*-)
TOP10        33071    27.0   160.2         (*
UC           10097    42.4   233.9             (*
US           85669    31.6   183.2            *
EntireSet   260880    26.2   147.1         (*
Japan        22358    24.2    85.5         *)
European    118429    20.5    94.9        *
Others       63654    15.1    74.5     (*
                                    -------+---------+---------+---------+--
                                          40        80       120       160
```

Chen at al. 2012 (Ref [8])

NSF-funded PIs (1991-2010) have a higher number of citations (166 in average) than researchers in other groups: IBM, UC, US (32 in average), Entire world Set (26 in average), Japan, European, Others

Number of patent citations by NSF P.I.-Inventors

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                                    Individual 95% CIs For Mean Based on Pooled StDev
Level          N   Mean   StDev     ---------+---------+---------+---------+
NSF         1887  30.93  113.90                                         (--*-)
IBM         3614  10.21   30.04               (-*-)
TOP10      14076  11.65   87.53                  (*)
UC          2497  10.29   35.08               (-*-)
US         96962   9.04   51.08               *)
EntireSet 140855   7.32   44.04             *
Japan      20562   3.43   19.43       (*)
European   20211   1.79    9.03     (*)
Others      8133   2.10    9.99     (-*)
                                    ---------+---------+---------+---------+
                                           8.0      16.0      24.0      32.0
```
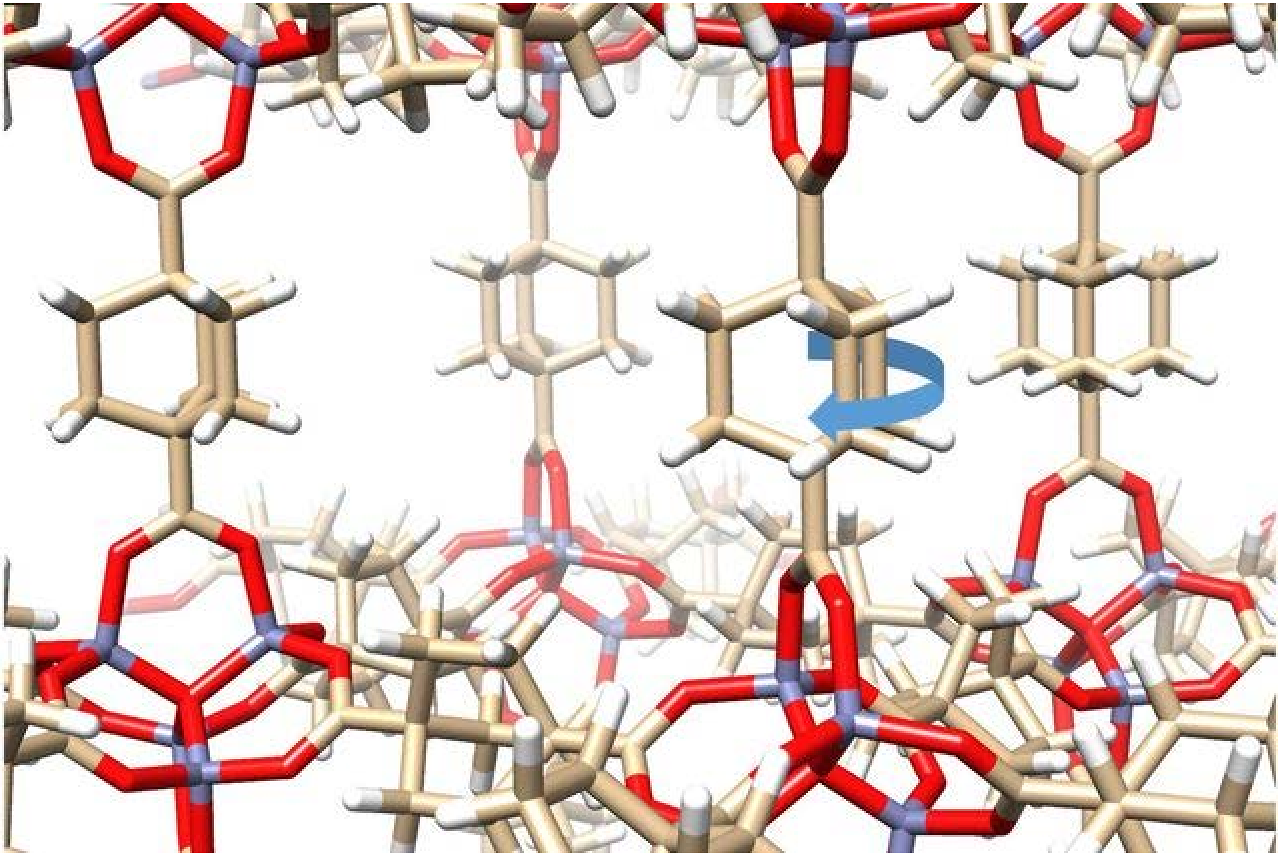

Chen at al. 2012 (Ref [8])

NSF-funded PI-Inventors (1991-2010) have more citations (31 in average) than inventors in the TOP10, UC, IBM, US (9 in average), Entire World Set (7 in average), Japan, Others, and European group

Example discovery in nanoscale materials

Gyroscope' molecules form crystal that has a solid exterior but contains moving parts

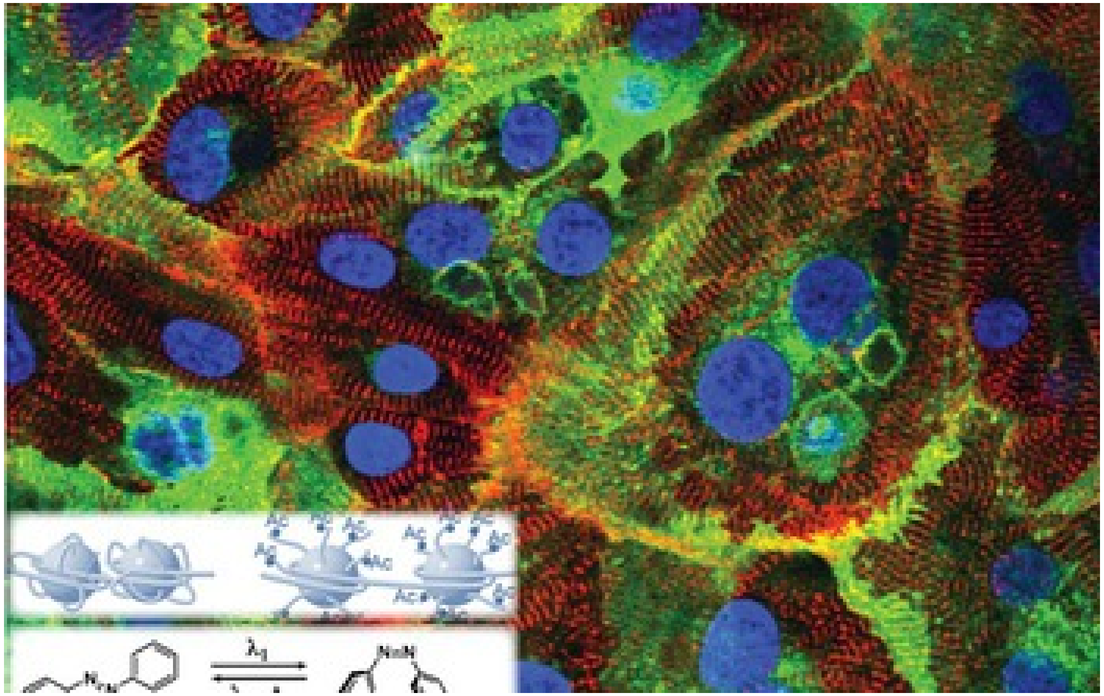


Credit: Miguel García-Garibay et al, Kendall Houk Laboratory/UCLA, 2018

Example discovery in nanobiology

Engineering biology through DNAs environment

Chromatin and Epigenetic Engineering (NSF 17-578 & 18-077)



Light-mediated epigenetic control at the nanoscale in human induced pluripotent stem-cell-derived cardiac muscle cells

Credit: R. Mazitschek, Mass General Hospital/Harvard U.; E. Entcheva and A. Villagra, GWU

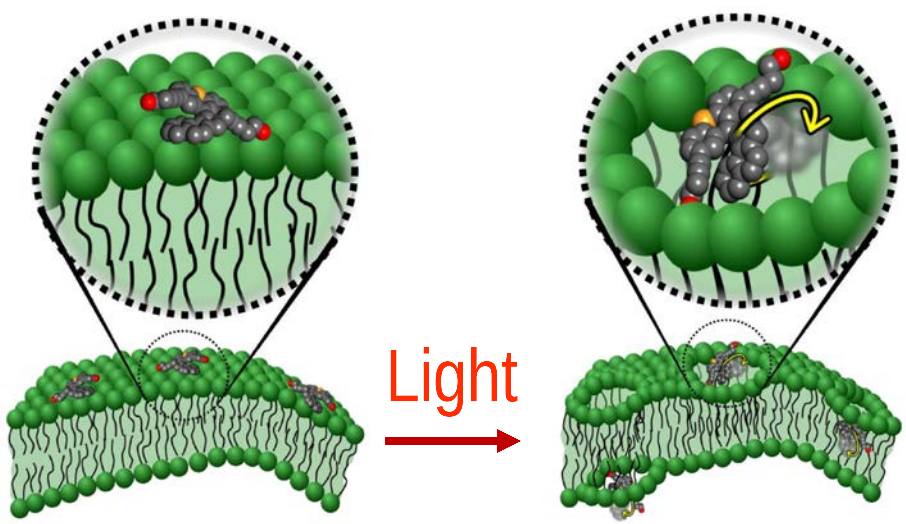
Example discovery in nanobio-medicine

Motorized molecules drill through cells

Motorized molecules driven by light can drill holes in the membranes of individual cells, promising to bring therapeutic agents into the cells or directly inducing the cells to die

Rotors in single-molecule nanomachines activated by ultraviolet light - spin at 2 to 3 million rotations per second

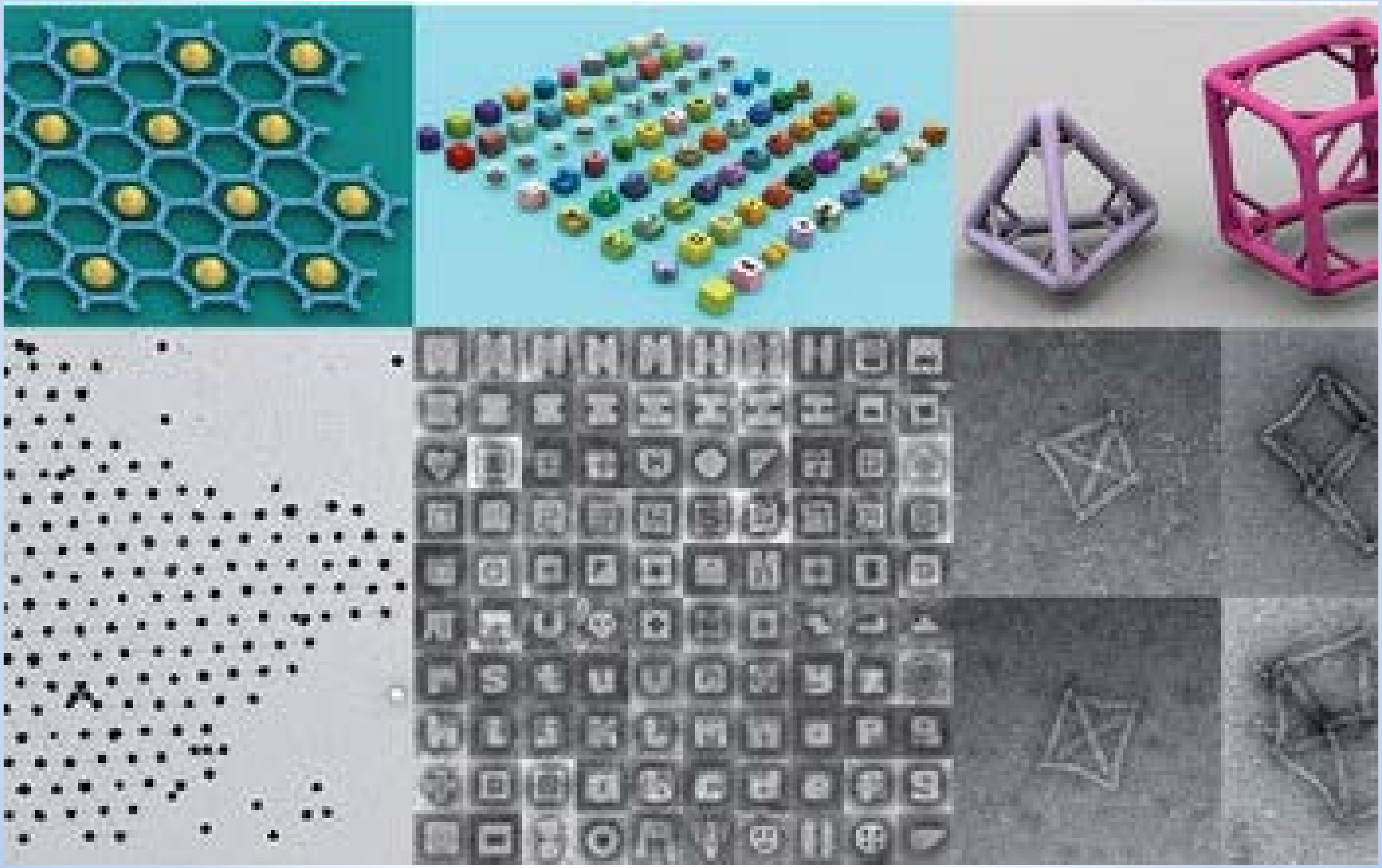
Credit: James Tour group, et al., Nature Aug 2017, Rice U., Durham (U.K.) and NCSU



Example discovery in nanobio-electronics

Creation of bio-based semiconductors (2018)

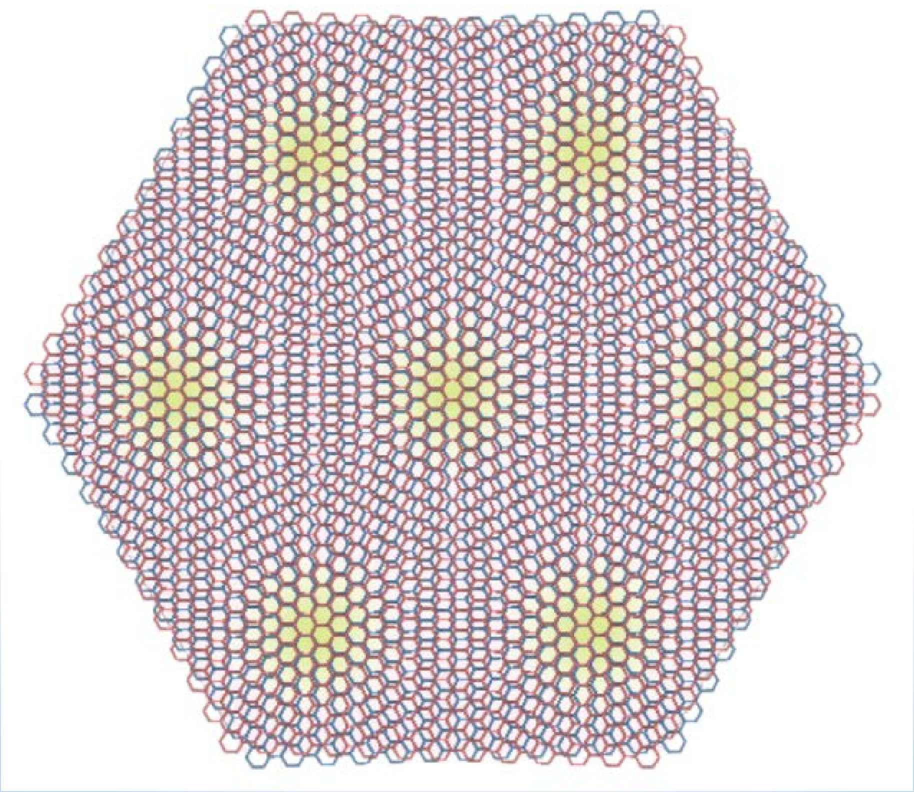
Program: SemiSynBio (Semiconductor Synthetic Biology)



Credit: Yonggang Ke, Emory University and Georgia Tech

Twistronics: rotating adjacent layers of materials
'Magic-angle graphene' in bilayer graphene that behaves like a high-temperature superconductor is *Physics World* 2018 Breakthrough of the Year

PABLO JARILLO-HERRERO, MIT



Simple hands-on simulation of moire patterns produced by twist angles in layered 2D materials -
leading to fine control of electrical properties.

A general trend:

Convergence of nano with other emerging fields

- NS&E discoveries on accelerated path; New spin-off fields *("push")*
- Setting visionary goals, via: National initiatives, Grand Challenges, Big Ideas, societal goals, risk governance goals *("pull"),*
- Integration of knowledge & innovation across fields *(need for "integration")*

Convergence is: a problem solving strategy to holistically understand and change an ecosystem for reaching a common goal

(Refs 1, 5)

Further defining S&T convergence

"Convergence of Knowledge, Technology and Society", 2013 et al (Refs 6-10)

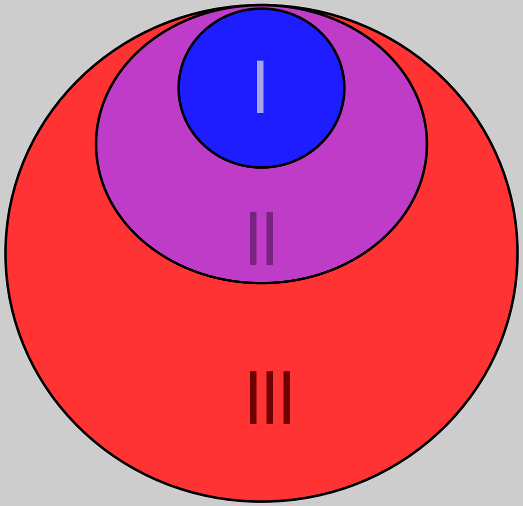
The convergence approach includes:

- ***Deep integration*** of knowledge, tools and modes of thinking driven by unifying concepts to a common goal
- ***To form*** a new framework, paradigm or ecosystem
- ***From where emerge*** novel pathways and opportunities

Convergence science includes:

guiding principles and methods,
to facilitate efficient convergence to a goal

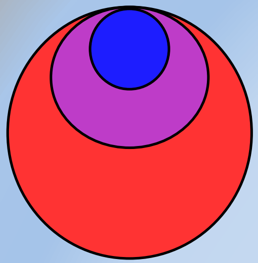
Three hierarchical stages of ST&I *convergence*



I Nanotechnology (N)

II Foundational fields (NBICA)

III Society ecosystem (CKTS)



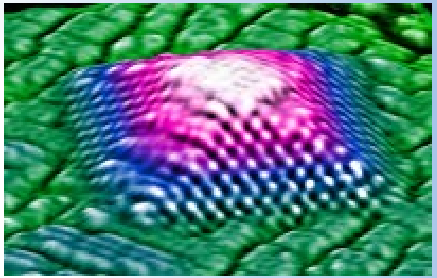
Three stages of convergence

of foundational, general-purpose S&T fields

(Refs 3 to 6, Springer, 2000-2013)

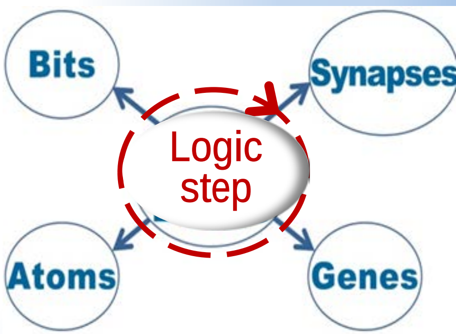
I. Nanoscale Science, Engineering and Technology: "Nanotechnology"

<u>Integrates disciplines</u> and knowledge of matter from unifying concepts at the nanoscale



II. Nano-Bio-Info-Cognitive-AI foundational Converging Technologies: "NBICA"

<u>Integrates foundational and emerging technologies</u> from unifying, basic elements using similar system architectures and dynamic networking



III. Convergence of Knowledge, Technology and Society: "CKTS"

<u>Integrates the essential platforms of human activity</u> using seven convergence principles

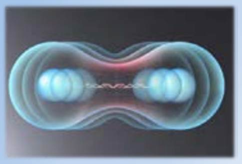

I. Nanotechnology programs: S&T divergence
OSTP
DOE
HHS/NIH
OSTP
OMB
NSF
DOD
DOC/NIST
HHS/FDA
NASA
USDA/NIFA
USDA/ARS
HHS/CDC/
NIOSH
USDA/FS
phys
DOS
EPA
Control of
matter at the
nanoscale
DOTr
neur
bio
NRC
DOT
DOC/
USPTO
chem
IC/DNI
DOI/
USGS
DOJ
DOL
DOC/EDA
DOC/BIS
DHS
CPSC
ITC
DOEd
U.S. National Nanotechnology Initiative, 2000-2030

Ex I. **Nanotechnology Spin-offs**

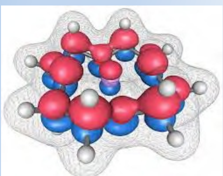
- Quantum systems - *Quantum S&T 2003; NQI 2018*
- Metamaterials - 2004
- Plasmonics – 2004
- Synthetic biology - 2004
- Modeling / simulation - *Materials Genome Initiative 2011*
- Nanophotonics - *National Photonics Initiative 2012*
- Nanofluidics
- Carbon electronics
- Nano sustainability
- Nano wood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

Ex I. Quantum information systems

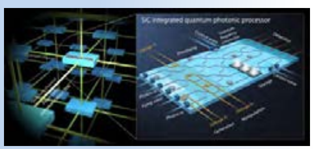
NSF contributions in NNI core and “The Quantum Leap” ($31 million in 2018)



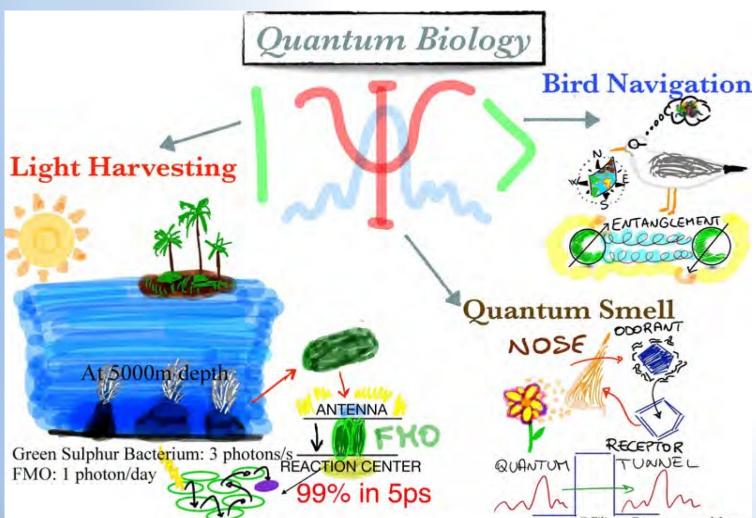
- <u>Fundamental science</u> (particle entanglement, collective coherence, squeezing)



- <u>Understanding natural and engineered quantum systems</u> (emergent particle behavior, transition quantum/classical, system complexity)



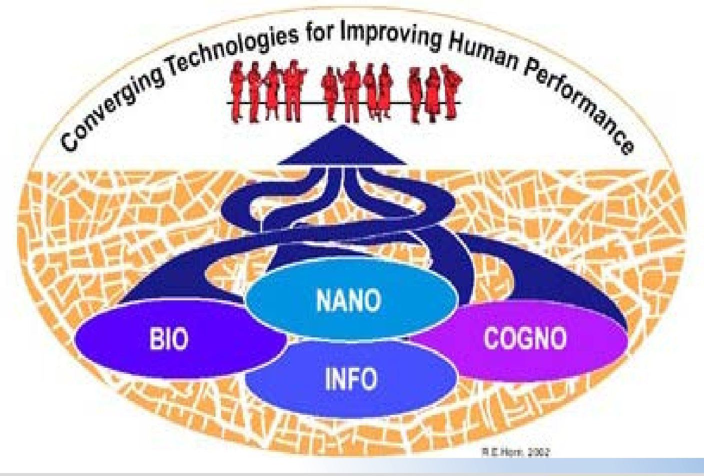
- <u>Technologies and devices</u> (quantum materials, nanoscale sensors and metrology, quantum communications and computing, devices, architectures and control)



[Filippo Caruso (Lindau Meeting, 2016)]

- <u>Env-Bio occurring and engineered quantum ecosystems</u> (quantum biology, dispersions, others)

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



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

NBICA 2015: added "systems *Artificial Intelligence*" as a foundational emerging field affecting human performance

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

Converging foundational technologies (NBIC) leads *to*

II. U.S. emerging S&T initiatives

OSTP

Brain–like Computing; Smart systems

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

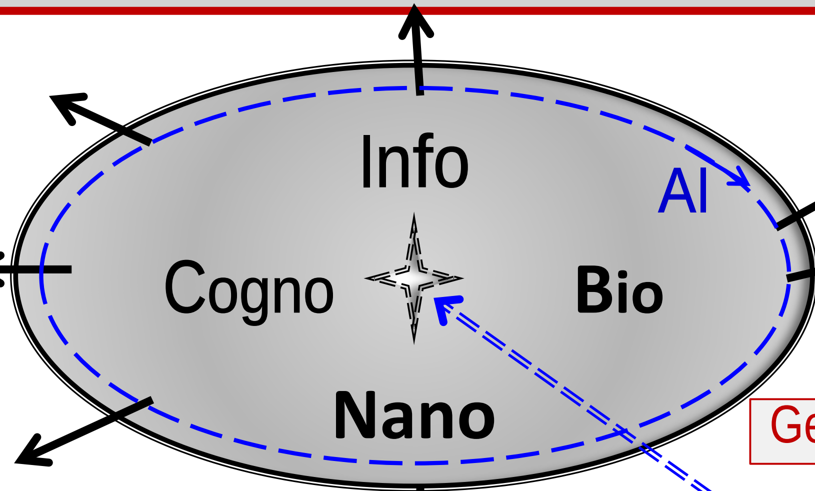
National Information Technology R&D

(nitrd.gov)(with coordinating office)

Artificial Intelligence

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

National Robotics Initiative



Biology centered

Biomedical / Health focus

Precision Med

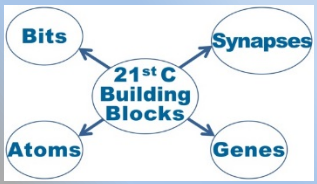
Genome(s) | Microbiome

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

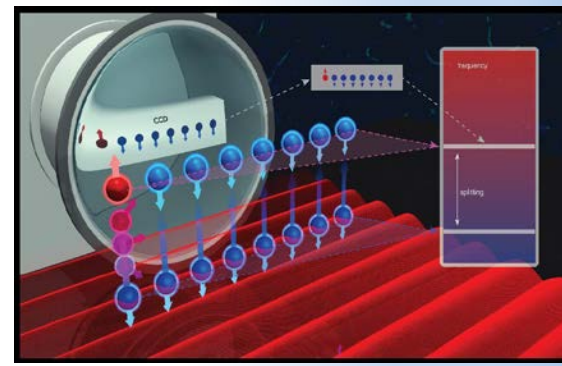
Ex II. Examples of NBICA domains (2005-2019) with U.S. National Science Foundation awards

- **Quantum information science** (IT; Nano and subatomic physics; System approach for dynamic/ probabilistic processes, entanglement and measurement)
- **Eco-bio-complexity** (Bio; Nano; System approach based on molecular mechanisms, evolutionary mechanisms; interface between ecology and economics; epidemiological dynamics)
- **Neuromorphic engineering** (Nano, Bio, IT, neurosc.)
- **Cyber-physical systems** (IT, NT, BIO, AI, others)
- **Synthetic biology** (Bio, Nano, IT, neuroscience)
- **Brain-like computing** (neuroscience, IT, NT, Bio, psychology)
- **General purpose AI systems** (NBICA)

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

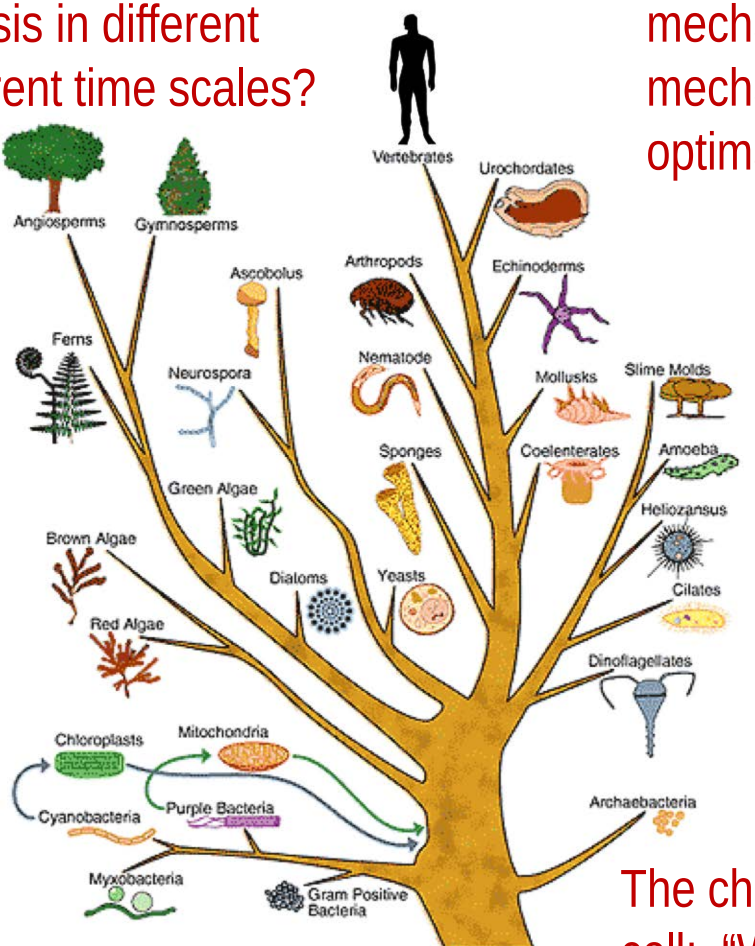
What different mechanisms enable adaptation and homeostasis in different environments and at different time scales?

What are the set of constant mechanisms and the set of variable mechanisms that comprise the optimal solution to life's challenges?

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

What mechanisms of signaling are used between cells and between organisms, and how do they change as a function of time and length scales and in diff. environments?

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



What is the minimal cell?

The challenge to build a synthetic cell: "What I cannot create, I do not understand." – Richard Feynman

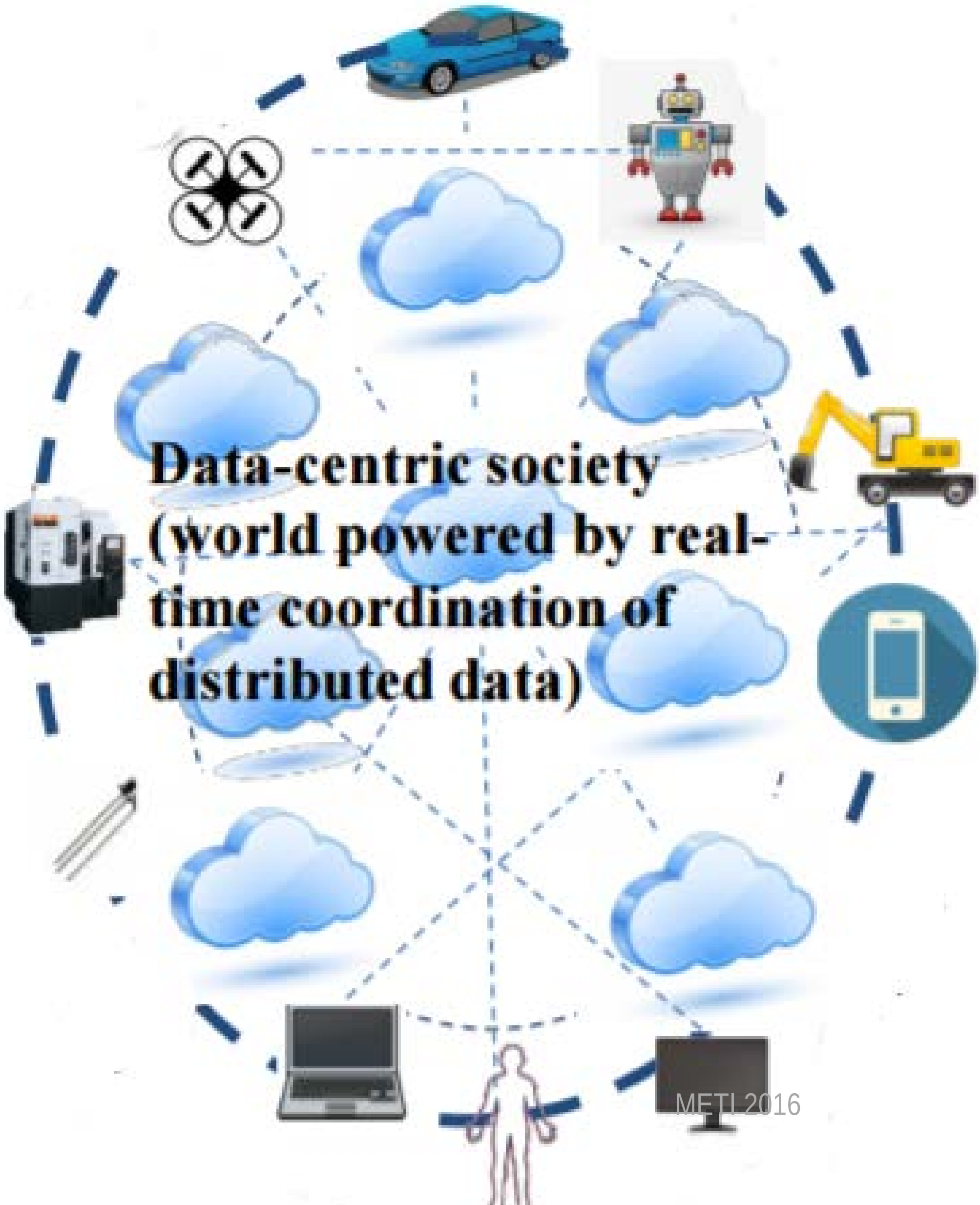
Understanding from the nanoscale, "synthetic cells", nanobiosystems

Ex II. Smart Systems programs with nanotechnology components

- National Robotics Initiative (NRI)
- Cyber-Physical-Social Systems (CPS)

  Integration of intelligent decision-making algorithms and hardware into physical systems
- Human-Centered smart service systems
- Smart and Connected Communities

Ex II: **IoT with Nanosensors**



Nanotechnology for Sensors

www.nano.gov/SensorsNSIPortal

Goals:

1 nm sensors self powered

Wireless networked links

Distributed network

Cyber-Physical Systems

Ex II: "<u>Brain like computing</u>" (NNI Grand Challenge)

combining National Nanotechnology Initiative (NNI), National Strategic Computing Initiative (NSCI) & BRAIN Initiative

- *Nanotechnology-Inspired Grand Challenge for Future Computing* (DOD, DARPA, DOE, IARPA, NSF), announced by OSTP on Oct 21, 2015

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

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

OSTP

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

SunShot GC (DOE..)

Climate Action Plan

Navigating the New Artic

Smart and Connected Communities

I-Corps

Innovation

Aging Population

Global Change Research Program

(Global Change.gov) (with coord office)

Societal

Earth *Human*

NBIC+

STEAM Education Initiative

Asteroid GC (NASA..)

Space Station (NASA..)

Windows to Universe (NSF)

Productivity, Sustainability, Equality, Safe

Advanced manufacturing:

National Network for Manufacturing Innovation (NNMI)

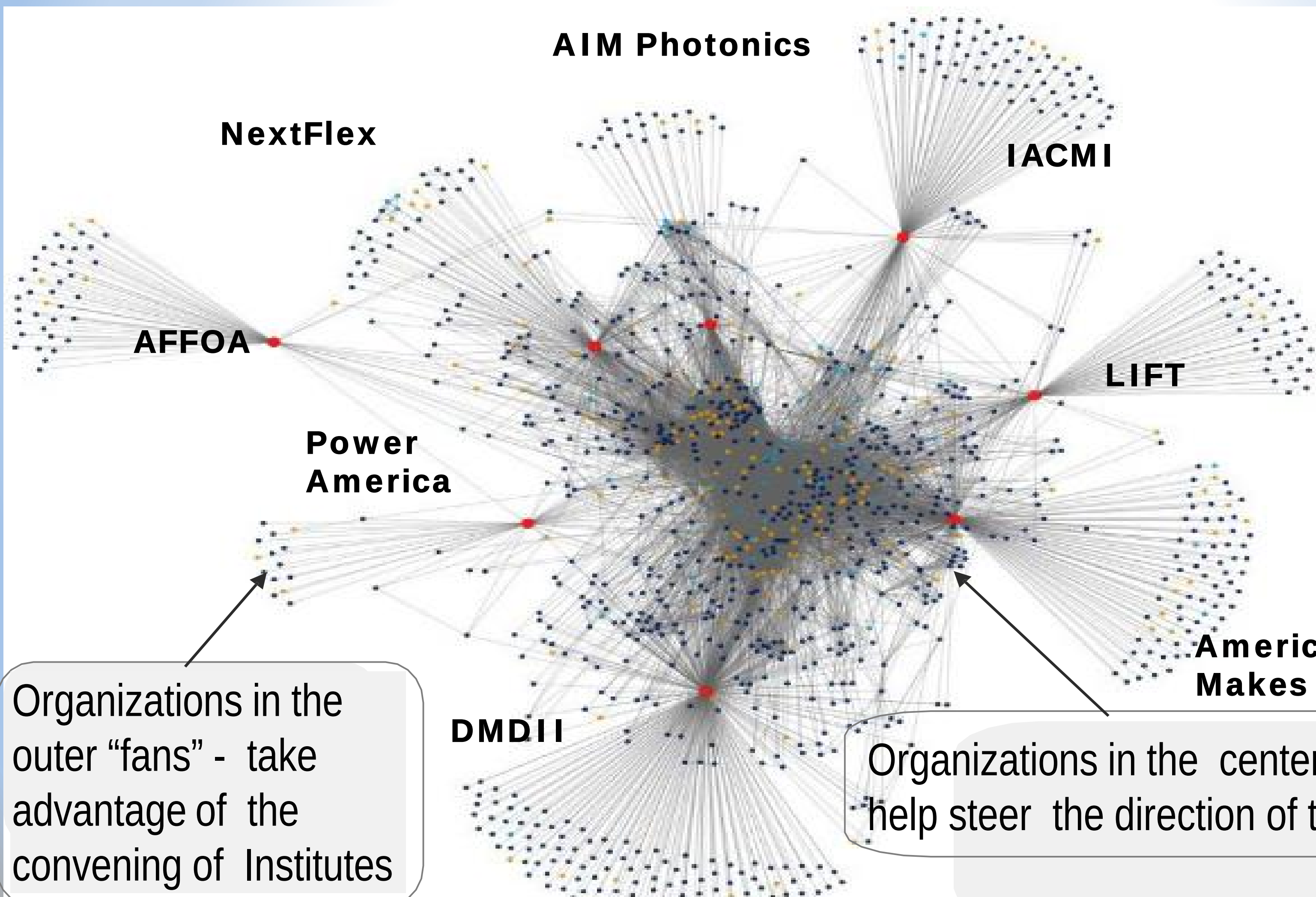
(http://www.manufacturing.gov/nnmi)

“Principles and methods that facilitate convergence” (Ref 8)

Ex III: 14 Manufacturing USA Institutes

Deloitte evaluation report (2017):

The Power of Connections is a Key Advantage



Addressing the "valley of death"

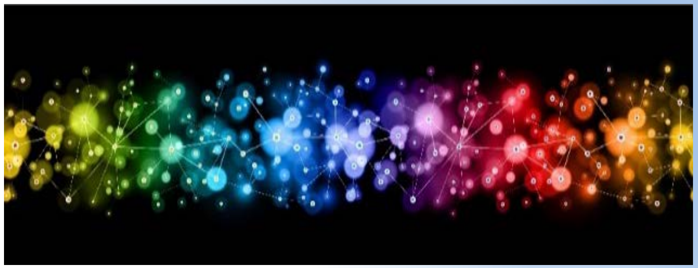
~ 1,200 core organizations in an inter-industry Network comprised of > 9,000 organization networked/ coordinated

Organizations in the outer "fans" - take advantage of the convening of Institutes

Organizations in the center of the network - help steer the direction of the network.

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

- Mid-scale Research Infrastructure

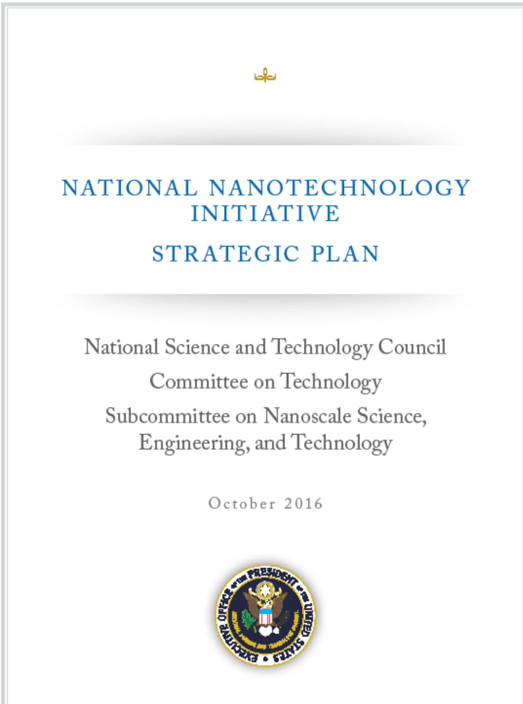
Ex III: **WH-OSTP Industries of the Future**

(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**

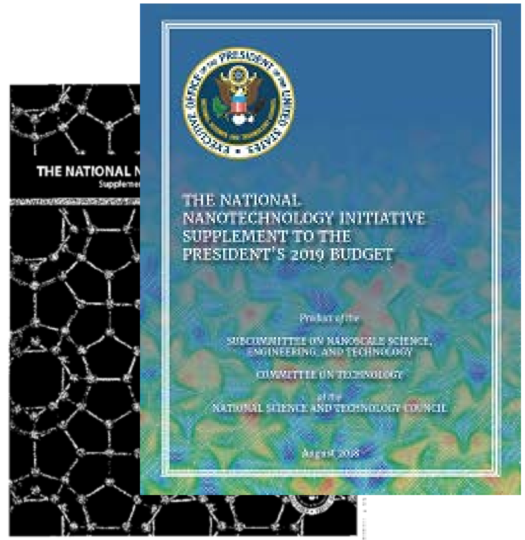
NNI at NSF in 2019

I. National Nanotechnology Initiative in 2019



2016-2019 NNI Strategic Plan approved by WH and 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

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 2018 Budget planned: $421 M

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

– Fundamental research
  > 6,000 **active projects** in all NSF directorates
  (# increases ~15% first decade, then ~ constant, with qualitative changes)

– Establishing the infrastructure
  > 30 **centers & networks**, 2 general user facilities

– Training and education
  > 10,000 **students and teachers/y**; ~ $50M/y

Several NSF NSE awards in FY 2017-2019

(1) From solicitations dedicated to NSE www.nsf.gov

- National Nanotechnology Coordinated Infrastructure, NNCI
- Network for Computational Nanotechnology, nanoHUB et al.
- Scalable nanomanufacturing, SNM (2017), Adv Manu (2018-)
- "Two-Dimensional Atomic-layer Research and Engineering, 2-DARE"; "Advancing Communication Quantum Information Research in Engineering (ACQUIRE)" & "NewLAW", 2017-19
- NSE in Nexus of Food, Energy, and Water ("INFEWS")
- NSE in Understanding the Brain ("UtB")
- NSF Nanosystems Eng. Res. (water filtration, biomedicine)
- International nano-EHS collaboration: US (NNI)-EU (EC) Communities of Research (7COR http://us-eu.org/)

Several NSF NSE awards in FY 2017-2018

(2) From core programs www.nsf.gov

- Core research in: BIO, CISE, E.H.R., ENG, GEO, MPS, SBE
- Materials Research Science and Engineering Centers (MRSEC); Nanotech Engineering Research Centers (NERC)
- Science and Technology Centers (STC) (Ex: UCB, Harvard U., MIT-GA Tech, U. Colorado-Boulder, U. Penn), $5M/year
- Other centers in core programs (Ex: Center for Sustainable Development of Nanotechnology in CHE)
- Environmental, Health and Safety (EHS) (~5% of NSF NNI)
- Part of Converging Knowledge, Technologies & Society (CKTS)
- Translational: GOALI; I/UCRP; PFI; Nano-ERC; I-Corps

Examples of NSF programs (2018-2019)

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

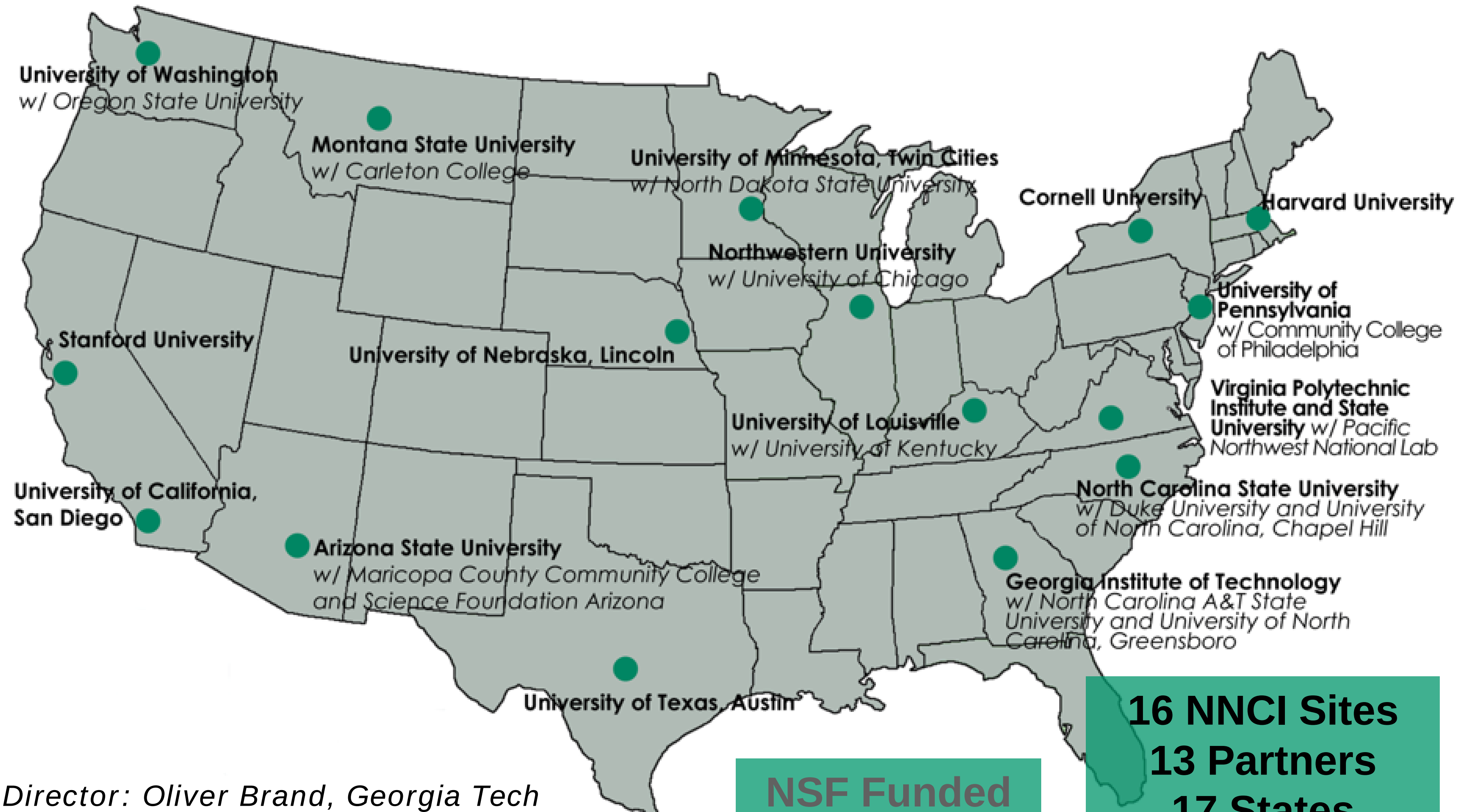
Energy-Efficient Computing: from Devices to Architectures (E2CDA)

- Radical new approaches – from new devices architectures to hybrid digital-analog designs
- Partnership between NSF (ENG and CISE) and Semiconductor Research Corporation (SRC)

Examples:

- 2D Electrostrictive FETs for Ultra-Low Power Circuits & Architectures,
- Energy Efficient Computing with Chip-Based Photonics,
- Energy Efficient Learning Machines,
- Self-Adaptive Reservoir Computing with Spiking Neurons: Learning Algorithms and Processor Architectures

National Nanotechnology Coordinated Infrastructure (NNCI)



Director: Oliver Brand, Georgia Tech

NSF Funded
2015-2020
$81M total

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

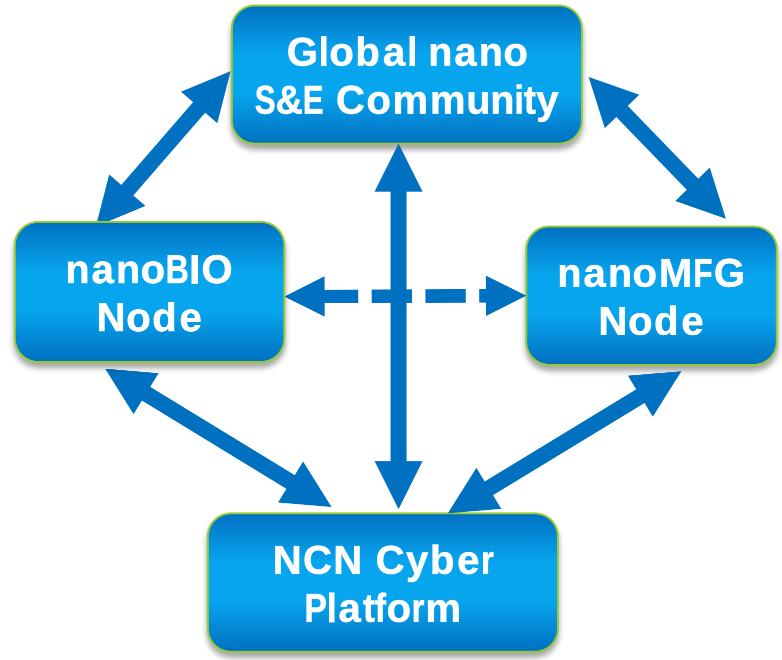
NEHI and ELSI Research and Programs in the NNCI

- NNCI has four main sites that do work researching, training, and communicating some of the social and ethical issues raised by and inherent to Nanoscale S&E:
  - North Carolina State University
  - Arizona State University
  - University of Texas at Austin
  - Northwestern University
- Their goal: "integrating research on societal, ethical, and environmental concerns with nanotechnology research and development, and ensuring that advances in nanotechnology bring about improvements in quality of life for all Americans"

National Nanotechnology Coordinated Infrastructure

Network for Computational Nanotechnology (NCN)

nanoHUB



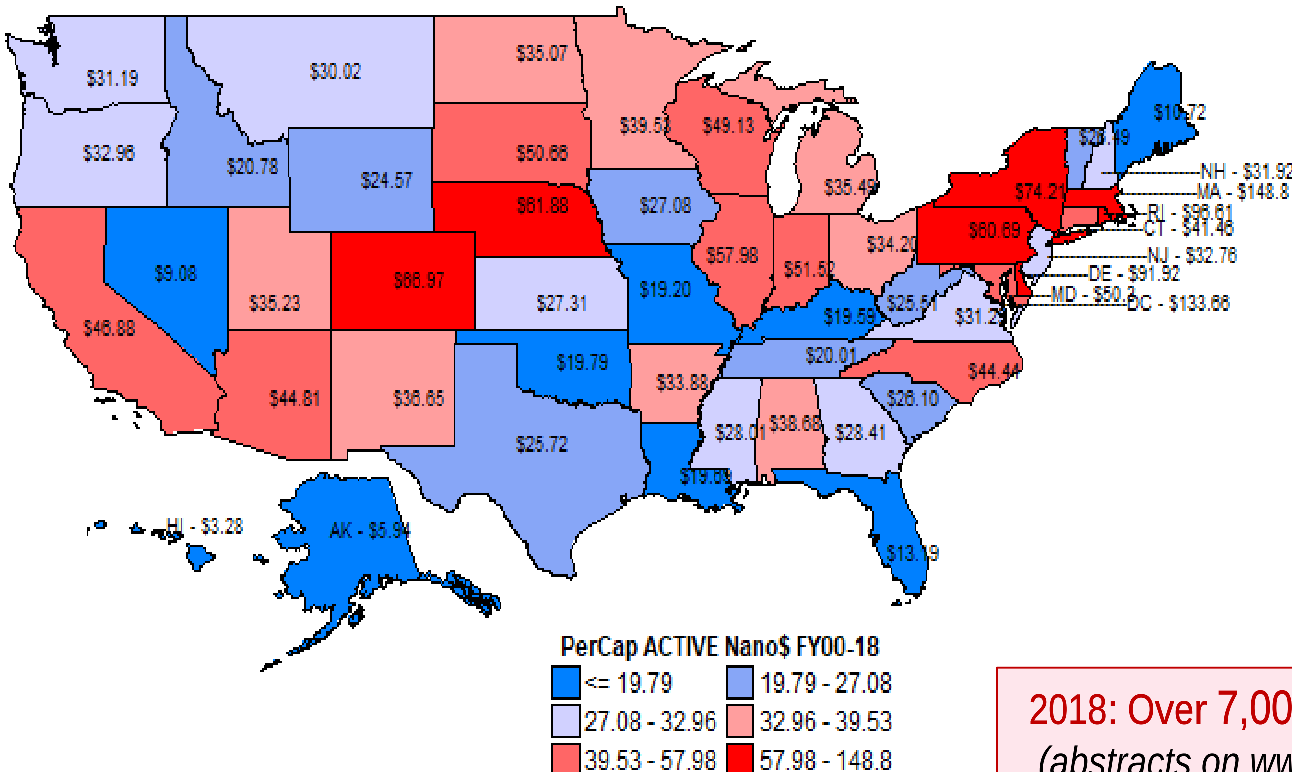
Cyberinfrastructure: 500+ nano-Apps in the cloud

5,500+ lectures and tutorials 100+ courses => MOOC 185 institutions

Director: Gerhard Klimeck, Purdue U.

NSF's NS&E amount new awards per capita

FYs 2000 - 2018: U.S. average amount <u>~ $41 /capita</u>

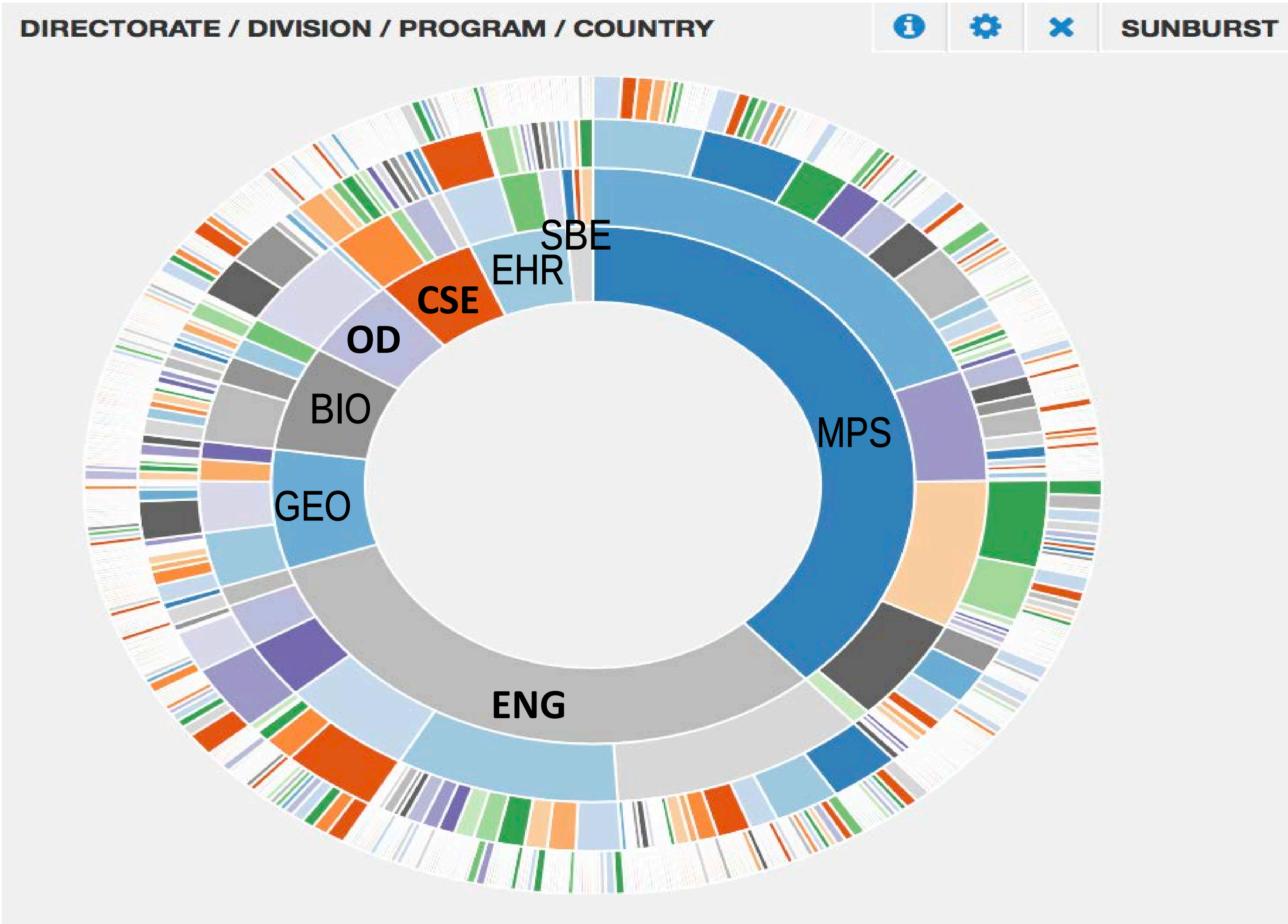


2018: Over 7,000 active awards
(abstracts on www.nsf.gov/nano)

<u>#1 MA $149 / capita (2000-2018)</u>

AK 5.93; AL 38.68; AR 33.88; AZ 44.81; CA 46.88; **CO 66.97** ; CT 41.45; **DC 133.66** ; **DE 91.92** ; FL 13.19; GA 28.41; HI 3.27; IA 27.08; ID 20.78; IL 57.98; IN 51.52; KS 27.31; KY 19.59; LA 19.69; **MA 148.80** ; MD 50.30; ME 10.72; MI 35.49; MN 39.53; MO 19.20; MS 28.01; MT 30.02; NC 44.44; ND 35.07; **NE 61.88**; NH 31.92; NJ 32.75; NM 36.65; NV 9.08; NY 74.21; OH 34.20; OK 19.79; OR 32.96; **PA 60.69** ; PR 20.10; **RI 96.61** ; SC 26.10; SD 50.66; TN 20.01; TX 25.72; UT 35.23; VA 31.23; VT 26.49; WA 31.19; WI 49.13; WV 25.51; WY 24.57

Awards in Nano with International Activity (21%)



Dec 4, 2018;
http://dis-checker-p02:8002/solr/banana-sankey/dist/index.html#/dashboard

Related/interacting nano-inspired programs in other NNI agencies

- DARPA: Atom to Product

  http://www.darpa.mil/work-with-us/opportunities

- DOE: Atomically Precise Manufacturing

  https://science.energy.gov/sbir/funding-opportunities/

- NIH: Image Guided Drug Delivery (PAR 16-044)

  http://grants.nih.gov/grants/guide/pa-files/PAR-16-044.html

- Other opportunities NIST, NIOSH, USDA, …

New responsibilities, and opportunities

Context

- ✓ Increased size & complexity of nanostructures – *higher uncertainties, opportunities and risks*
- ✓ Integration with other emerging fields: quantum S&E, AI, synthetic biology, … – *new goals and implications*
- ✓ Accelerating innovation – *new methodologies*

- Relative increase of importance - Nano ELSI vs Nano EHS;
  - Societal sustainability
  - Human development aspects (needs, human values)
- International challenge - Uneven development per regions,
  - *Collaboration & competition*

Several trends *(1)*

- **Generalized theories, models and tools** for larger nanostructures (with complex information contents and interacting phenomena), and control of fundamental processes (such as self-assembling and quantum transition)
- Hierarchical, modular, nano-precise **NBICA integrated design and manufacturing**
- **Nanotechnology for sustainability:** recyclability, water, energy, food, improve carbon-cycle
- **Nano-controlled gene editing** for medicine, agric., energy

Several trends *(2)*

- Brain–to-brain, -machine, -like devices and systems
- Hardware for quantum entanglement, communication and computing
- Nanotechnology for smart systems: general purpose AI & Intelligence Augmentation (IA); Intelligent Cognitive Assistants, cyber-physical-human systems; personalized education, healthcare and other services.
- Convergence with other foundational technologies to create new emerging S&T platforms

Related publications

(5 reports with R&D recommendations for 2020)

1. *"Coherence and Divergence of Megatrends in Science and Engineering" (Roco, JNR, 2002)*
2. *"Nanotechnology: Convergence with Modern Biology and Medicine", (Roco, Current Opinion in Biotechnology, 2003)*
3. *NANO1: "Nanotechnology research directions: Vision for the next decade" (Report OSTP/WH, 1999, also Springer, 316p, 2000)*
4. *NANO 2020: "Nanotechnology research directions for societal needs in 2020" (Springer, 690p, 2011a)*
5. *NBIC: "Converging technologies for improving human performance: nano-bio-info-cognition" (Report sponsored by NSF & DOC, Springer, 468p, 2003)*
6. *CKTS: "Convergence of knowledge, technology and society: Beyond NBIC" (Report sponsored by six NNI agencies; 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, 2016)*