Progress in Convergence: Basic Concepts and Applications

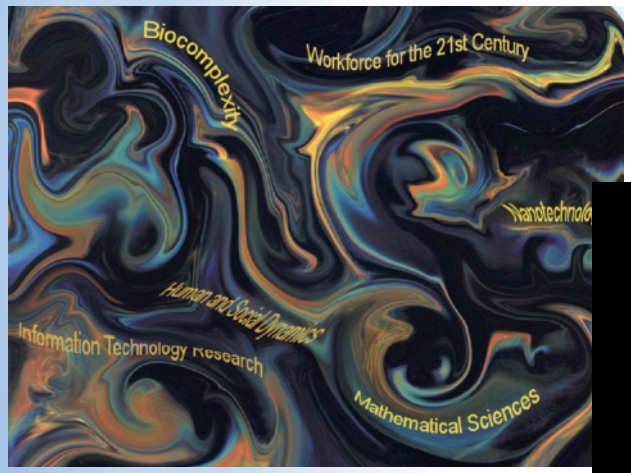
Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative

RED Convergencia Congress, Mexico City, August 17 2017

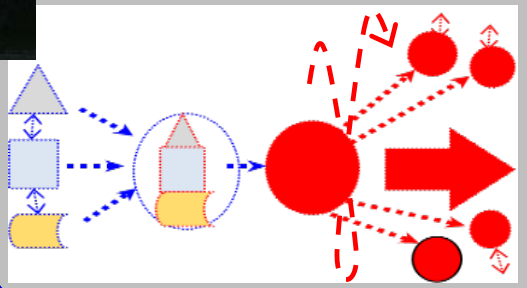
Evolution in nature, science, technology, society is

- ***Turbulent***
- ***Coherent***
- ***Emergent***



S&T trends

(Ref. 1-5, Roco 2002)



Convergence approach is a general strategy to holistically understand and transform

Convergence is a core opportunity for progress

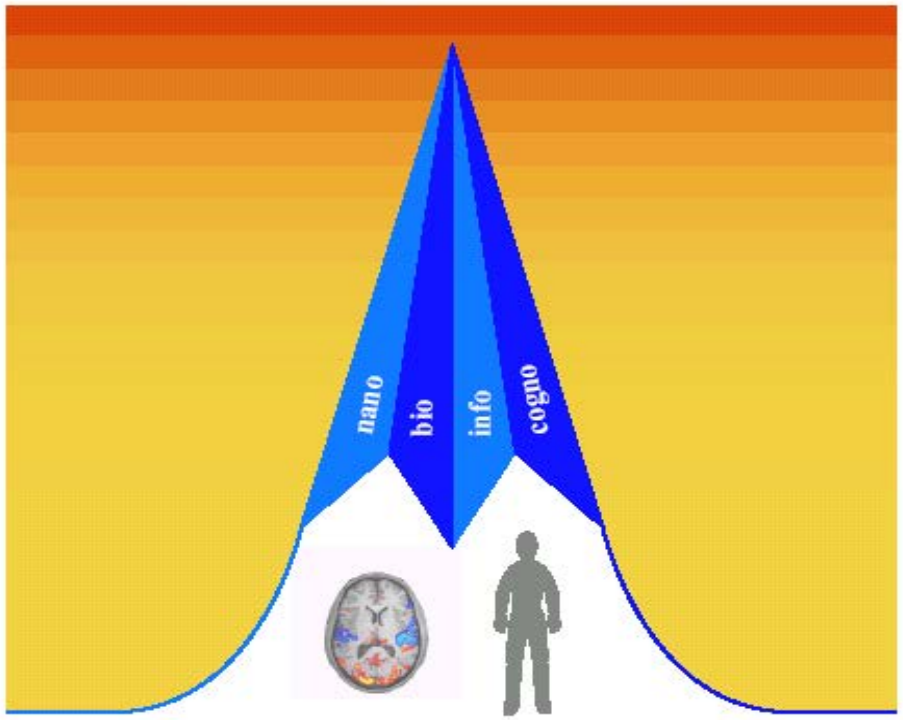
Making the case

- ✓ Defining convergence
  in science, technology and innovation
- ✓ Basic Concepts
  theory, principles and methods
- ✓ Applications and trends
  convergence for general purpose technologies, production, research & education, governance

Earlier studies on technology convergence

Seven reports on convergence

2003, 2006 and 2007 Springer; 2004 NYAS; NSF 2004; 2013 (world view), 2016 (handbook)



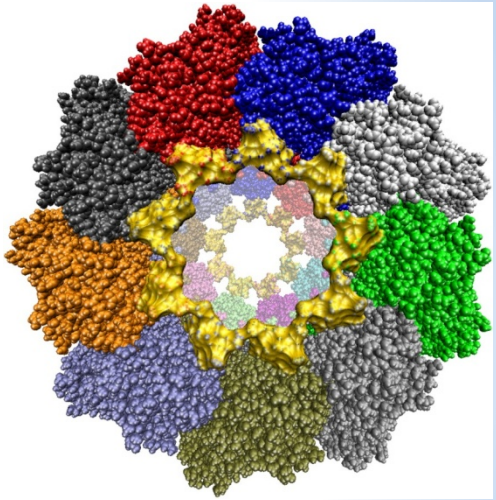
CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

Workshop, Dec. 2001
Volume Springer, 2003

Ref. 5

Coevolution of Human Potential and Converging New Technologies



In: Annals of the New York, Academy of Sciences, Vol. 1013, 2004

(M.C. Roco and C. Montemagno)

Convergence: timely, broad opportunity

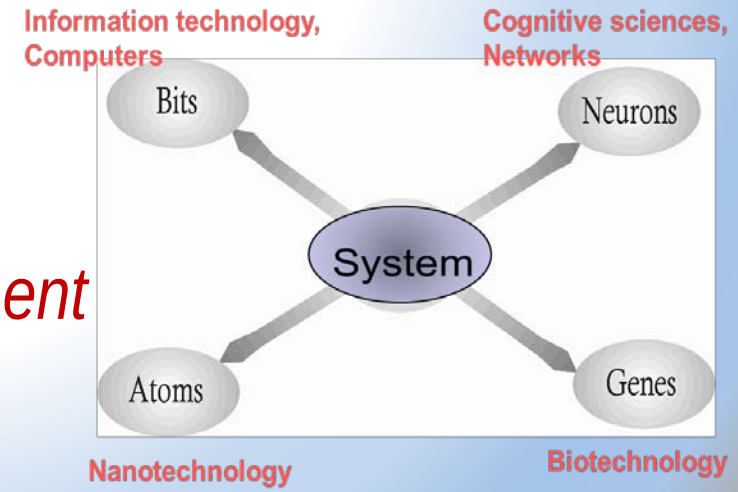
after 2000

- Material unity at the nanoscale and technology integration from the nanoscale, "science beyond the Renaissance ideal"
- Powerful transforming tools (nano-bio-info-cogno-AI system) and technology platforms developing concurrently at the confluence of disciplines, integrated from the nanoscale
- Towards an "universal domain of exchange" for ideas, etc.
- Improvement of human potential becomes possible
- New social relations (adapting organizations and business)
- New opportunities for innovation; for anticipatory, holistic and adaptive governance measures ('Learning before doing')
- Needs for increasingly interacting and more crowded world

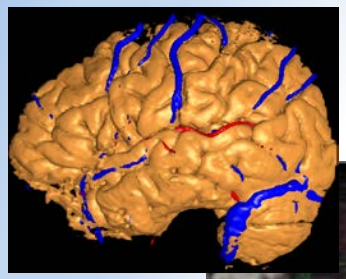
Refs: 1,2,and 5

Twelve challenging ideas from 2001 NBIC Report that are reality or in development in 2017

- Hierarchically interconnected world – *a reality in 2015*
- Non intrusive brain-to-brain communication – *accepted*
- Computer Personal advisor – as laptop or cell – *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 NBIC - *modules*
- Intelligent environments – *in development*
- ELSI community – *organized in 2013*



Vision of the world as a distributed, interconnected "brain" with various architectural levels- cybernet



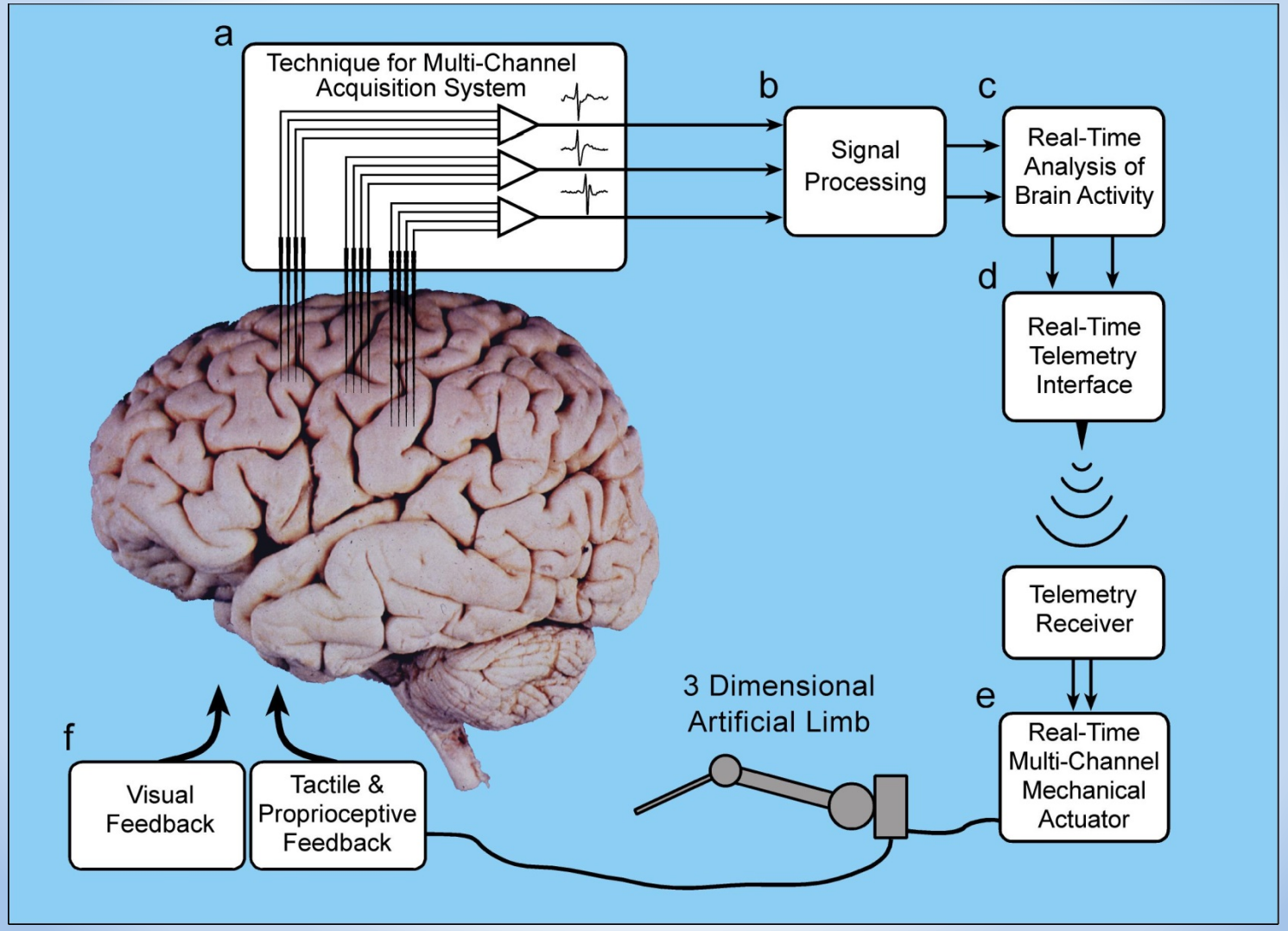
Based on individual rights to privacy, access and progress

(NBIC Report, 2001 / 2003) (Ref. 5)

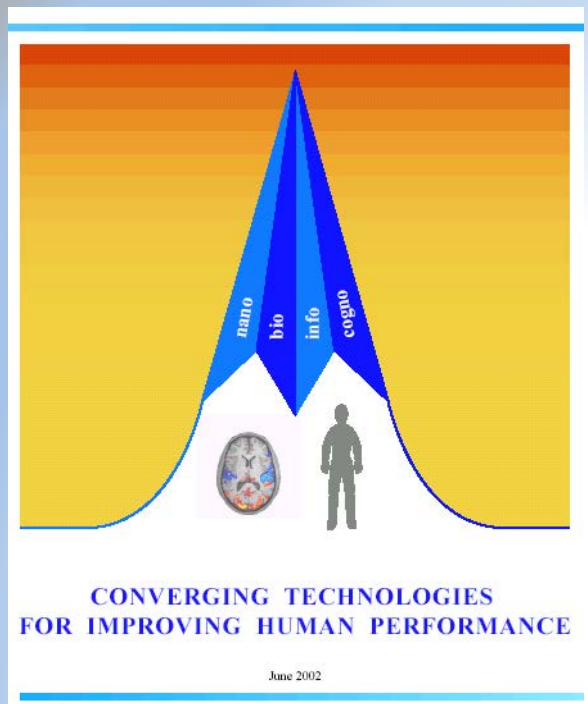
Closed loop control brain-machine interface

Neuroprosthesis for restoring motor function of damaged brain areas

Duke University and MIT



(NBIC Report, 2001 / 2003) (Ref. 5)



Nature (2002): 'too exploratory'

"Futurists predict body swaps for planet hops"

"Direct brain-to-brain communication and the transfer of minds between bodies seem more like the stuff of Hollywood movies than of government reports — but these are among the advances forecast in a recent report by the US National Science Foundation and Department of Commerce.

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

NATURE|VOL 418 | 25 JULY 2002 |www.nature.com/nature

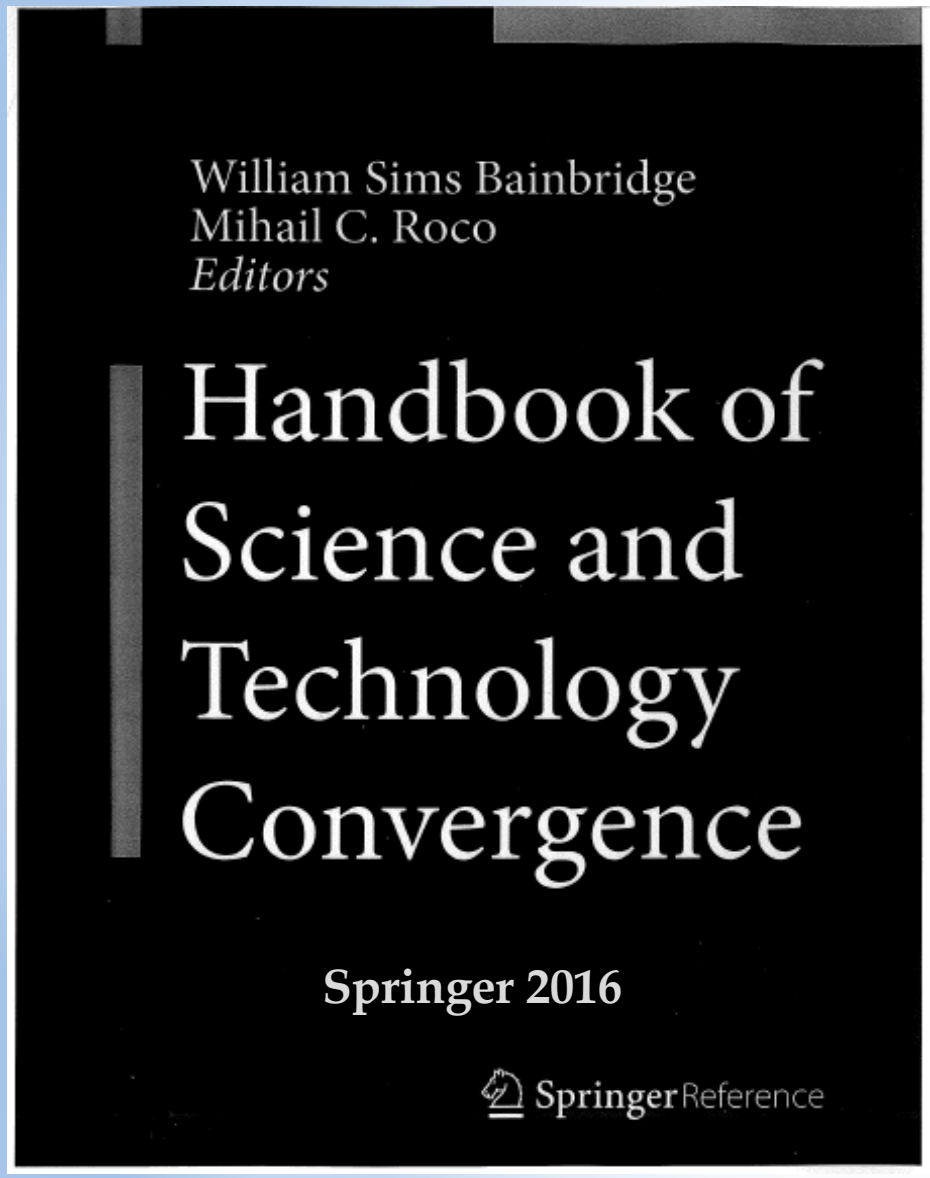
WH/OSTP (2003): 'too transformative'

Convergence of Knowledge, Technology, and Society:

Beyond Convergence of Nano-Bio-Info-Cognitive Techologies

Springer 2013; *www.wtec.org/NBIC2-Report;* M. Roco et al.

INTERNATIONAL BENCHMARKING
of METHODS and APPLICATIONS



Convergence principles and methods

applied to:

science and technology, research and education, and various societal applications

Ref. 10

Defining convergence

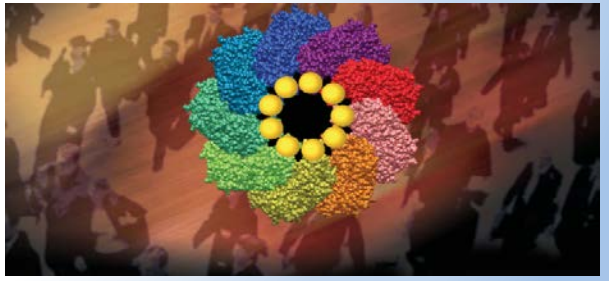
1. Defining S&T convergence

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

Convergence is deep integration of knowledge, tools, domains and modes of thinking, driven by common goal

- leading to a unified framework or ecosystem -
  that allows to answer questions, resolve problems and build things that isolated capabilities cannot *(convergence stage of changing the system),*

- that creates new pathways, opportunities and frontiers
  – in competencies, knowledge, technologies and applications *(divergence stage)*



Convergence science – Creating or changing the unified ecosystem based on *10 theories, 6 convergence principles, and specific methods*

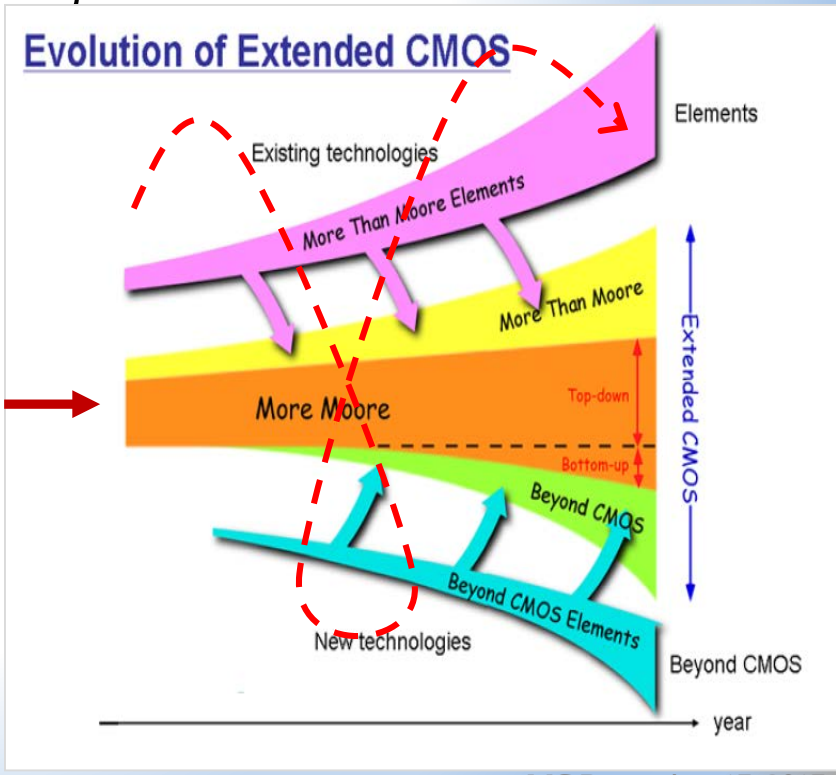
2. The convergence process

(Ref 6: CKTS, Springer, 2013)

Convergence process is the escalating and transformative interaction of seemingly different disciplines, technologies, application domains, and communities

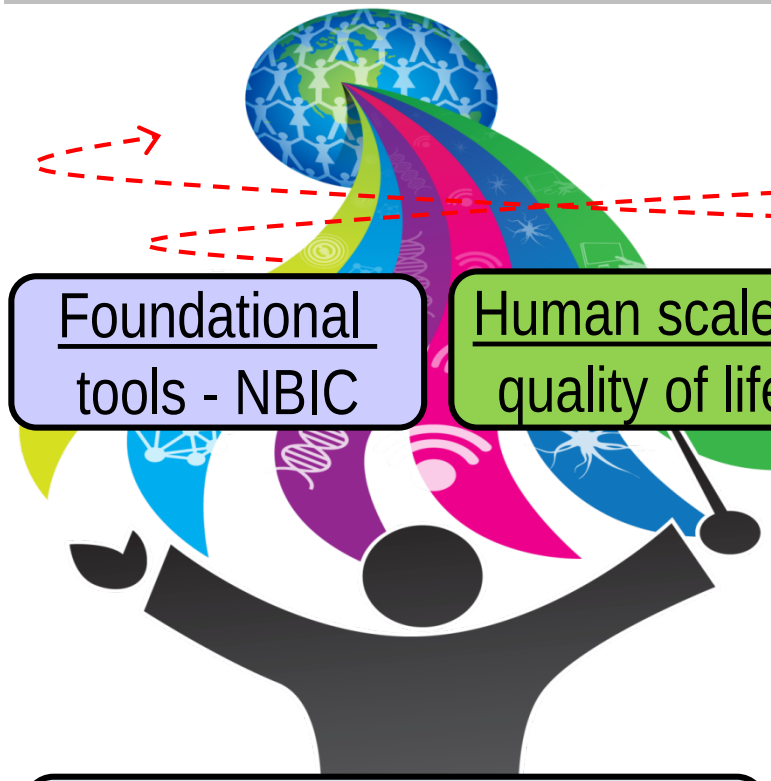
(it is a dynamic process)

- to achieve their mutual compatibility, synergism and integration,
- and through this process to *create added-value* and *branch out* for shared goals *(driven by the convergence driver)*



3. Convergence of five human activity platforms

For societal benefit,
Progress in human development



Earth scale platform

Foundational tools - NBIC

Human scale & quality of life

Societal scale platform

Innovative & responsible system behavior (governance)

Societal values and needs

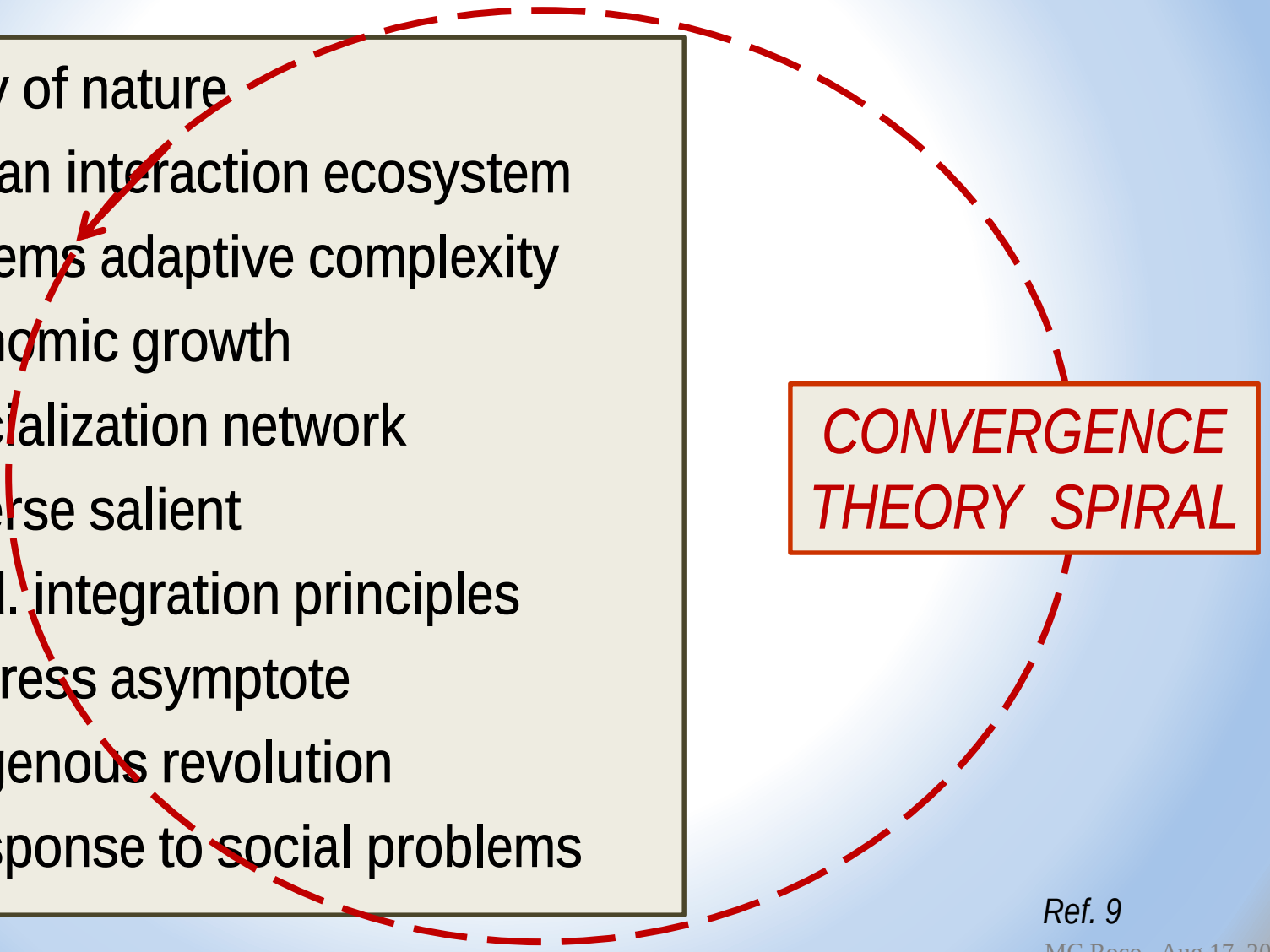
The conductor suggests societal governance of K&T converging platforms for societal benefit.

Current opportunities for production, cognition-, biomedicine- convergence

CKTS, Springer, 2013 (Ref. 6)

4. Convergence is realized in conjunction with *ten theories*

1. Unity of nature
2. Human interaction ecosystem
3. Systems adaptive complexity
4. Economic growth
5. Specialization network
6. Reverse salient
7. Fund. integration principles
8. Progress asymptote
9. Exogenous revolution
10. Response to social problems



Ref. 9

5. Convergence of knowledge, technology and society is guided by six general principles

A. The interdependence in nature and society

B. Evolutionary processes of convergence and divergence

C. System-logic deduction in decisions

D. Higher-level cross-domain languages

E. Confluence of resources leading to system changes (S curve)

F. Vision-inspired basic research for long-term challenges

PRINCIPLES FOR CONVERGENCE

Ref. 8

A. Interdependence principle
in nature, technology and society

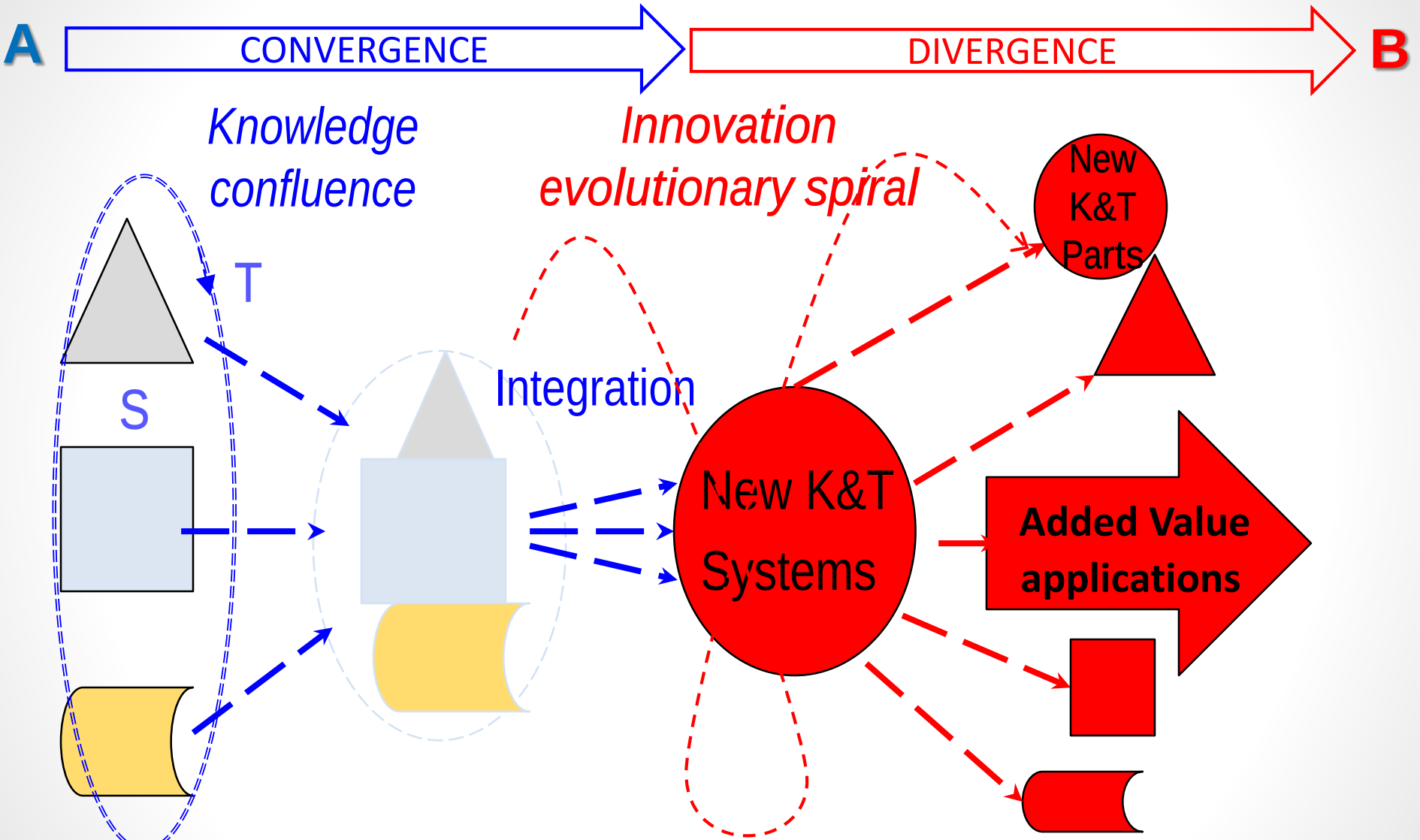
The interdependence:

- determines coherence of processes in the system:
  structuring, transformation, convection, diffusion
- determines system changes:
  changing the links, nodes, and overall system in time
- requires system view w. team approach: team science

Examples

- Communication across cells in a tissue or organism (ecosystem)
- Changing the manufacturing / enterprise: from vertical and large to more distributed and specialized because of the connectivity
- Societal polycentric system
- Circular solutions in science and economy

Evolutionary processes of convergence and divergence in S&T



The spiral is driven by the added-value goal through the convergence of domains S, in the external context ENV (imagine a "**tornado**" or "**hurricane**" with surrounding air flow and Earth rotation). After Refs. 1 (Roco 2002) and 6 (CKTS Report 2013)

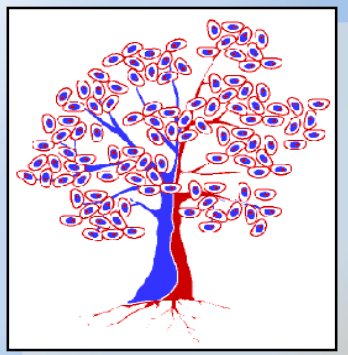
B. Convergence-divergence Evolutionary Process

A typical process in Science and Technology development

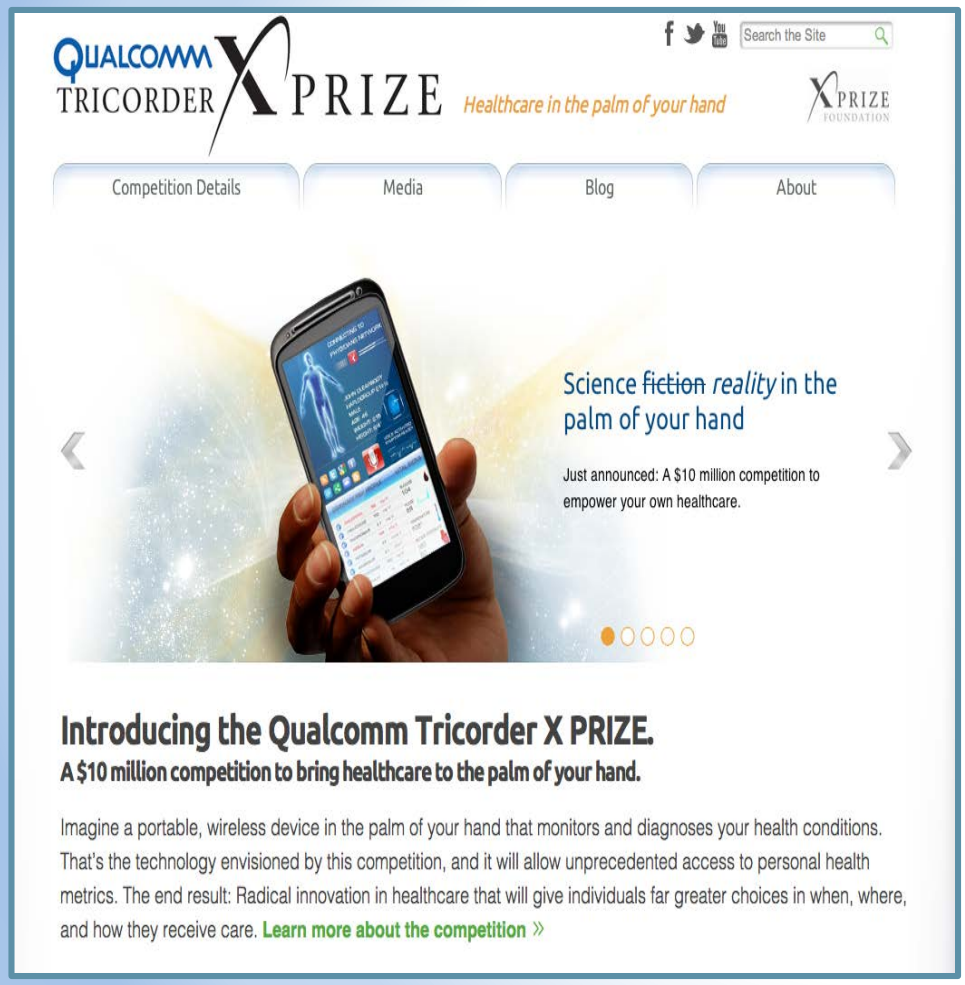
It consists of four phases
(cause-and-effect confluence of fields and methods driven by a goal):

- *creative assembling* of contributions from multiple fields leading to new concepts or ideas,
- *system integration* leading to a new assembly or invention for known uses,
- *technological innovation* outputs leading to new products and applications, and
- *spin-off outcomes* that lead to solutions not possible before and that produce new competencies, tools, and applications.

Examples: Biological life cycle; Tree growth with roots branches; Decision-making and problem solving; in art – the "Endless Column", "Divergent" social movie; Megatrends in S&T programs; Cell phone



Example convergence-divergence opportunities: cellular phone



http://www.qualcommtricorderxprize.org

Coincidental convergence:

- **Creative phase**: Confluence energy, environment, cognition, security, electronics, personalized learning, healthcare.
- **Integration phase**: Including high-frequency communications and packet switching protocols; data storage, touch screens, antennas, and cognitive science and human–computer interface technologies
- **Innovation phase**: Smart phone and its platform, form groups
- **Outcomes, spin-off phase**: Social networks, controlling swarms, inexpensive miniaturized satellites, healthcare and many other examples affecting virtually every aspect of our society.

Innovation index in a convergence process

$$I \sim k(S,E)\, S^2\, O / T^3 \qquad (1)$$

I - potential increase of outcomes as a function of the process characteristics (innovation index describing augmentation of the effects or convergence intensity)

T - time scale for the convergence–divergence cycle (~ information exchange)

S – the size of the convergence domain from where information is collected (the domain circumscribed by the innovation spiral, or the number of disciplines or application areas intersected by the circumferential spiral, in the activity system)

O - outcome ratio between the output and input; O/T – divergence angle (diffusion coefficient)

k - coefficient of proportionality (a function of convergence domain S and external context E)

Particular cases of (1) are: (a) "Metcalf's Law" (the value of a network scales as the square of the number of nodes (S^2) in network; Shapiro and Varian 1999); (b) "Moore's law" in the semiconductor industry (The proportionality with the (O/TT) agrees with the exponential growth of technological developments); (c) The rate of technology diffusion (The remaining (1/T) term)

(Ref 6: CKTS Report 2013)

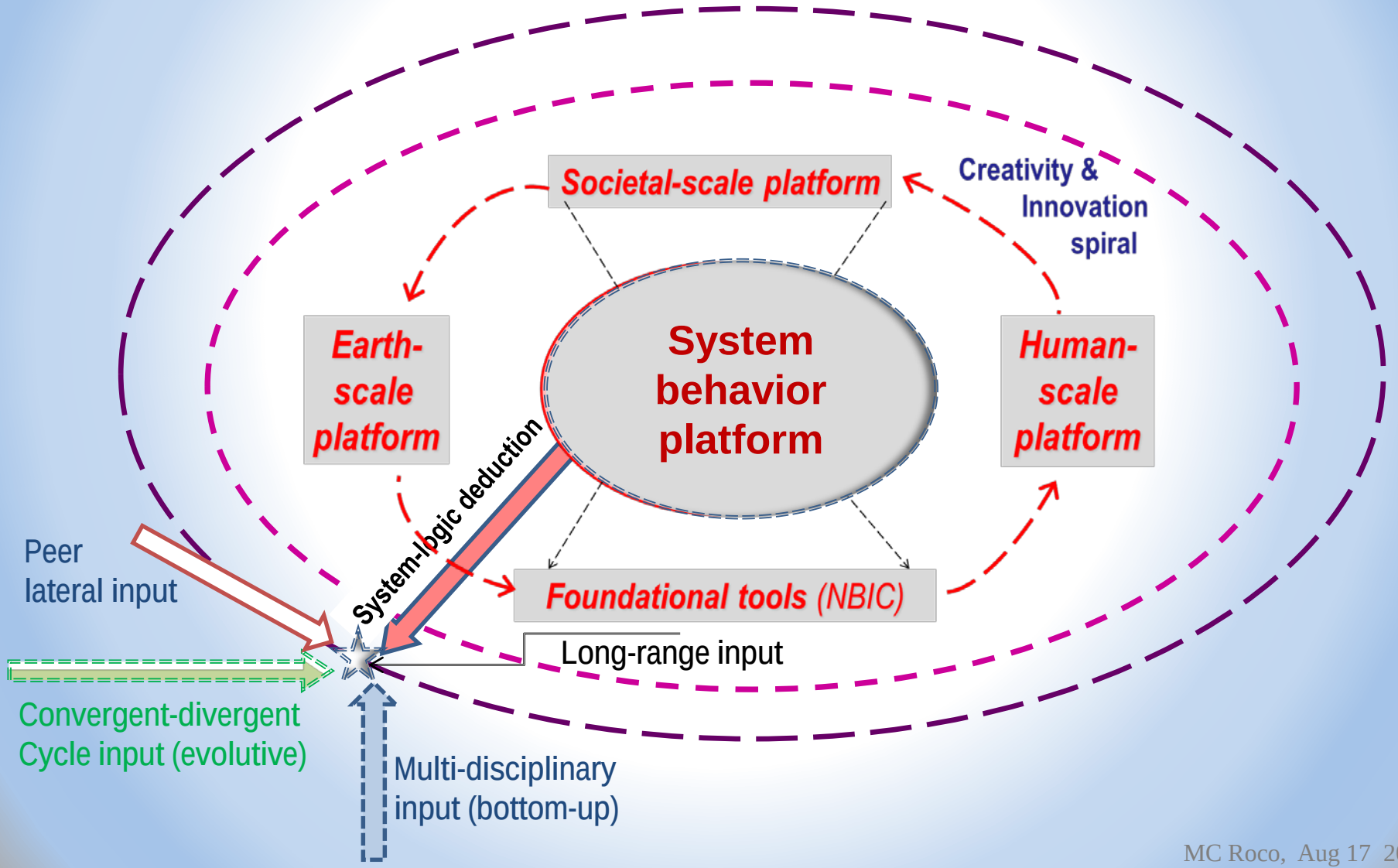
“Endless Column”, sculpture by C. Brancusi (1937)

Convergence-divergence elements

CKTS Report, brochure, 2013

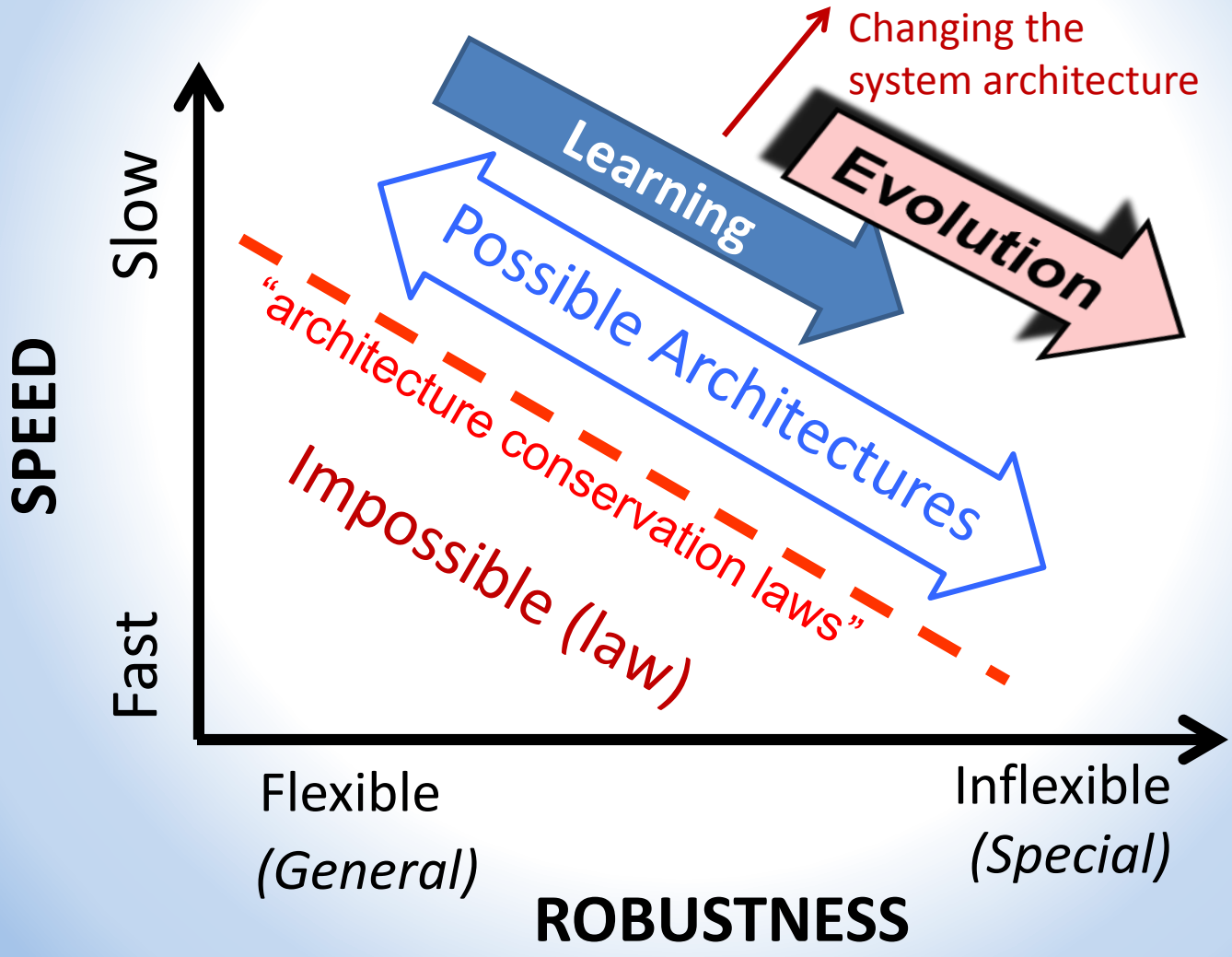
C. System-logic Deduction in decision making and problem solving

Results are better if larger system with faster information circulation



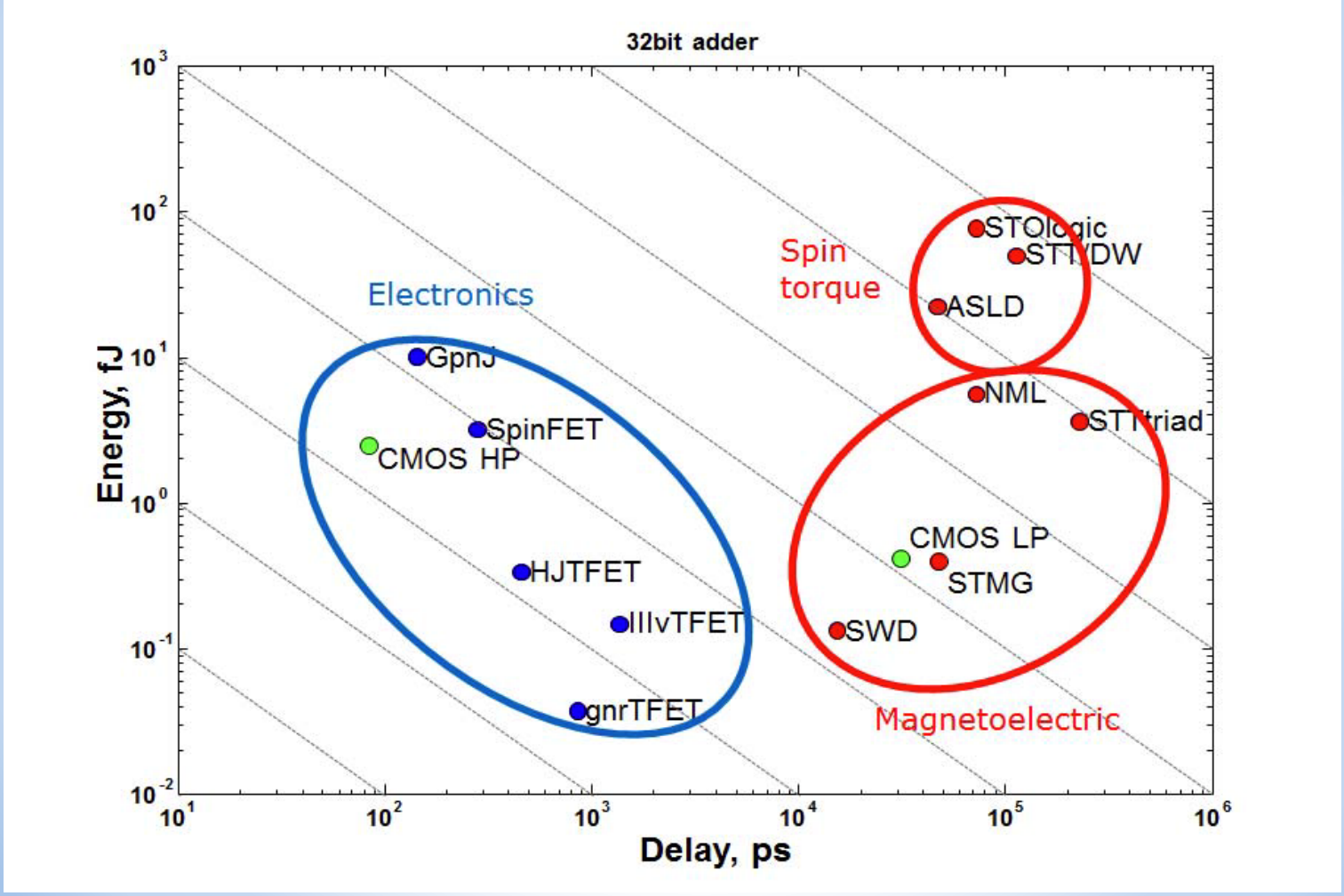
D. Example higher level multi-domain languages
Universal laws for system architectures

(Ref. 8, 2015, based on concepts suggested by Turing; Doyle and Csete)



D. Example higher level multi domain languages:

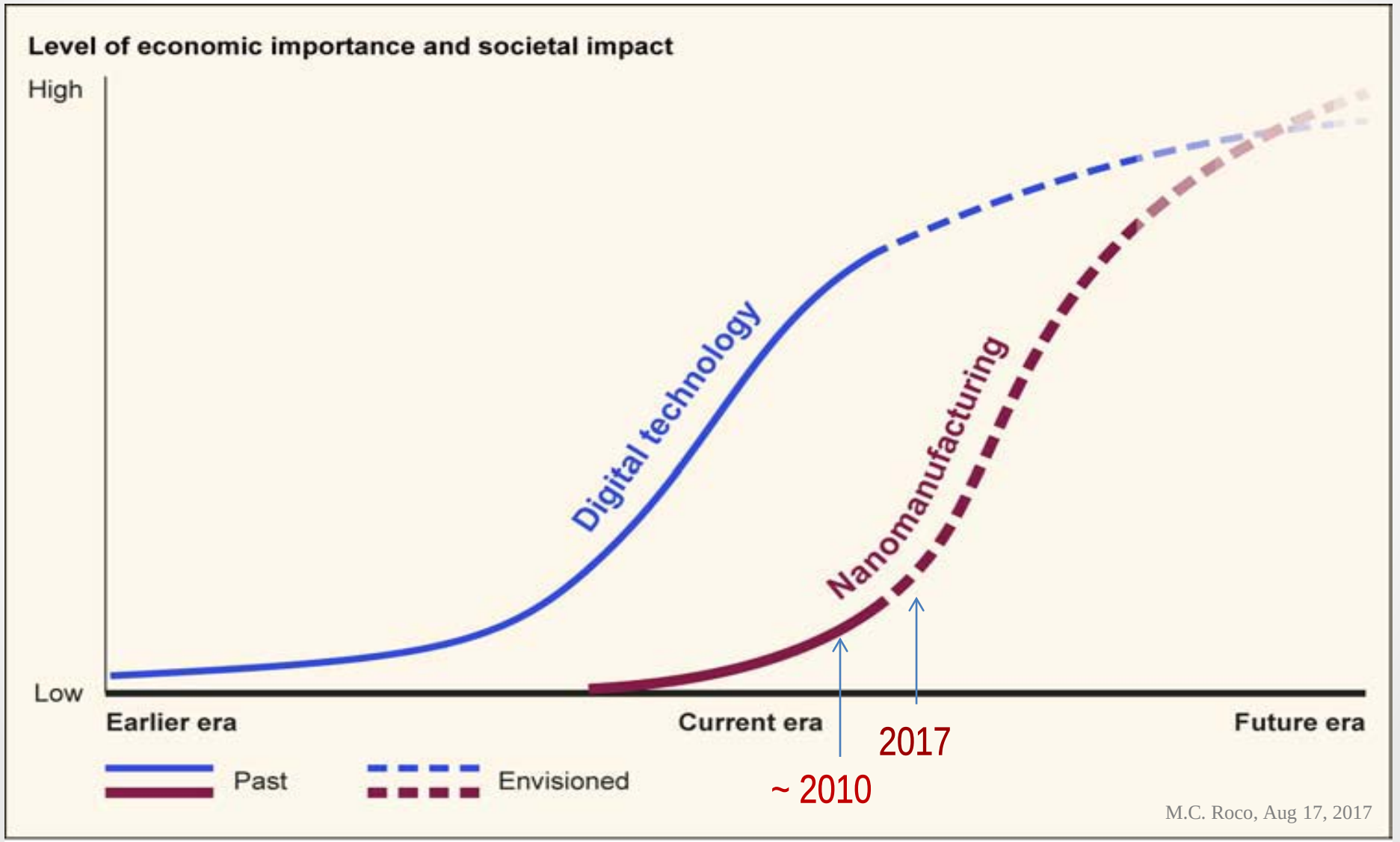
Universal characteristics for performance benchmarking of semiconductors: *Energy – Delay*



Nanoelectronics Research Initiative, 2013; Nikonov and Young, Proc. IEDM, Dec. 2012

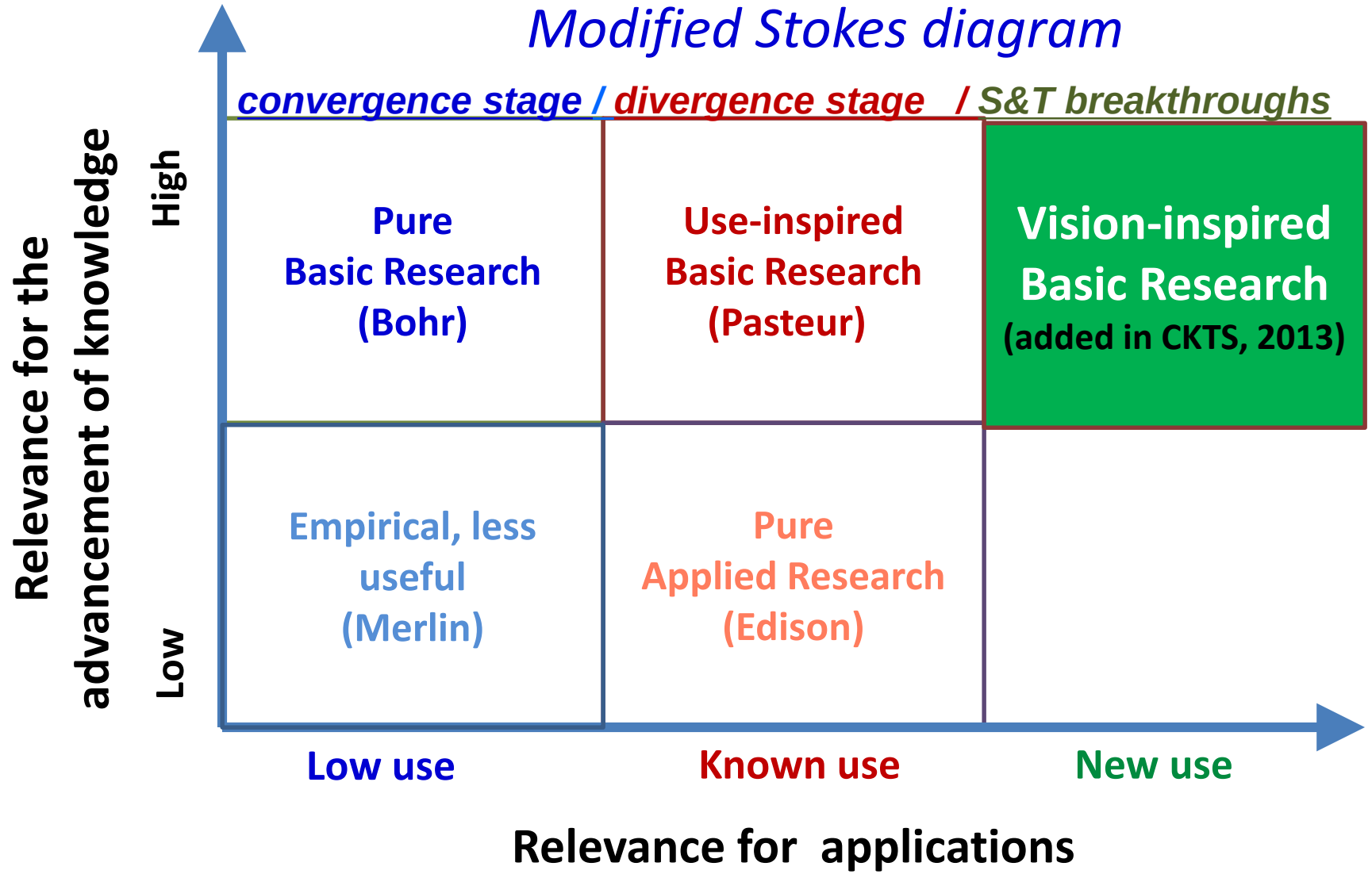
E. Confluence of resources leading to system changes (the *S-curve)*

(Ex: GAO-14-181SP Forum on Nanomanufacturing, Report to Congress, 2014)



M.C. Roco, Aug 17, 2017

F. Vision inspired discovery and inventions are essential for the future of innovation



Ref 5: "Convergence of Knowledge, Technology and Society: Beyond NBIC" (Springer,2013)

Vision-inspired S&T breakthroughs underpinning GCs

(examples of new 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); 12-atom structure (IMB, 2012), DNA structure (Harvard, 2012; on one cubic mm) "*Millions times smaller*"
- **Exploit nano-photonics:** change direction and frequency of light (2004, then succession of solutions) "*New phenomena and devices*"
- **Molecular cancer detection and treatment** (first gold-shells, Rice, 2002 - 2016 to many solutions in progress) *"Not possible before"*
- **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"*

6. Why convergence is important?

(Ref 6: CKTS, Springer, 2013)

Convergence is both:

- a fundamental principle of nature

- core opportunity for S&T progress in knowledge society

Using integrative approaches in convergence aims at:
value-added (cost benefit; ex gene sequencing)
and changing the systems (things not possible before)

"It must be remembered that there is nothing more difficult to plan, more doubtful of success, nor more dangerous to manage, than the creation of a new system. " Machiavelli 1513

Convergence effect: Outcomes not possible before
by convergence of three research directions

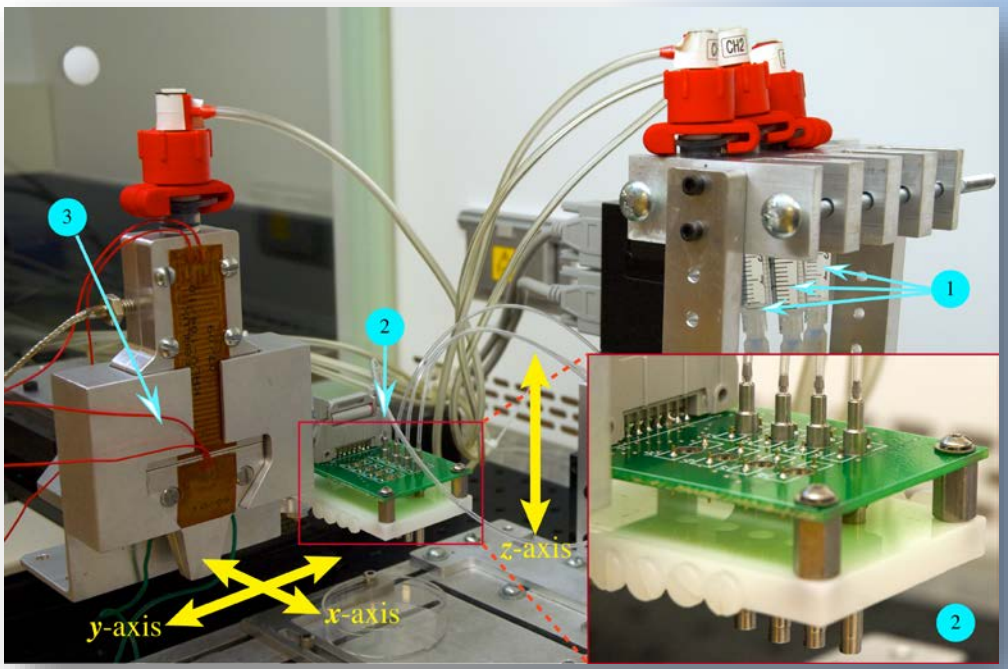
Tissue Engineering and Nanotechnology meet 3-D Printing
(example of convergence)

(i) 3D printing technology

(ii) Tissue engineering

(iii) Nanotechnology

for additive manufacturing of scaffolds with nanoscale precision

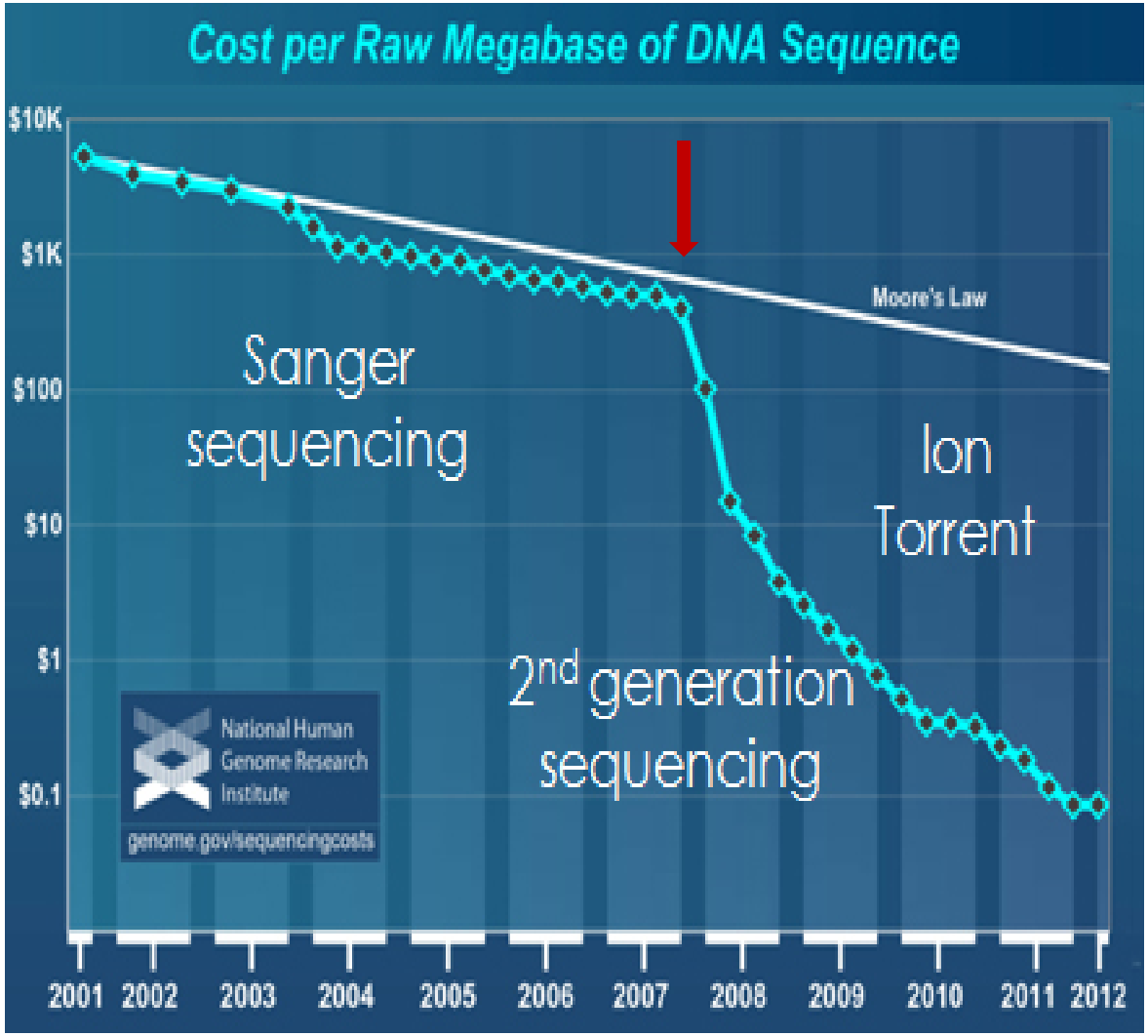


Doi, RPI

Convergence effect: *Gene sequencing cost benefit*

after integration of biomed and nanoelectronics methods

(after NIH/NHGRI, K.A. Wetterstrand, 2013)



2001: Begins $3B research program for ~3B DNA letters

2016: Whole genome sequencing much faster **with less than $1,000** (Veritas Genetics, Oxford Nanopore, portable devices,….)

(convergence inspired bio-nano research)

Estimated progress in NBIC2 convergence

NBIC study in 2001-2002

2001-2010: Reactive convergence (coincidental, based on ad-hoc collaboration of partners or individual fields for a predetermined goal)

NBIC2 study in 2011-2012

2011-2020: Pro-active convergence (include decision analysis in convergence approach)

After ~ 2020: Systemic convergence (holistic, higher purpose, convergence organizations)

Perceptions

"Convergence" is not

- Not "just multidisciplinary research" - Convergence is a goal-driven process of a system that may include various disciplines, sectors and players creating new entities, and then spinning off in to new capabilities and applications
- Not "just coincidental links" - convergence is an interactive, purpose driven process, with node contributions. Ex: Links alone may lead to "information silos" or "eco chambers"
- Not "top-down governing" - but governance is dominated by horizontal links and self-organization principles
- Not "just a large number of contributors" - but how they collectively interact and contribute to the goal

- Applications -

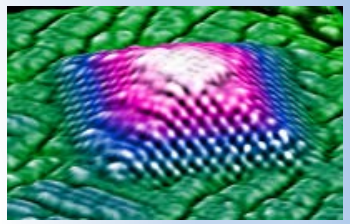
Three implemented stages
of Science/Technology/Innovation Convergence

Three stages of convergence
applied to general-purpose technologies

(Ref 6: CKTS, Springer, 2013)

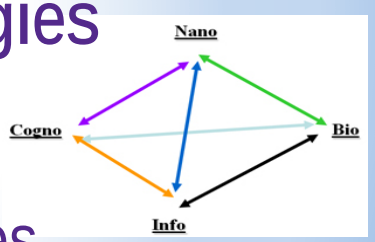
I. Nanoscale Science, Engineering and Technology "Nanotechnology"

Integrates disciplines and knowledge of matter from the nanoscale



II. Nano-Bio-Info-Cognitive Converging Technologies "NBIC"

Integrates foundational and emerging technologies from basic elements using similar system architectures

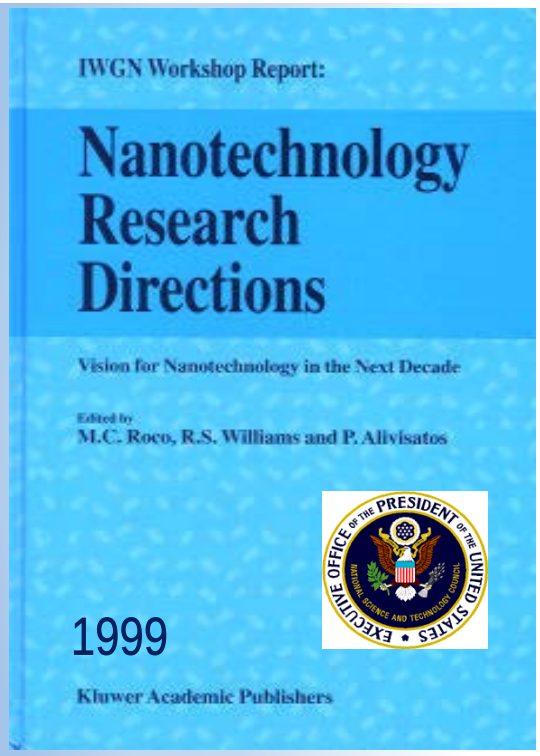


III. Convergence of Knowledge, Technology and Society "CKTS"

Integrates the essential platforms of human activity using five convergence principles

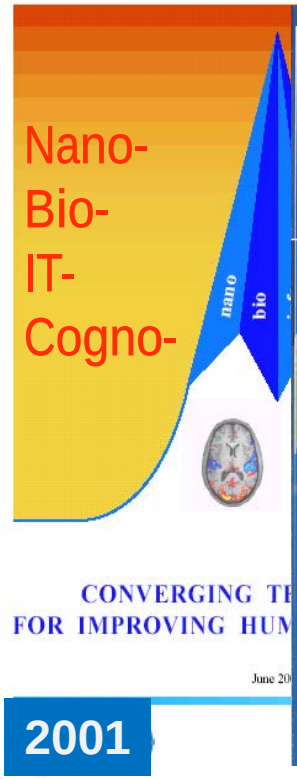
Nanotechnology: from scientific curiosity to immersion in NBIC & CKTS socioeconomic projects

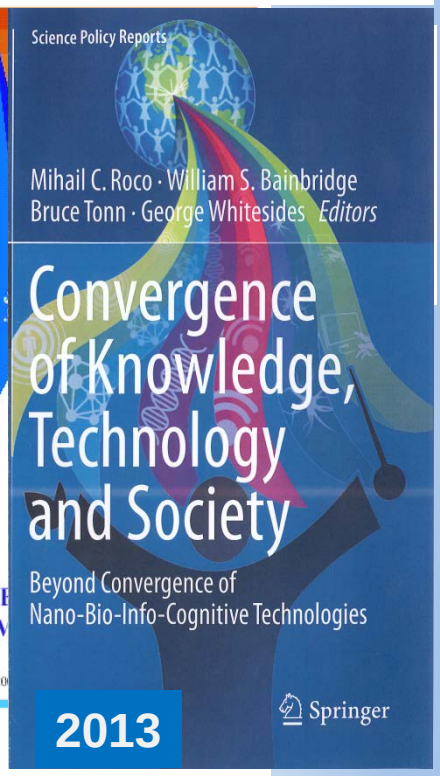
nano1 (2001-2010)



nano2 (2011-2020)

NBIC1 & 2 (2011-2030)

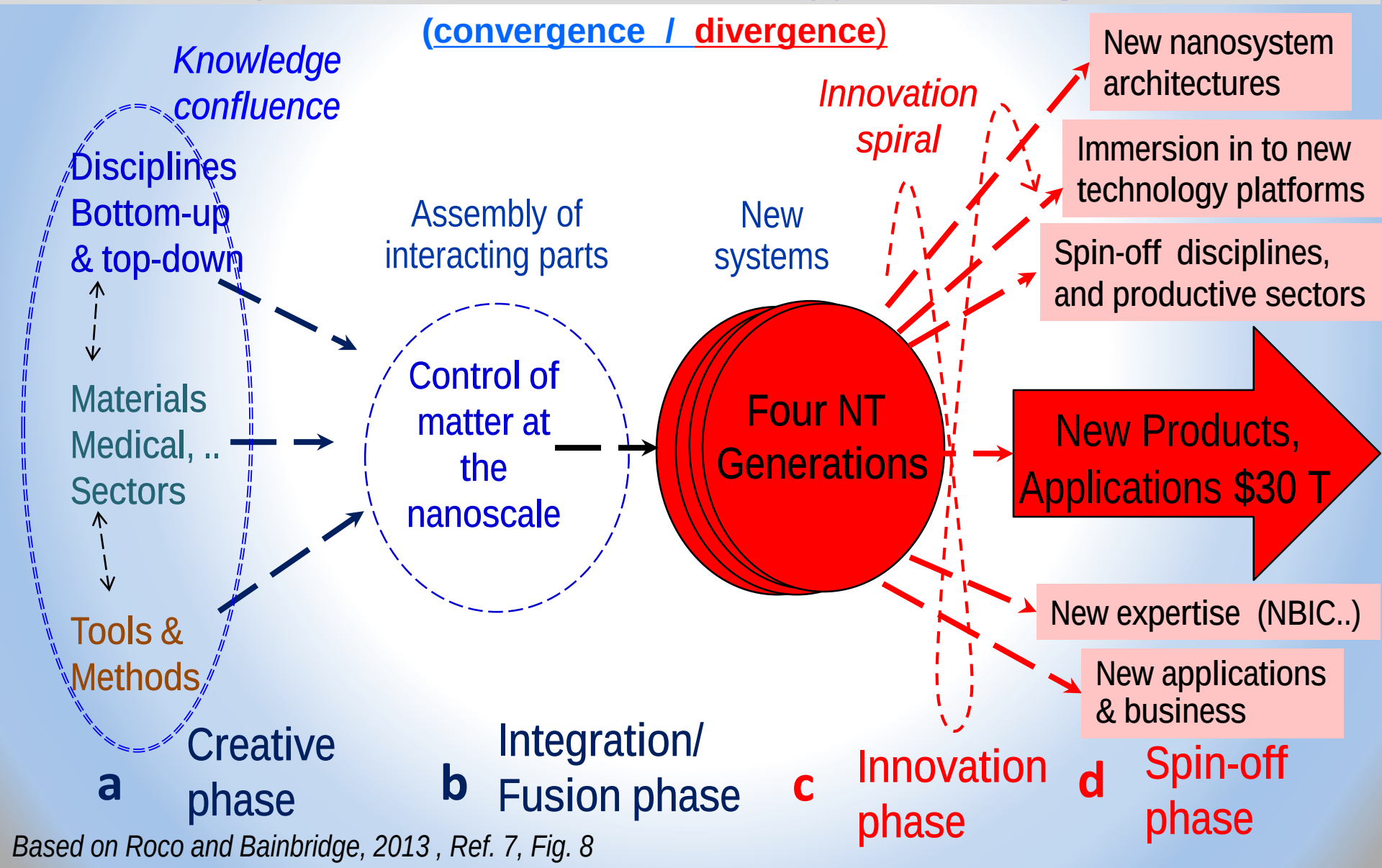




30 year vision to establish nanotechnology and convergence:
In 3 stages changing focus and priorities

Reports available on: www.wtec.org/nano2/ and www.wtec.org/NBIC2-report/ (Refs. 3-6)

I. 2000-2030 Convergence-Divergence cycle for global nanotechnology development



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

I. Nanotechnology programs: S&T divergence

OSTP

DOC/NIST

NASA

HHS/CDC/ NIOSH

DOS

DOTr

DOT

IC/DNI

DOJ

DOE

HHS/NIH

OSTP

OMB

NSF

DOD

HHS/FDA

USDA/NIFA
USDA/ARS

USDA/FS

EPA

NRC

DOC/ USPTO

DOI/ USGS

DOL

DOEd

ITC

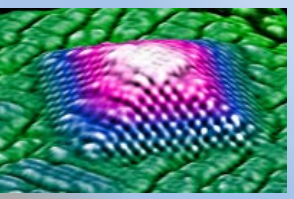
CPSC

DHS

DOC/BIS

DOC/EDA

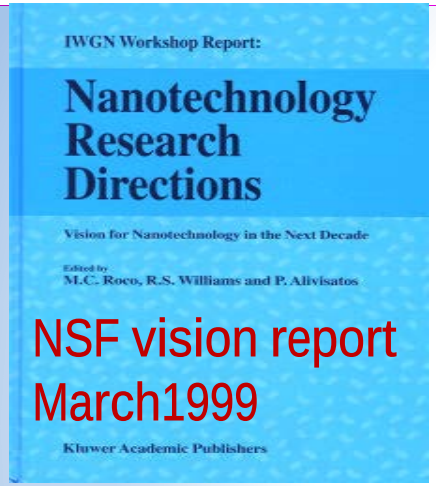
Control of matter at the nanoscale



U.S. National Nanotechnology Initiative, 2000-2030

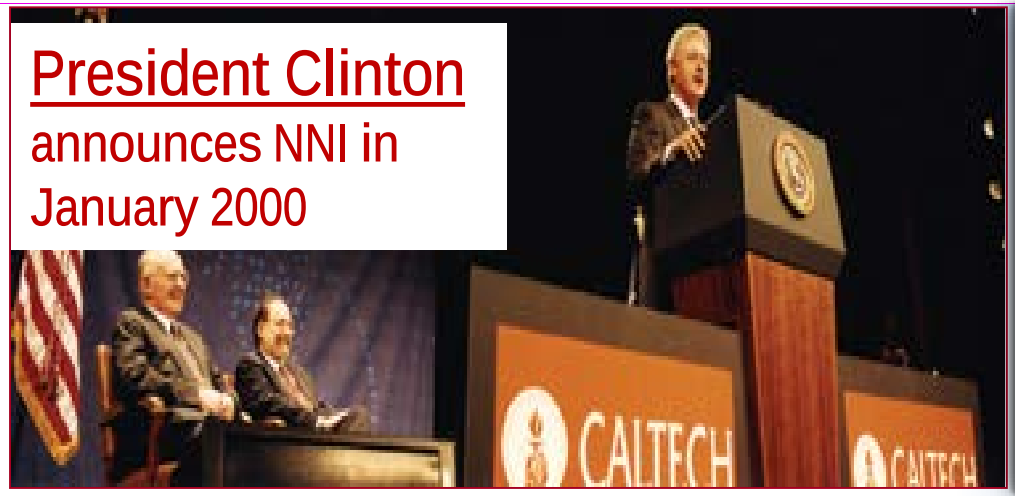
I. The 30 year vision has sparked imagination in Congress and 4 WHs

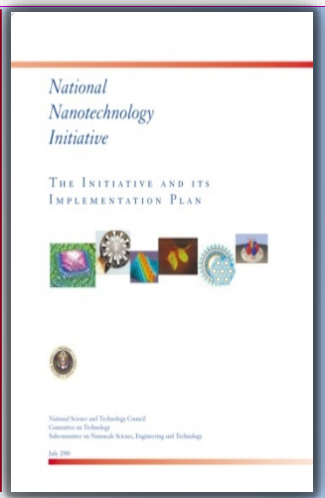
NNI in four administrations: Clinton, Bush, Obama, Trump



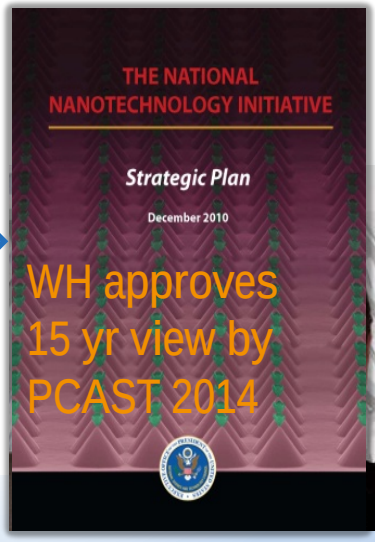
NSF vision report March1999

President Clinton announces NNI in January 2000





President Bush Signing 21st Century Nanotechnology R&D Act – December 2003

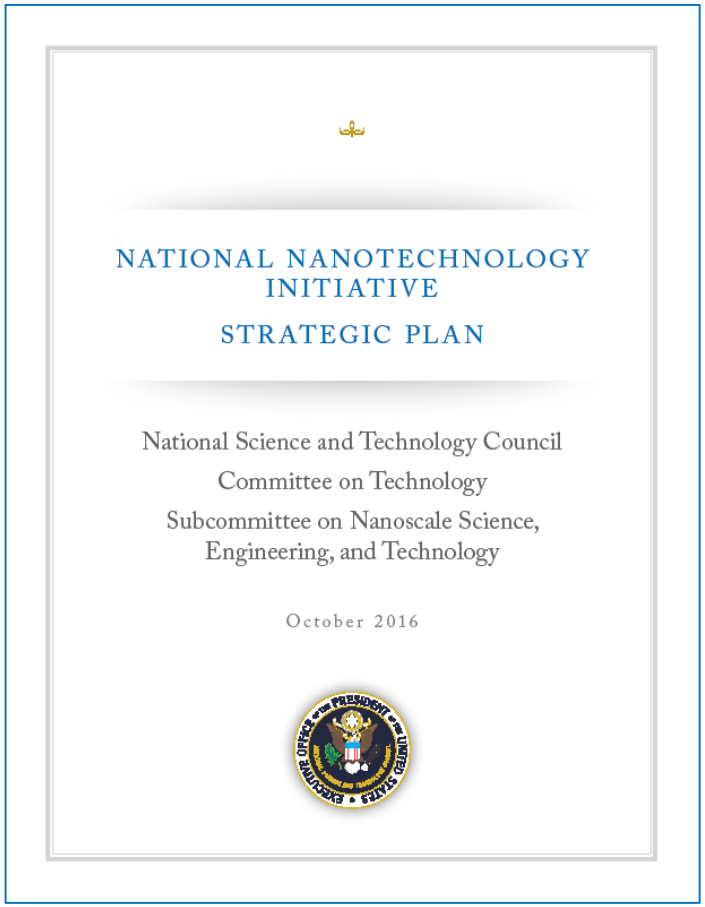


WH approves 15 yr view by PCAST 2014

President Obama

2017–2018 NNI budgets President Trump

I. Preparations for National Nanotechnology Initiative in 2017


NATIONAL NANOTECHNOLOGY INITIATIVE

STRATEGIC PLAN

National Science and Technology Council

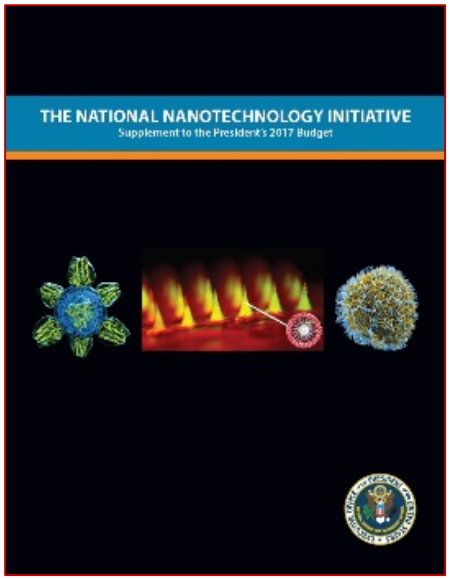
Committee on Technology

Subcommittee on Nanoscale Science, Engineering, and Technology

October 2016

2016-2019 NNI Strategic Plan approved by WH and submitted to Congress

(available on www.nano.gov)



2017 NNI Supplement 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-)

I. Ex: 2000-2030 Convergence-Divergence in NRI

NIST
(co-funds NRI centers)

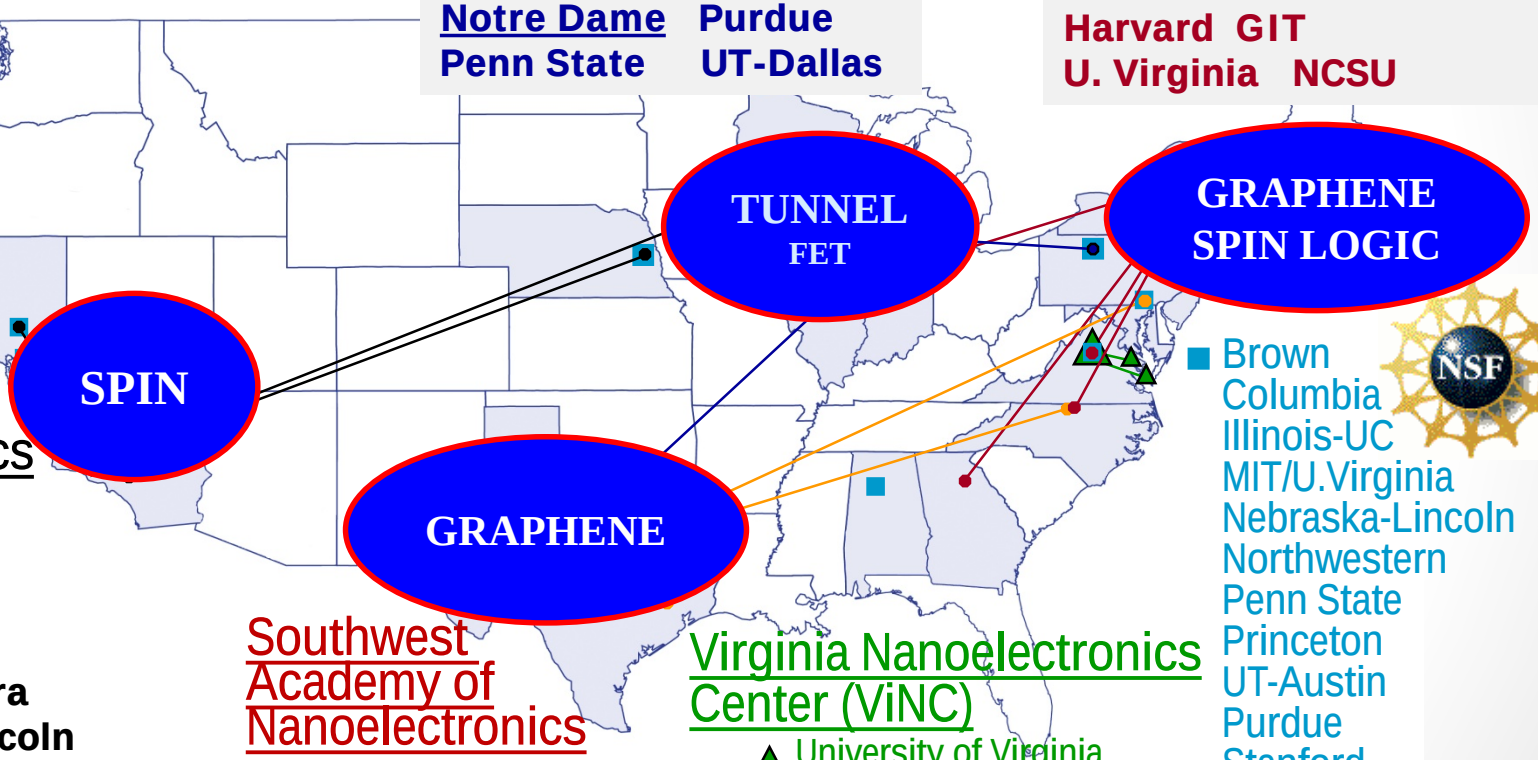
❖ Awards made In 2011- for collaborative group research (NNI Signature Initiative)

Midwest Institute for Nanoelectronics Discovery

Notre Dame **Purdue**
Penn State **UT-Dallas**

Institute for Nanoelectronics Discovery and Exploration

SUNY-Albany
Purdue MIT Columbia
Harvard GIT
U. Virginia NCSU



Western Institute of Nanoelectronics

UC Los Angeles
UC Berkeley
UC Irvine
UC Riverside
UC Santa Barbara
U. Nebraska-Lincoln
U. Wisconsin-Madison

Southwest Academy of Nanoelectronics

UT-Austin **Rice**
UT-Dallas **Texas A&M**
U. Maryland **NCSU**

Virginia Nanoelectronics Center (ViNC)

▲ University of Virginia
Old Dominion University
College of William & Mary

■ Brown
Columbia
Illinois-UC
MIT/U.Virginia
Nebraska-Lincoln
Northwestern
Penn State
Princeton
UT-Austin
Purdue
Stanford
U. Alabama
UC Berkeley

2016: Partnerships NSF, NIST, SIA, SRC with > 30 Universities in 20 States

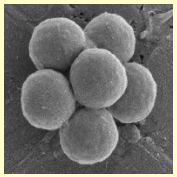
II. Nano-Bio-Info-Cognitive Converging Technologies

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

NBIC: Synergistic combination of four foundational emerging fields from their basic elements (atoms, bits, genes, and neurons) up and using similar system architecture concepts, for common core goals such as learning, productivity & aging

On this basis: 20 visionary scenarios for 20 years ahead

II. NBIC: *concurrence of capabilities*



Modern biology and nanomedicine

Molecular Assembling Nanomanufacturing

Atom Assembling

IT and Cyberinfrastructure

From Brain to Mind, Neuroscience

Transdisciplinary concepts

Other converging technologies

2000-2030

Integration NBIC

II. Emergence & divergence of foundational N B I C

Information Technology Spin-offs: Large databases, cyber-physical-social infrastructure, Internet of Things, connected sensorial systems, topical computer-aided design, cyber networks, ...

Ref: 1: Roco & Bainbridge 2013

Information Technology

Spin-offs

Spin-offs

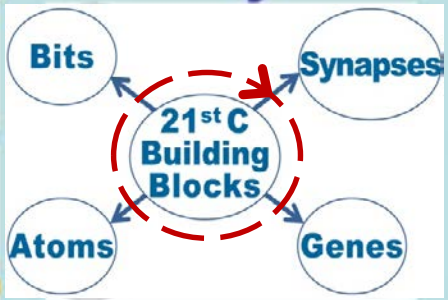
Brain simulation
Cyber networking
Personalized education..

Nanobioinformatics
DNA computing
Proteomics, ...

Re-combine

NBIC System

Cognitive Sciences



Biotechnology

Neuromorphic engng.
Synapses to mind
Smart environments,
Cogno aid devices ..

Nanobiomedicine
Nanobiotechnology
Synthetic biology; epigenetics
Bio-photonics; Microbiome;...

Spin-offs

Nanotechnology

Spin-offs

Nanotechnology Spin-offs : Nanophotonics, plasmonics, materials genome, mesoscale S&E, metamaterials, nanofluidics, carbon electronics, nanosustainability, wood fibers, DNA NT, ..

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

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

Artificial Intelligence

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

National Robotics Initiative

Info

Cogno | Bio

Nano

Biology centered

Biomedical / Health focus

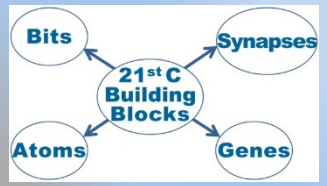
Precision Med

Genome(s) | Microbiome

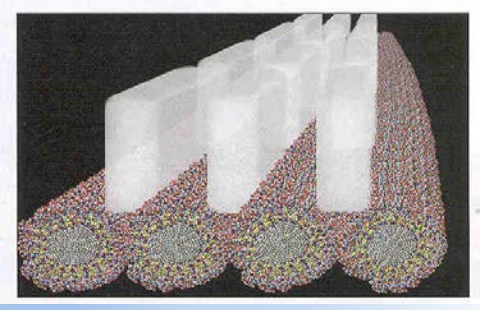
Architecture, Life, Human-technology

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

Materials Genome | Photonics | NNI Grand Challenges



Ref 9: Roco, "NBIC", in Handbook of S&T Convergence, 2015



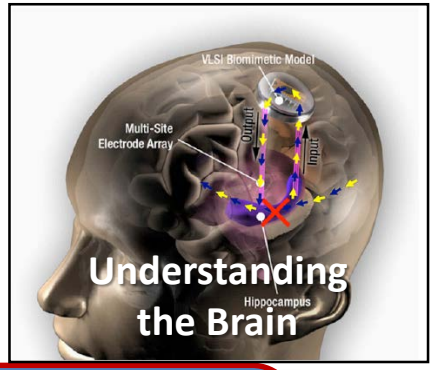
II. U.S. seed R&D programs in 2002-2004 had a lasting impact

- Converging S&E components in: **Nanoscale Science and Engineering**, ITR, **Biocomplexity**, **Sensors** (all 2002-)
- DARPA **nano-bio-info-cognitive** research focus (2002 -)
- Improving human performance in **NSF Human and Social Dynamics** (2003-)
- NSF **SBIR** focus on **converging technologies** (2003-2004)
- NSF-NIH on computer **simulation of the brain** (2004-)
- NSF centers for "**science of learning**" (2004 -) from brain R&D)
- NASA **improving human performance** for space exploration, and nano-bio-info programs (2004 -)
- About ten **NSF and NASA centers** on domains of NBIC (2004 -)

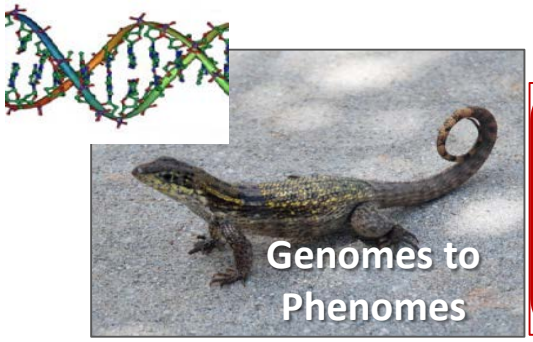
II. Examples of NBIC domains (2005-2017) with U.S. National Science Foundation awards

- **Quantum information science** (IT; Nano and subatomic physics; System approach for dynamic/ probabilistic processes, entanglement and measurement)
- **Eco-bio-complexity** (Bio; Nano; System approach for understanding how macroscopic ecological patterns and processes are maintained 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, others)
- **Synthetic biology** (Bio, Nano, IT, neuroscience)
- **Brain-like computing** (neuroscience, IT, NT, Bio, psychology)

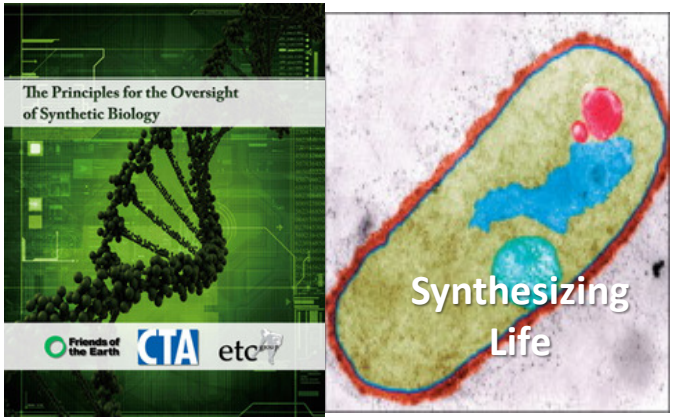
Biology-centered convergence at NSF programs



Molecular and Cellular Biosciences

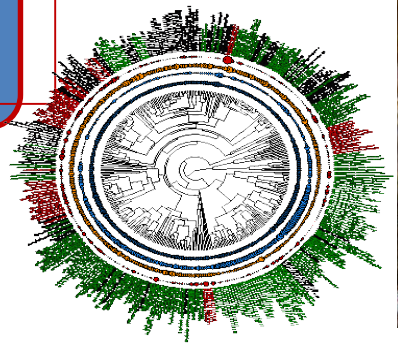


Integrative Organismal Systems



Methods & Bio-Data: Integration

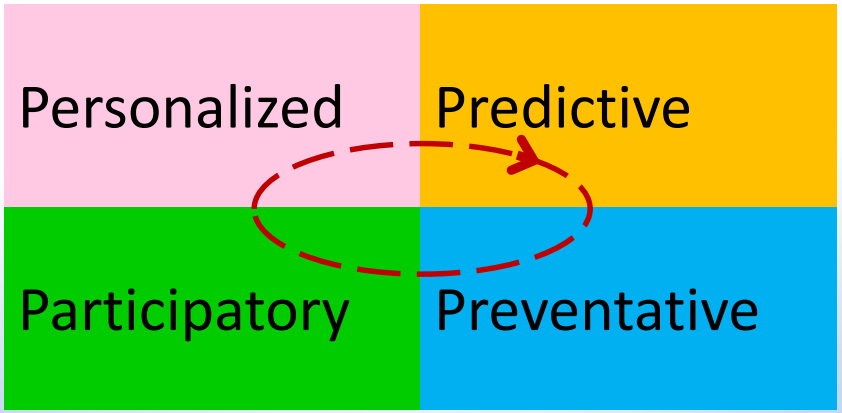
Biological Infrastructure



Environmental Biology

Human Health and Physical Potential Goals Enabled by Convergence

- Advance cancer detection and treatment w/ reduced side effects
- Health data analysis and delivery for real-time health monitoring
- Regenerative medicine and advanced prosthetics
- Next generation vaccines
- Wellness-focused: distributed P4 medicine



CKTS, 2013

Example of inter-field

Human / co-robot interaction (National Robotics Initiative)

Cognition: Learning,
Knowledge representation,
Planning, Navigation

Smart structures
and environments

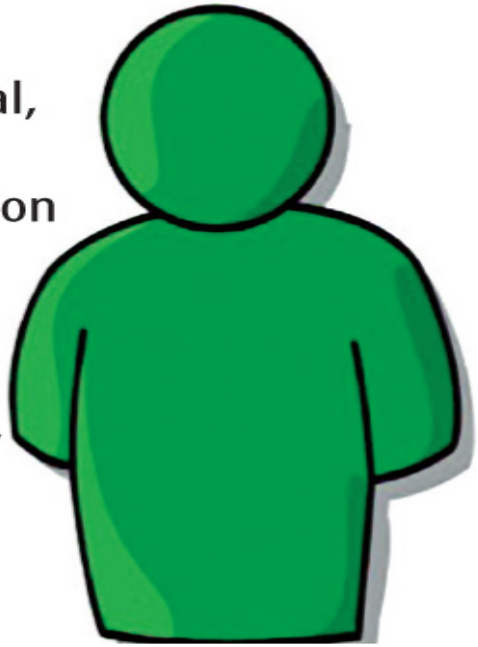
Intelligent
Co-Robot

Sensors &
perception

Cognitive
prosthetics

Networked
Multi-Agent

Human-robot
interaction:
physical & social,
language
& communication



HW/SW Architecture
platforms—
Mechanisms, Control,
Modeling

Manipulation:
Haptics, Tactile

Mobility: legged, wheeled, aquatic,
aerial

Exo-skeleton
augmentation

Soft structures

"Brain like computing" (NNI Grand Challenge)

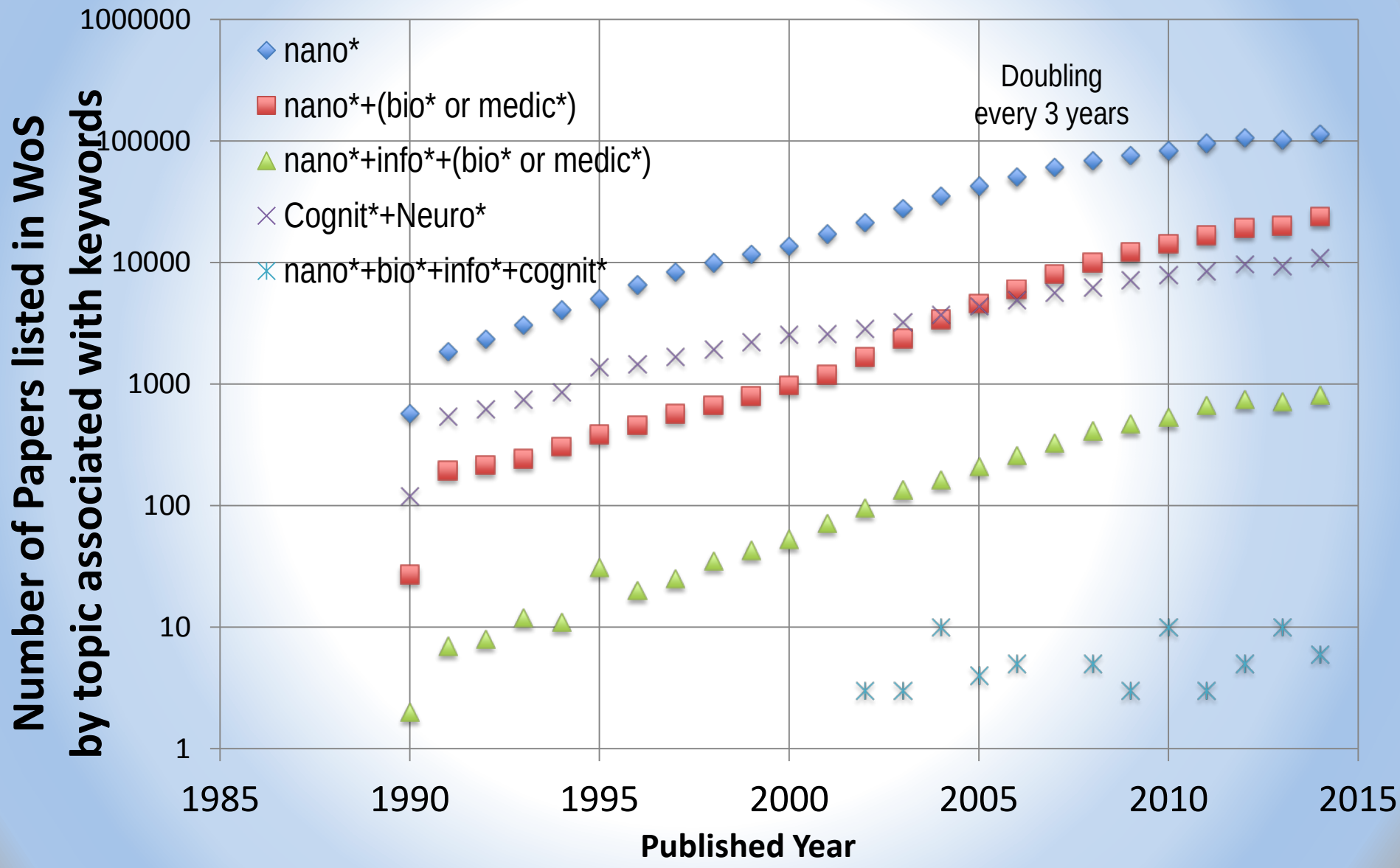
combining National Nanotechnology Initiative (NNI), National Strategic Computing Initiative (NSCI) & BRAIN Initiative

- *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,

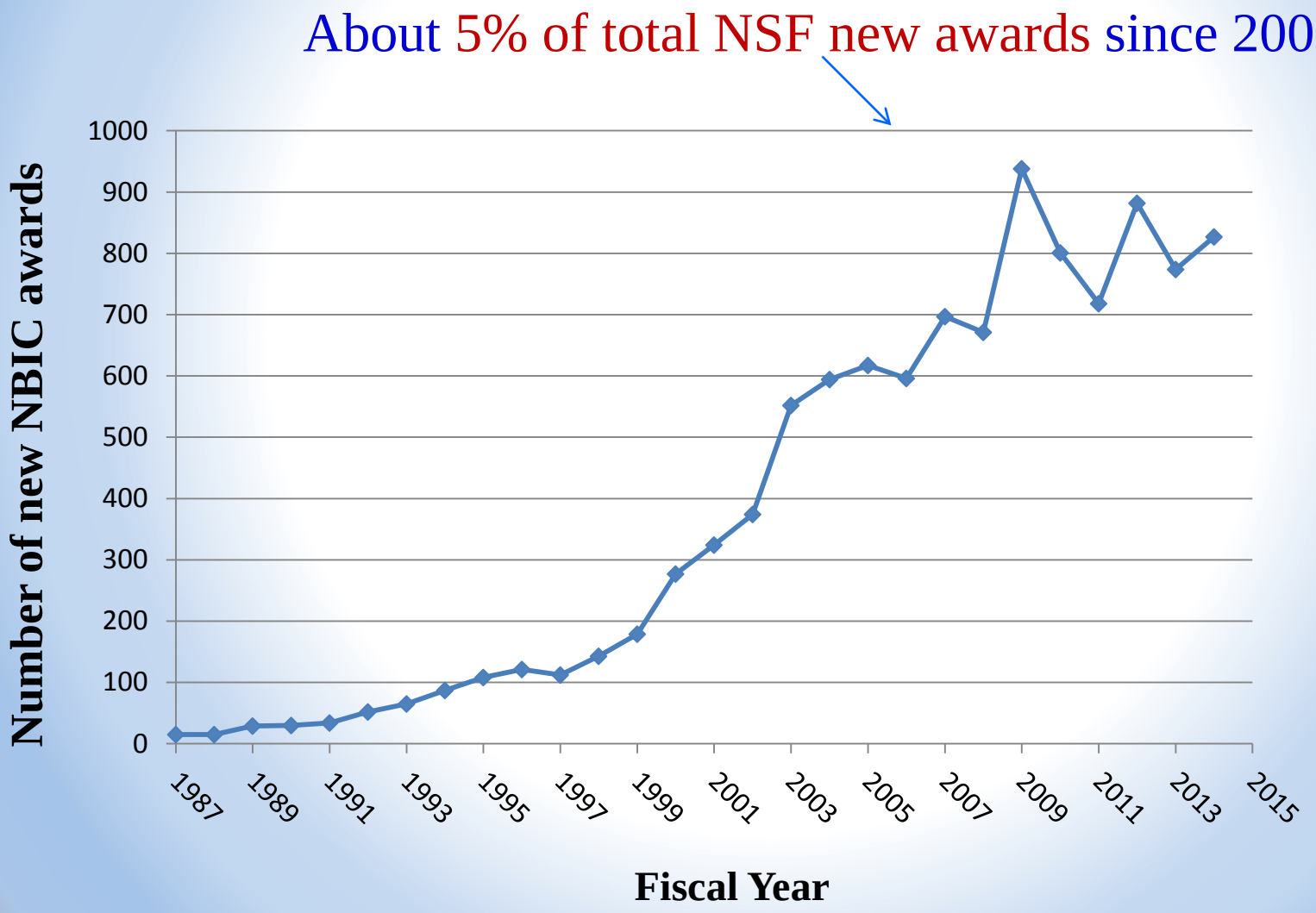
Thomson Reuters Web Of Science (WoS) Papers on Foundational Tools NBIC (1990 - 2015)



MC Roco, Aug 17 2017

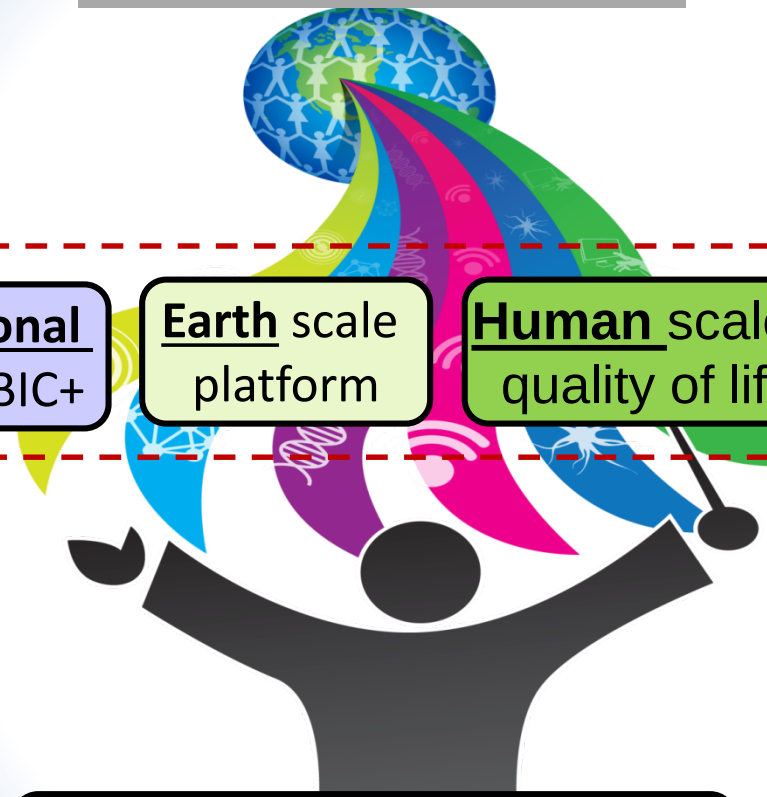
Number of NBIC Awards at NSF (1987-2015)

Search by combined keywords



III. Convergence of Knowledge, Technology and Society

For societal benefit, human development



Innovation circuit

Foundational tools – NBIC+

Earth scale platform

Human scale & quality of life

Societal scale platform

System feedback

Innovative & responsible governance- **System behavior**

Societal values and needs

Human activity system

The conductor suggests societal governance of K&T converging platforms for societal benefit.

Ref: 6: "Convergence of knowledge, technology and society: Beyond NBIC" 2013

OSTP

Convergence of Knowledge and Technology (CKTS) leads to

III. U.S. global society-oriented initiatives

Smart and Connected Communities

I-Corps

SunShot GC (DOE..)

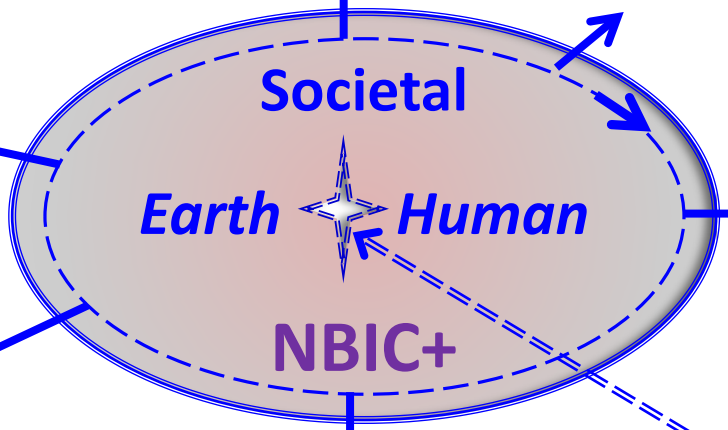
Climate Action Plan

Strategy for Arctic Region

Innovation
WH Office Am. Innovation

Aging Population

Global Change Research Program
(Global Change.gov) (with coord office)



STEAM Education Initiative (NSF, DoEd)

Asteroid GC (NASA..)

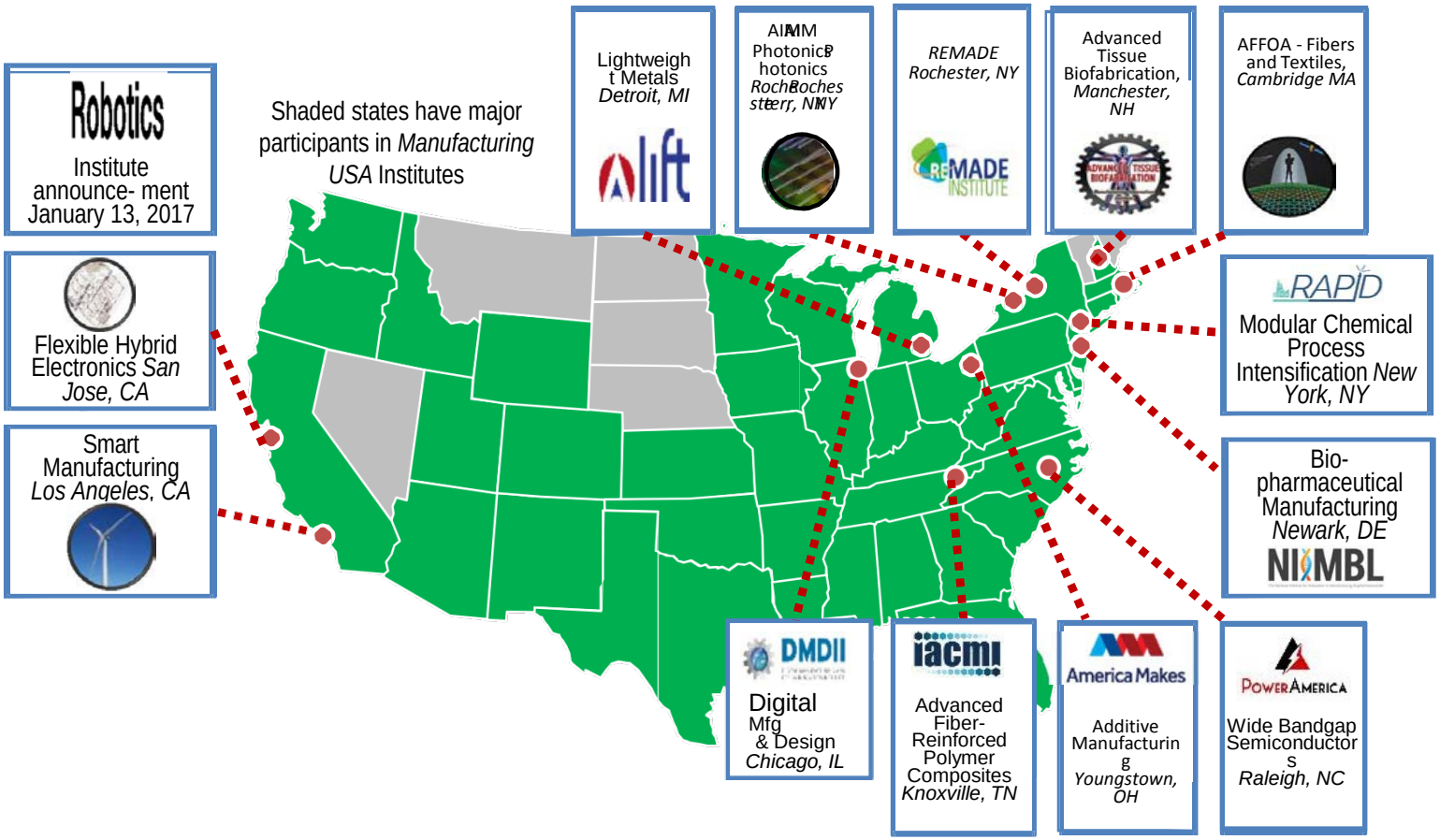
Space Station (NASA..)

Productivity, Sustainability, Equality, Safety

Advanced manufacturing:
National Network for Manufacturing Innovation (NNMI)
(Manufacturing.gov/nnmi) (with program office)

(Ref 8: "Principles and methods that facilitate convergence")

III. The National Network for Manufacturing Innovation (NNMI)



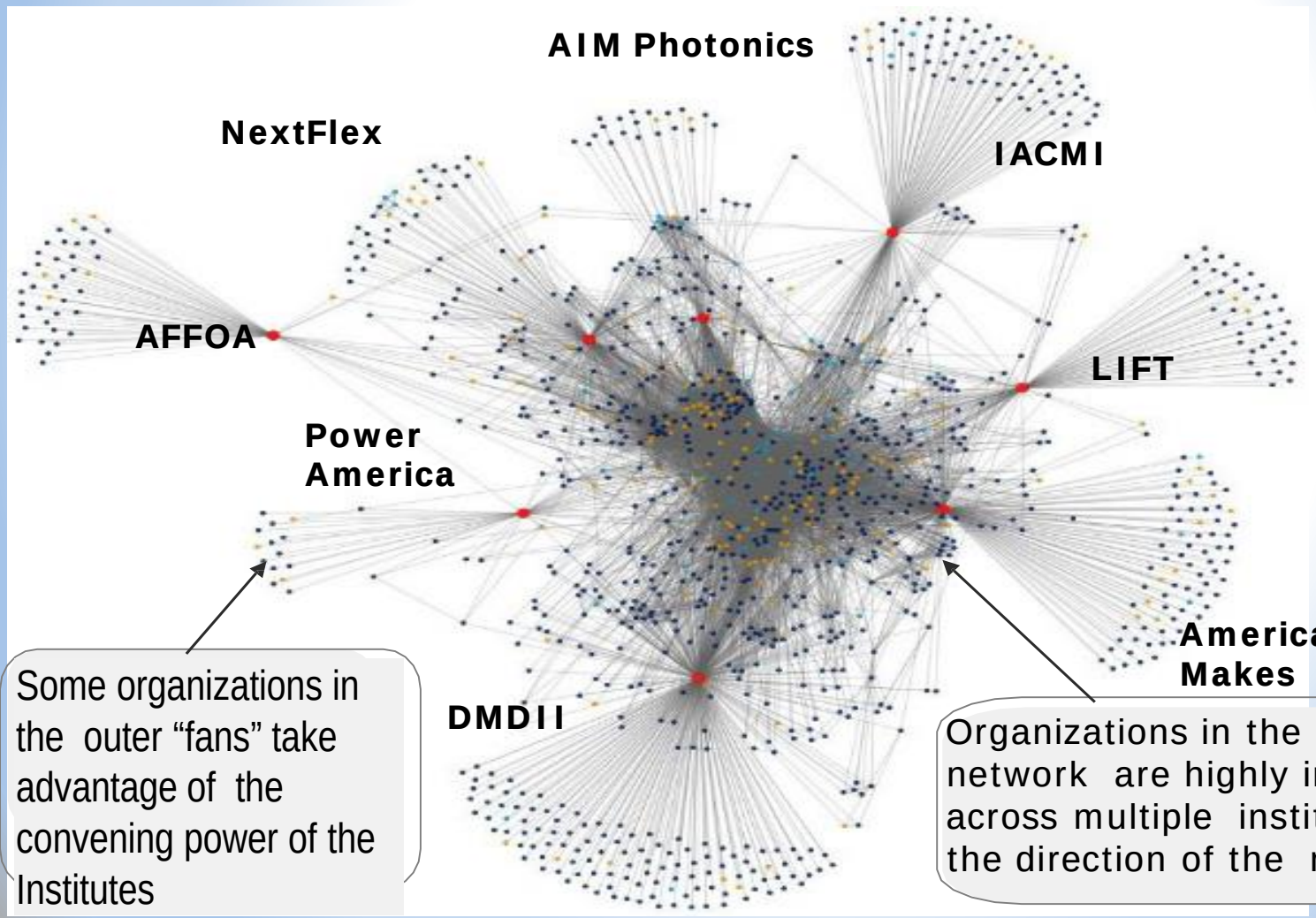
A network of 14 translational manufacturing institutes

III. 14 Manufacturing USA Institutes

https://www.manufacturingusa.com/institutes

Deloitte assessment: The Power of Connections

https://www2.deloitte.com/us/en/pages/manufacturing/articles/manufacturing-usa-program-assessment.html



Addressing the "valley of death" convene nearly 1,200 core organizations in an inter-industry Network comprised of over 9,000 organization networked/ coordinated

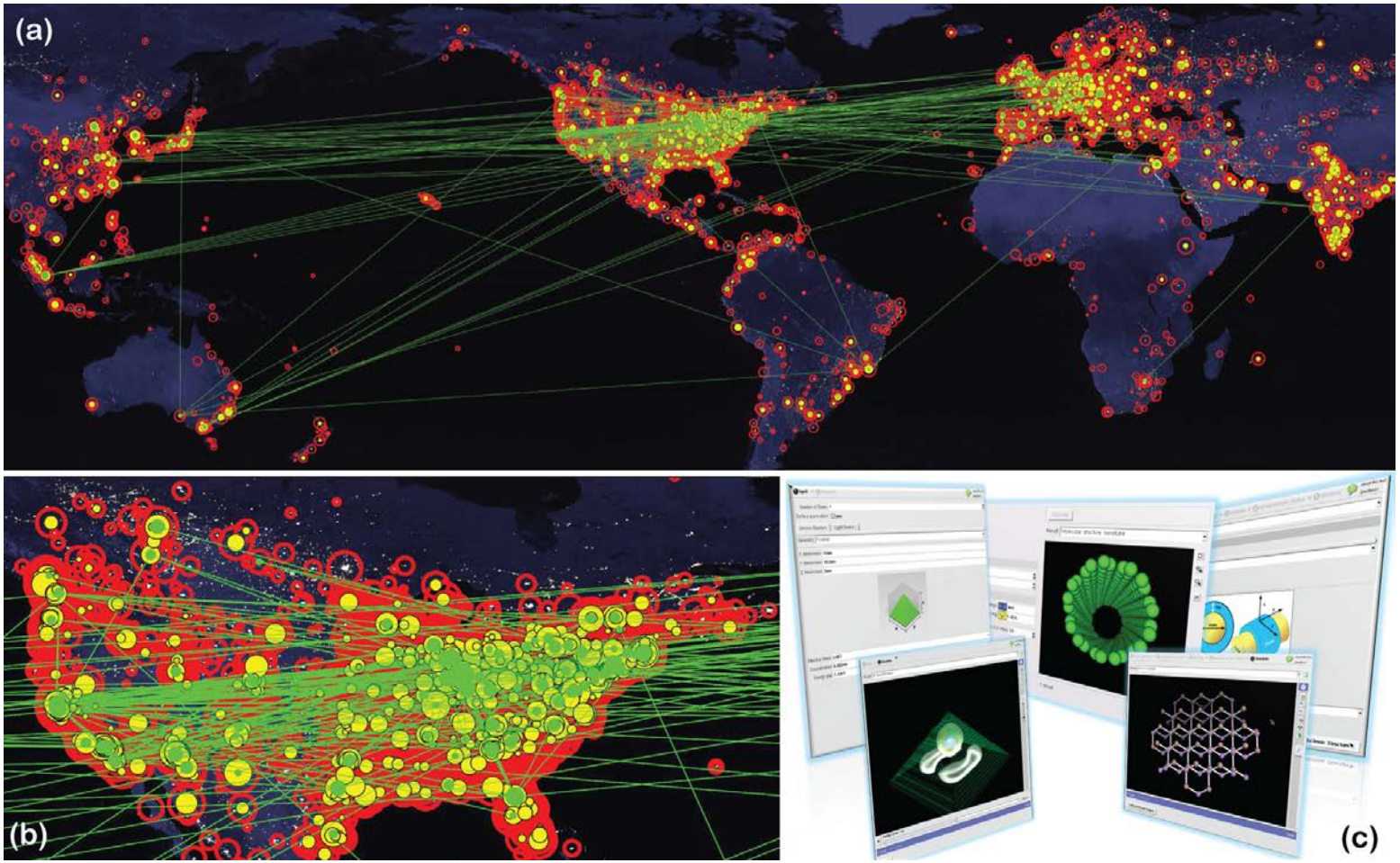
Some organizations in the outer "fans" take advantage of the convening power of the Institutes

Organizations in the center of the network are highly involved in projects across multiple institutes and help steer the direction of the network.

Needed infrastructure for convergence

- Centers for convergence science (theory and methods)
- Technology platforms for addressing societal grand challenges, including distributed NBIC manufacturing and global virtual factories, cognitive technologies and brain mapping
- Universal convergence databases
- Organizations to monitor and support increase in human potential, societal sustainability, and responsible governance
- Government support and coordination of convergence in STI investment planning and policies, decision-making

Example: Network for Computational Nanotechnology



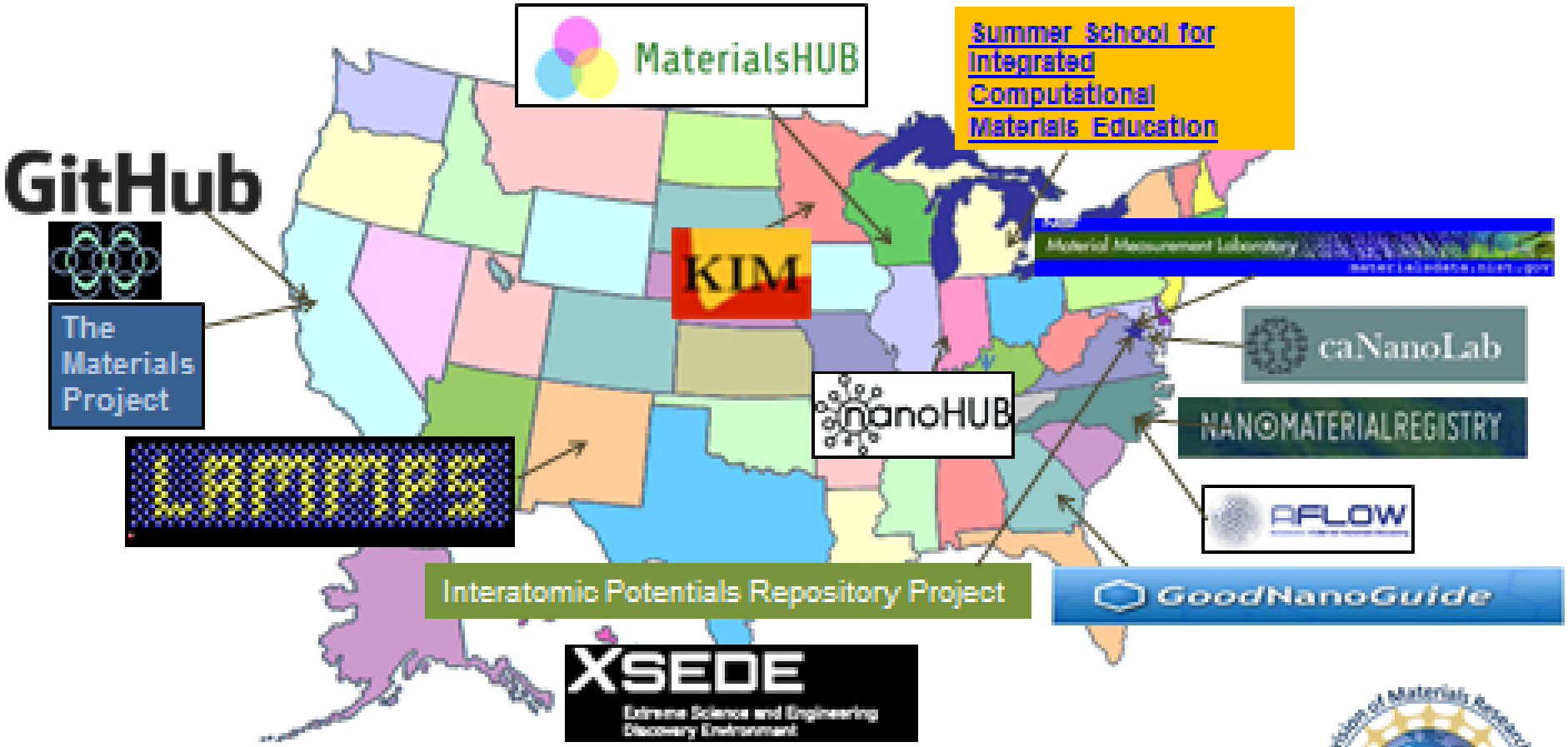
nanoHUB usage in 2015: 172 countries

Over 3,00 authors collaborating

Over 13,000 users running interactive simulations

Over 1.4 million visitors using lectures and tutorials

Key components of the Nanotechnology Knowledge Infrastructure



- Supported by NIH, NIOSH, NIST, NSF, ONR, DOE

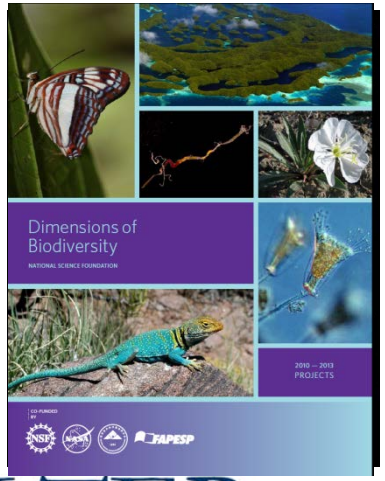
http://nanoinformatics.org/2015/agenda/

BioData: *Data Integration Across Scales of Time, Place and Size*

SESYNC

neon

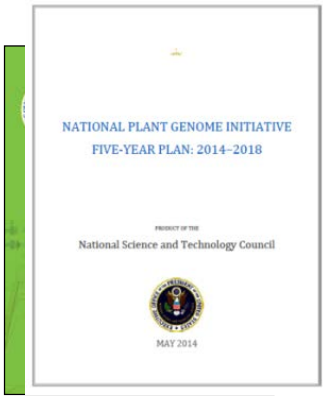
Enhancing the Value and Sustainability of Field Stations and Marine Laboratories in the 21st Century



National Socio-Environmental Synthesis Center

Museum collections and Field Stations

LTER



RCSB PDB PROTEIN DATA BANK

iPlant Collaborative™ *Cyberinfrastructure for the Life Sciences*

iDigBio Integrated Digitized Biocollections

GLEON global lake ecological observatory network

OOI OCEAN OBSERVATORIES INITIATIVE

earthscope

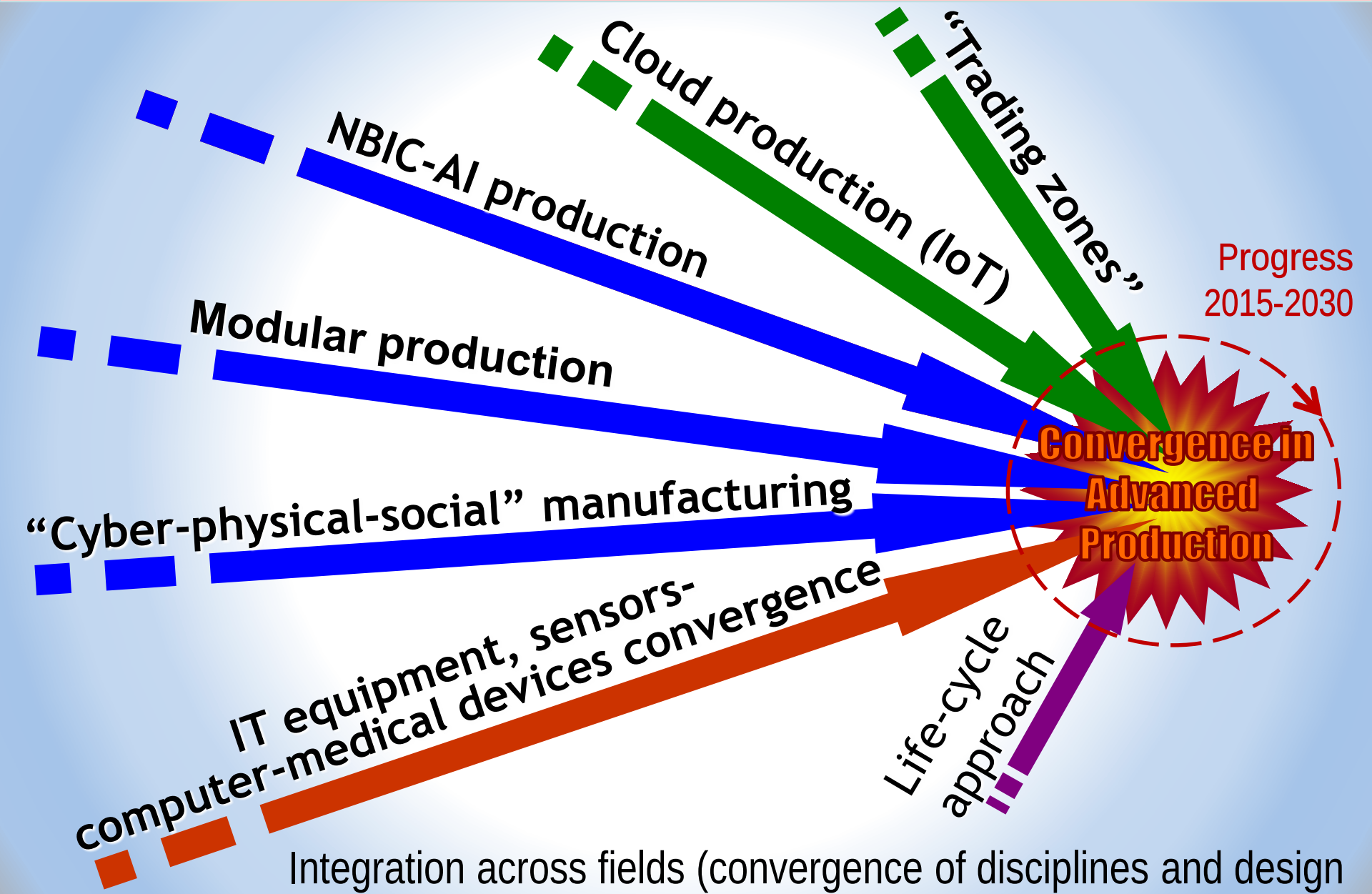
Gramene

- Applications -

Several opportunities of implementation of convergence

- **Production process**
- **Biomedicine, science and engineering**
- **Research and Education**
- **Intelligent cognitive assistants**
- **Citizen science**
- **Governance (local, national, global)**
- **Sustainability/global change (at NSF)**
- **Smart communities**

Advanced Production: convergence *of methods and capabilities*



Integration across fields (convergence of disciplines and design methods) and along time (life-cycle approach; benign by design)

Convergence in advanced production (1)

- The increased interactions - determines a change to **cloud production** (distributed growth with the Internet of Things)
- Exchanges of models between various domains – leads to "**trading zones" production**
- Penetration of foundational technologies – leads to **NBIC manufacturing** (nano-, bio-, digital-, cognitive-, and combined 2-4 technologies
- **Modular production**
- **"Smart" production** (incl. Artificial intelligence)

Convergence in advanced production (2)

- Converging “supply chains” from concept to internet, production and use – leads to **“cyber-physical-social” production**
- Integration of design methods, manufacturing and service lead to several fast growing areas, such as: **IT equipment convergence, sensors-computer-medical devices convergence**
- Considering the overall effects of production **over life time** of events leads to: **life-cycle design, benign by design, ethical governance.**

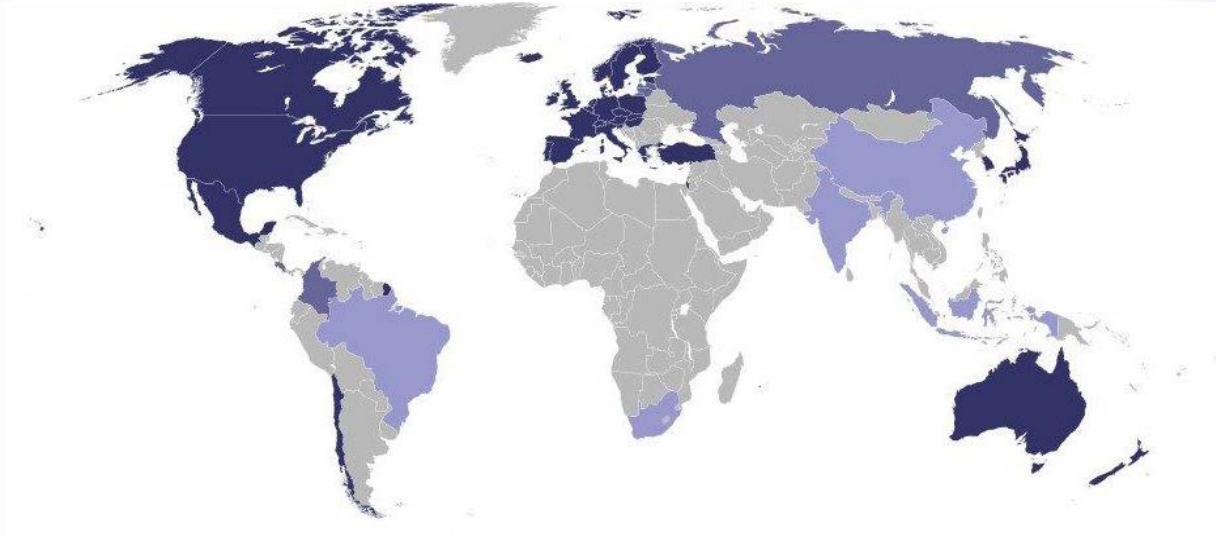
Example: U.S. Consortium for Advanced Manufacturing Foresights

- Result of the recommendations of the PCAST Advanced Manufacturing Partnership 2.0 Report
- Will “provide coordinated private-sector input on national advanced manufacturing technology R&D priorities.”
- Jointly NSF and NIST-funded
- $1-2 million/year for 3 years, renewable
- Proposals in July 20, 2015

OECD Working Party on
Bio- Nano- and Converging Technologies (BNCT)

Examples of BNCT activities (2017-2018):

- Harnessing Converging Technologies for the Next Production Revolution
- Gene Editing in an International Context: Scientific, Economic and Social Issues across Sectors



Convergence characterization in research and education (at NSF)

NSF identifies convergence as having two primary characteristics:

1. *Deep integration across disciplines*, *from which n*ew frameworks, paradigms or disciplines can form from sustained interactions across multiple communities.
2. *Driven by a specific and compelling challenge or opportunity*, whether it arises from deep scientific questions or pressing societal needs.

- **NSF Convergence Site: www.nsf.gov/od/oia/convergence/index.jsp**
- **International convergence characterization: CKTS 2013, NAS 2014**

Examples for:
Convergence methods in research

- Higher-level, multidomain perspective and methods of investigation: in calls for proposals and evaluation
- Funding the gaps between fields (such as using private foundations flexible funding, SGER, etc.)
- Bring together academic (high-level deliberations, depths in selected areas) with industry (sense of urgency and integration because of external factors) perspectives

NSF Overview

- **2014-2016 topic funded by NSF** (using full text proposals)
- **Convergence awards in the valleys**

Convergence-Divergence process (upstream):

Germination: Germination of Research Ideas for Large Opportunities and Critical Societal Needs

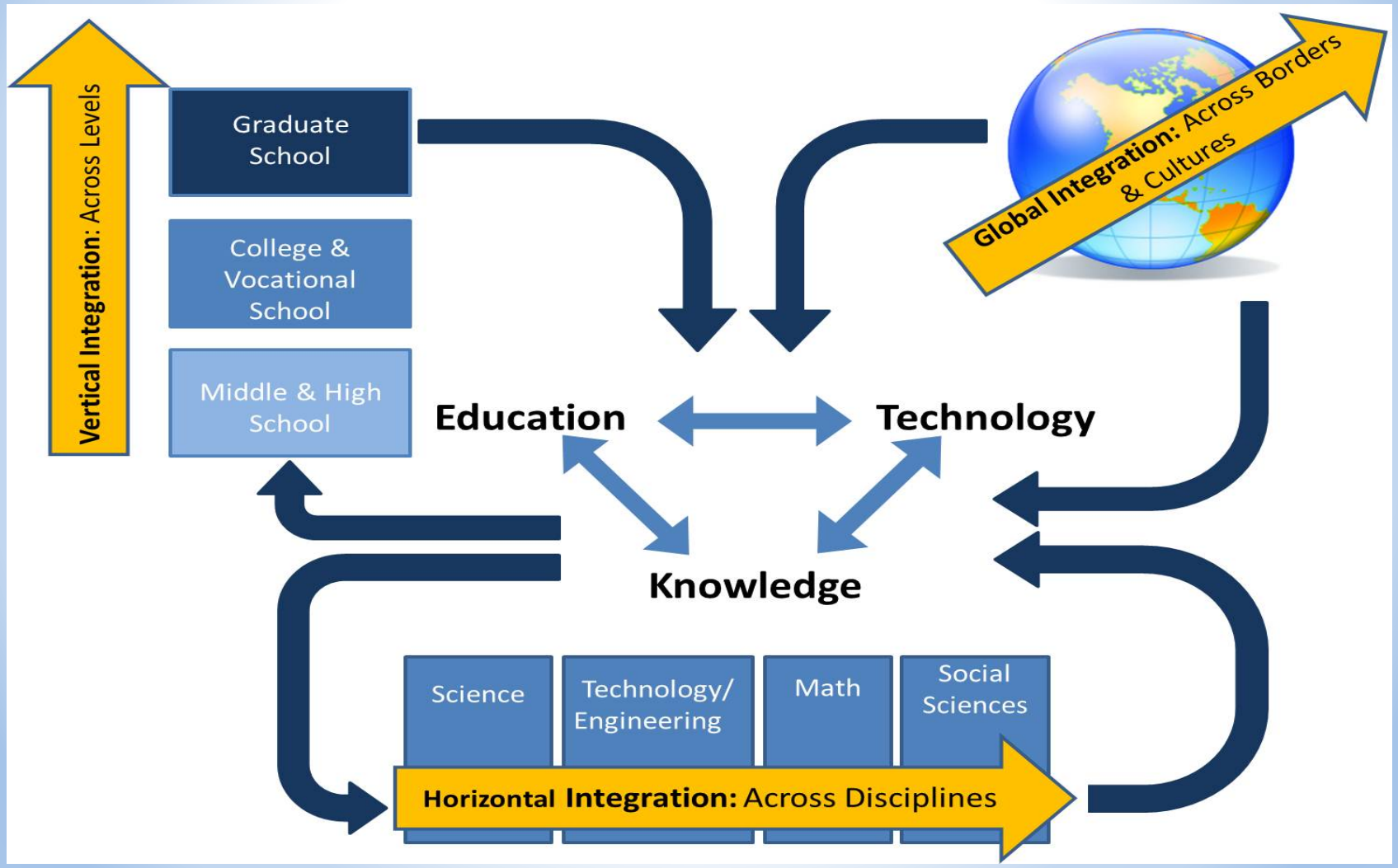
- To design learning frameworks, platforms, and/or environments to enable participants to conceive research ideas and questions with potentially transformative outcomes
- NSF 16-028 Dear Colleague Letter: Sought EAGER proposals with exploratory ideas to design learning frameworks, platforms, and/or environments

Convergence-Divergence process (downstream):

Innovation Corps (I-Corps™)

- Provides experiential entrepreneurial education to capitalize on NSF investments in basic research
- Supports I-Corps™ Teams, Sites, and Nodes to build, utilize, and sustain a national innovation ecosystem
- Plans approximately 230 new I-Corps™ Teams, up to 71 active Sites, and up to 9 active Nodes in FY 2017
- Scaling via partnerships and networks: Federal agencies, states, private sector; and National Innovation Network

Ex: Schematic highlighting six axes of integration required for convergence of knowledge & technology to further education



(CKTS 2013, Courtesy R. Chang)

Examples for:
Convergence methods in education

- **Trading zones** among various areas of relevance
- **Confluence of topics**: bringing together
  - ***Feasibility topics*** (science and engineering),
  - ***Desirabillity*** (art and humanistics) with
  - ***Viability*** (economics and management)
- **Using higher level languages** (such as music, mathematics, virtual reality connecting fields, value and intellectual driven fields, etc.). "Education is what remains after forgetting anything that you learned"

Example in Education:

National Convergence Technology Center

illustrated for Collin County Community College, CA

www.connectedtech.org

The National Convergence Technology Center (CTC)
leads the Convergence College Network (CCN),
a group of 50+ community colleges and universities
from across the country that shares resources
and best practices at both regularly scheduled meetings
and special one-off webinars.

Example program:

NSF's Science of Learning Centers

- from brain to learning processes using NBIC (2004 - 2014)

Center for Excellence for Learning in Education, Science, and Technology (CELEST), Boston U. (http://cns.bu.edu/CELEST/)

Center for Learning in Informal and Formal Environments (LIFE), U. of Washington, Stanford U., SRI International, (http://life-slc.org/)

Pittsburgh Science of Learning Center for Robust Learning (PSLC), Carnegie Mellon U. and the U. of Pittsburgh (http://www.learnlab.org/)

Spatial Intelligence and Learning Center (SILC), Temple U., Northwestern U., the U. Chicago, U. Penn., Chicago Public Schools

The Temporal Dynamics of Learning Center (TLC) UC San Diego (UCSD), with participation from scientists at Rutgers University, Newark, Vanderbilt University, UC Berkeley,

Visual Language and Visual Learning Center (VL2) Gallaudet University

New NSF competition in 2015-2020

Global Perspectives in Convergence Education

Workshop: NSF / OECD / U.S. National Academies / USC

Washington, D.C. , 2-3 November 2017

- Identify best-practices for evolving global educational systems facilitated by convergence
- Enhancing the capacity of workers, citizens and society to prepare for converging technologies
- Involve various stakeholder communities around the globe, including in developed and in-development economies

Intelligent cognitive assistants (ICA)

2016 & 2017 workshops (NSF, SIA, SRC)

- Systems that are highly useful to humans, specifically on the topic of Harnessing Machine Intelligence to Augment Human Cognition and Human Problem-Solving Capabilities – e.g., research that drives towards "Intelligent Cognitive Assistants"
- Explore scenarios for developing the novel architectures, concepts and algorithms which will be required for "assistants" to energy-efficient perceive, compute, and interact, and in this way to provide actionable information and informed advice to their human users. Modular functions and architectures.
- Establish a long-term vision (10-20 years), from "knowledge and data" in 2015 to "intelligence and cognition" in 2030

Convergence CKTS follow up projects (2017)

In preparation:

- NSF: R&Ed Convergence (2017-); Urbanization (GEO-lead)
- Improving decision making approach in R&D, other areas (ARMY-NSF)
- Study lead by MIT-Harvard: Biomedical
- EU Horizon 2020 (2013-2020) R&D Planning (used CKTS)
- Korea: Center for Convergence for R&D and Government activities (2013), The Advanced Institutes of Convergence Technology (2008-)
- Convergence for Education Workshop (2017), NSF-OECD-Academies

Suggested actions:

- Immediate targets: personalized health/biomedical(NIH), distributed manufacturing, service industry,.. re-defining operation of Internet of things
- *National Convergence K*nowledge and *T*echnology Office

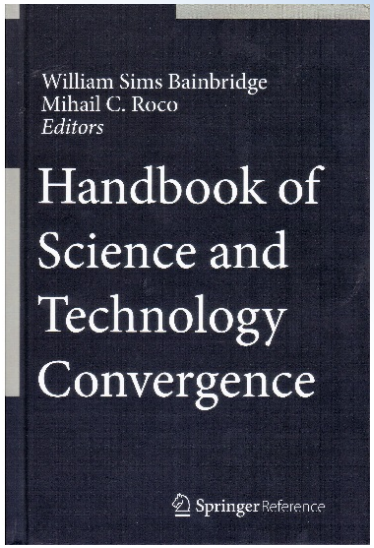
Opportunity: National convergence knowledge and technology office

- decisions to be taken by considering all the factors in a systematic way; bring more coherence and information flow
- not only connection, but approach how to do it considering creativity/ invention /innovation path, longer-range connections and potential for the future

Goal: increase added-value by improving the innovation spiral, synergism among programs, vision driven projects, with limited additional cost

Several recent U.S. activities

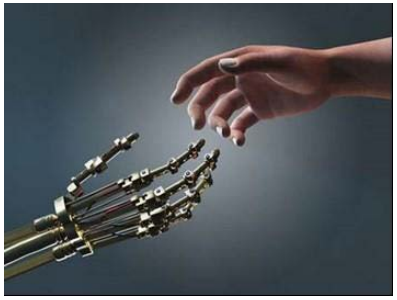
- NSF lead reports (2001-2016)
- US agency funding: NSF Big Ideas DARPA, EPA, NIH, AFOSR, others
- Academy study: Convergence - Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond (2014)
- *MIT-Harvard convergence for health (Biomed & S&E;2016)*
- *NSF priority areas: human-technology frontiers, microbiome, BRAIN, quantum computing systems, citizens science, longitudinal "science of education", convergence in governance of S&T*



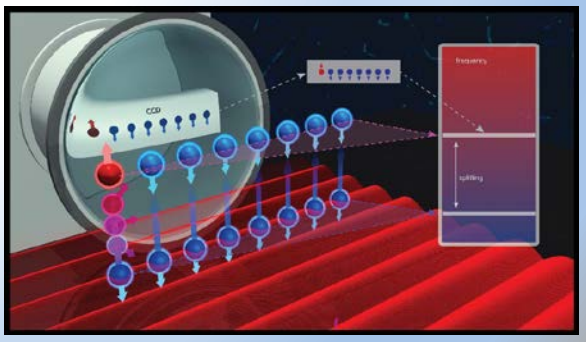
2016 NSF 10 Big Idea *(a. research)*

- **Understanding the Rules of Life: Predicting Phenotype**
- **Shaping the New Human-Technology Frontier**
- **Windows on the Universe: Era of Multi-messenger Astrophysics**





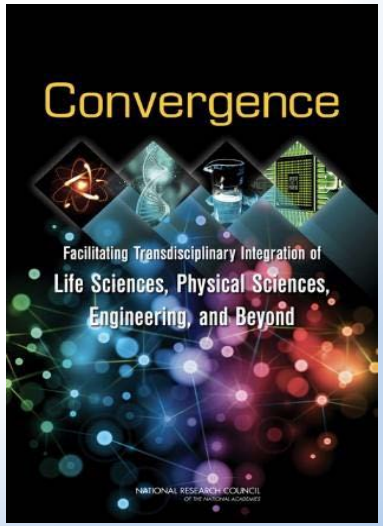

- **Navigating the New Arctic**
- **Data science**
- **The Quantum Leap**

2016 NSF 10 Big Idea *(b. operation)*

- **INCLUDES: Enhancing Science & Engineering through Diversity**
- **Mid-scale Research Infrastructure**

- **NSF 2050: The Integrative Foundational Fund**
- **Growing Convergent Research at NSF**



Global Action Possibilities

- An international convergence CKTS network
- Government coordination for supporting: *"science of convergence" & "convergence technology platforms"*
- Manufacturing, cognition-, biomedicine- convergence
- Cross-domain programs in universities & funding agencies
- Principles of convergence for conflict resolution
- OECD committee on convergence created in 2014

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" (Roco, Williams & Alivisatos, WH, 1999, also Springer, 316p, 2000)*
4. *NANO 2020: "Nanotechnology research directions for societal needs in 2020" (Roco, Mirkin & Hersam, Springer, 690p, 2011a)*
5. *NBIC: "Converging technologies for improving human performance: nano-bio-info-cognition" (Roco & Bainbridge, Springer, 468p, 2003)*
6. *CKTS: "Convergence of knowledge, technology and society: Beyond NBIC" (Roco, Bainbridge, Tonn & Whitesides; Springer, 604p, 2013b)*
7. *The new world of discovery, invention, and innovation: convergence of knowledge, technology and society*" (Roco & Bainbridge, JNR 2013a, 15)
8. *"Principles and methods that facilitate convergence" (Roco, Springer Reference, Handbook of Science and Technology Convergence, 2015)*
9. *"Science and technology convergence, with emphasis for nanotechnology-inspired convergence" (Bainbridge & Roco, JNR, 2016)*
10. *HSTC: "Handbook of Science and Technology Convergence" (Bainbridge & Roco, 2016)*

OISE supported programs for international collaboration

- **Early career researchers**
  - **International Research Experiences for Students (IRES)**
    - 3 year awards
    - Student cohorts conduct research at international site
  - **NSF-ERC Implementing Arrangement for CAREER Grantees and NSF Postdoctoral Fellows**
- **Partnerships**
  - **Partnerships for International Research and Education (PIRE)**
    - 5 year awards
    - Multimillion dollar budgets