Overview: Convergence science for Societal Solutions and Education

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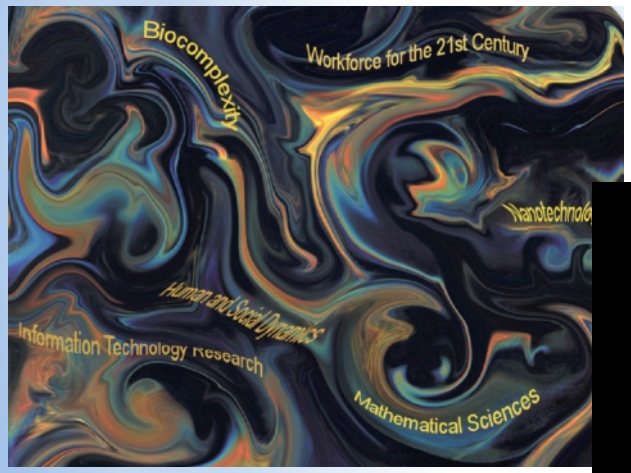
National Science Foundation and National Nanotechnology Initiative

Global Perspectives in Convergence Education, Washington D.C., November 2 2017

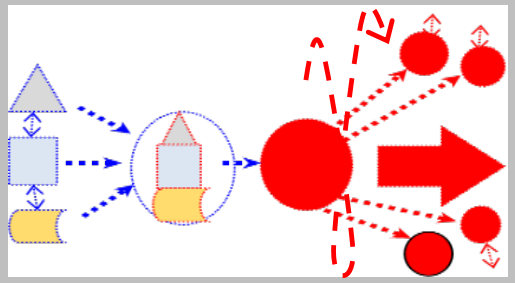
Evolution in nature, science, technology, society is

- ***Increasingly turbulent***
- ***Coherent***
- ***Emergent***



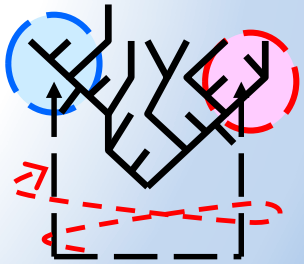
S&T trends

(Ref. 1-5) Coherence cycle



Education trends

(Ref. 1-5) Ex: Trading zones



Convergence is a general strategy to holistically understand and transform a system for reaching a common goal

Convergence is a core opportunity for progress

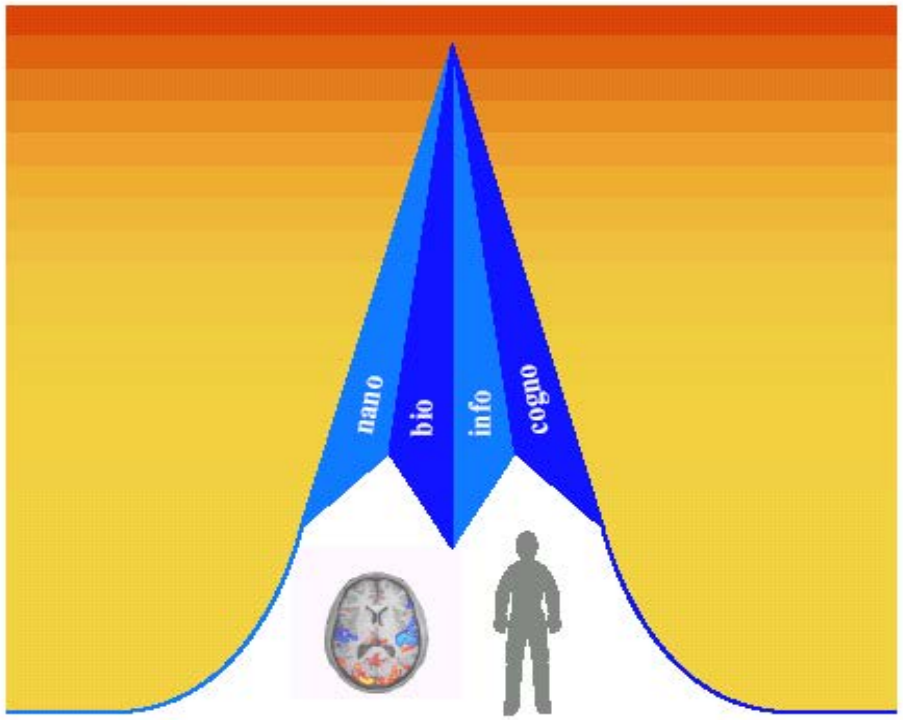
Making the case

- ✓ Defining convergence
  in science, technology and innovation
- ✓ General-purpose framework for problem solving
  theory, principles and methods
- ✓ Convergence for and by education
  education trends for emerging technologies

Earlier studies on technology convergence

Seven reports on convergence

2003, 2006 and 2007 Springer; 2004 NYAS; 2004; 2013 (worldwide), 2016 (handbook)



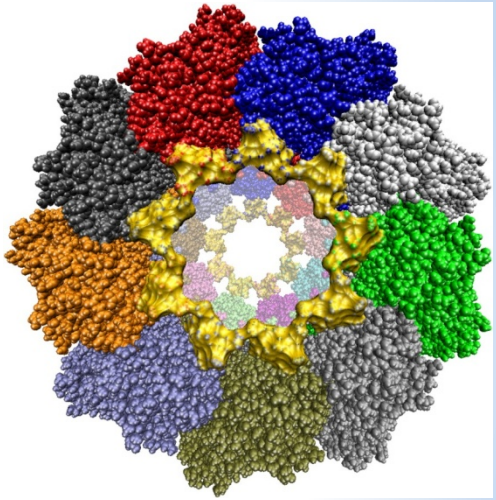
CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

Workshop, Dec. 2001
NSF-DOC Report 2002

(includes chapter on convergence education)

Coevolution of Human Potential and Converging New Technologies

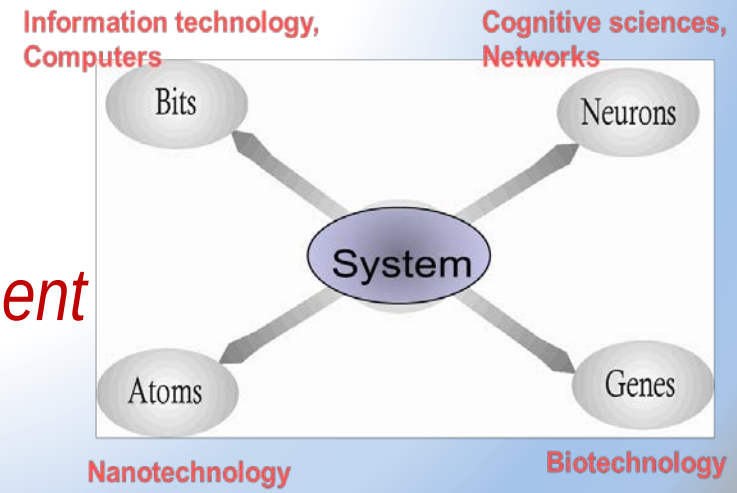


In: Annals of the New York, Academy of Sciences, Vol. 1013, Report 2004

(M.C. Roco and C. Montemagno)

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*



Convergence of Knowledge, Technology, and Society:

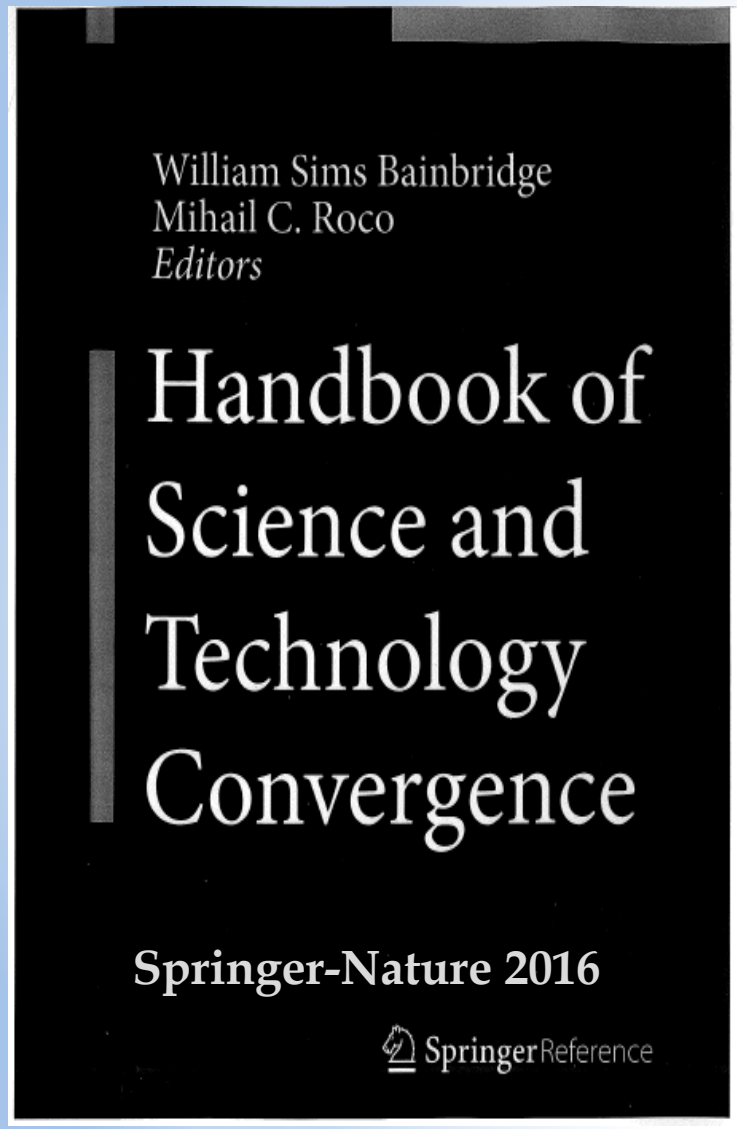
Beyond Convergence of Nano-Bio-Info-Cognitive Techologies

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

INTERNATIONAL BENCHMARKING of METHODS and APPLICATIONS

Springer-Nature, Report 2013

(includes chapter on convergence education)



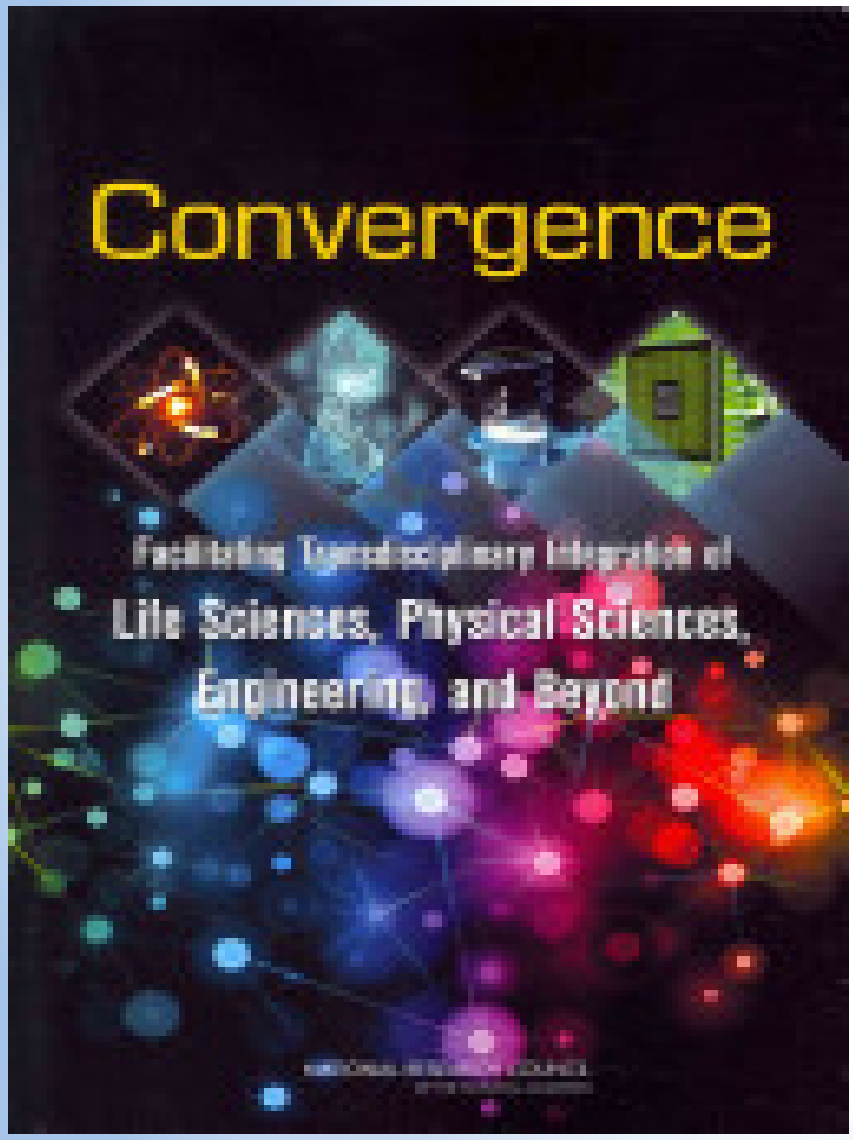
Convergence Science: focus on principles, methods and case studies

applied to

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

Ref 10: "Science and technology convergence, with emphasis for nanotechnology-inspired convergence" (Bainbridge & Roco, JNR, 2016)

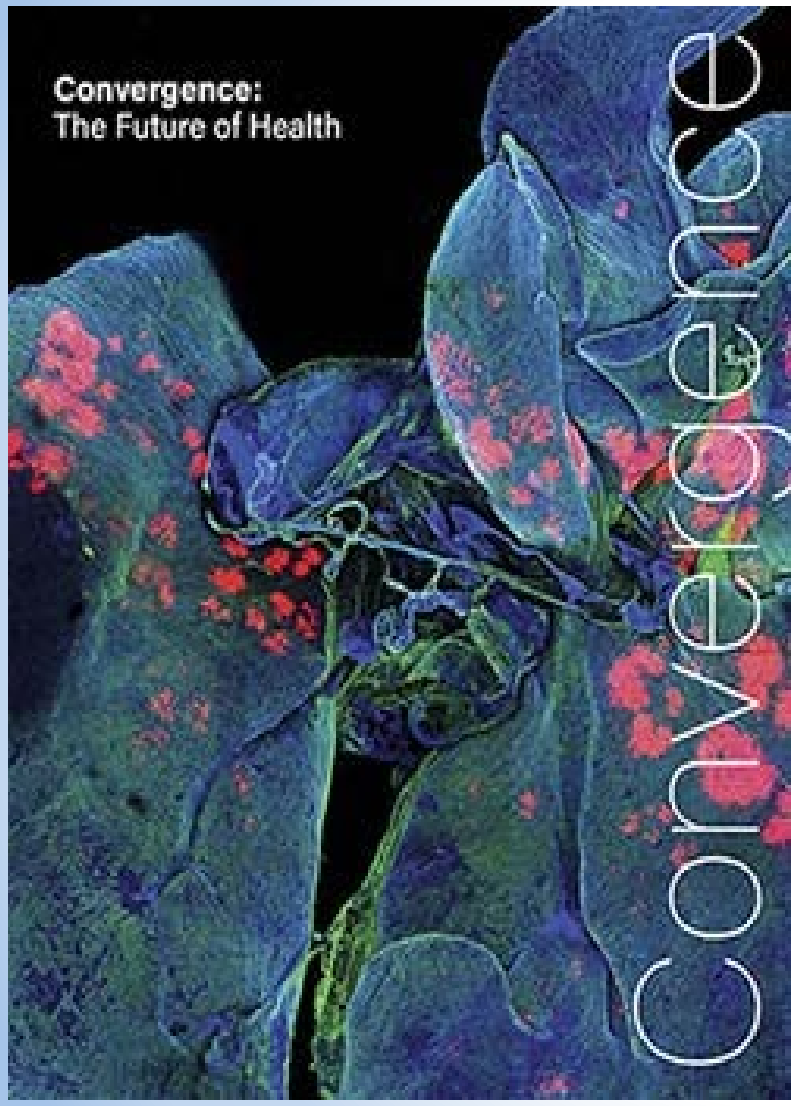
Application of convergence to biomedicine



National Academies study (2014)

"Convergence - Facilitating Transdisciplinary Integration of *Life Sciences, Physical Sciences, Engineering, and Beyond*"

Application of convergence to Future of Health



MIT - Harvard
convergence for health

2011 Paper in Science:
combines
Biomedicine, S&E

2016 Report:
Convergence:
The Future of Health

Application domain driven reports

- National Academies: Convergence for Life Sciences, Physical Sciences, Engineering, and Beyond (2014)
- MIT-Harvard: Biomedical applications of convergence (paper 2011), and The Future of Health (report 2016)
- OECD Bio, Nano, and Converging Technologies group: BNCT series of reports (2014-)
- NSF-SRC-industry: Intelligent Cognitive Assistants (2016-)
- NSF portal: Convergence for research and education (2016-)
- National Academies: Convergent ERC centers (2017); ……

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

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

Convergence science – Creating/ changing an ecosystem for a goal based on *10 theories, 6 convergence principles, and specific methods*

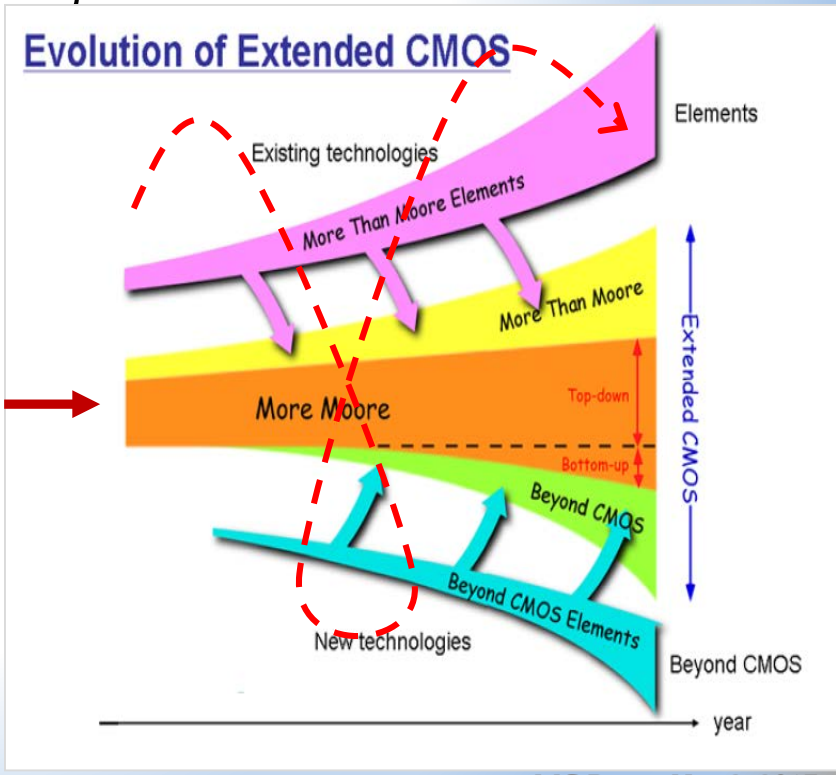
2. The convergence process

(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)*



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

CONVERGENCE THEORY SPIRAL

Ref. 9

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

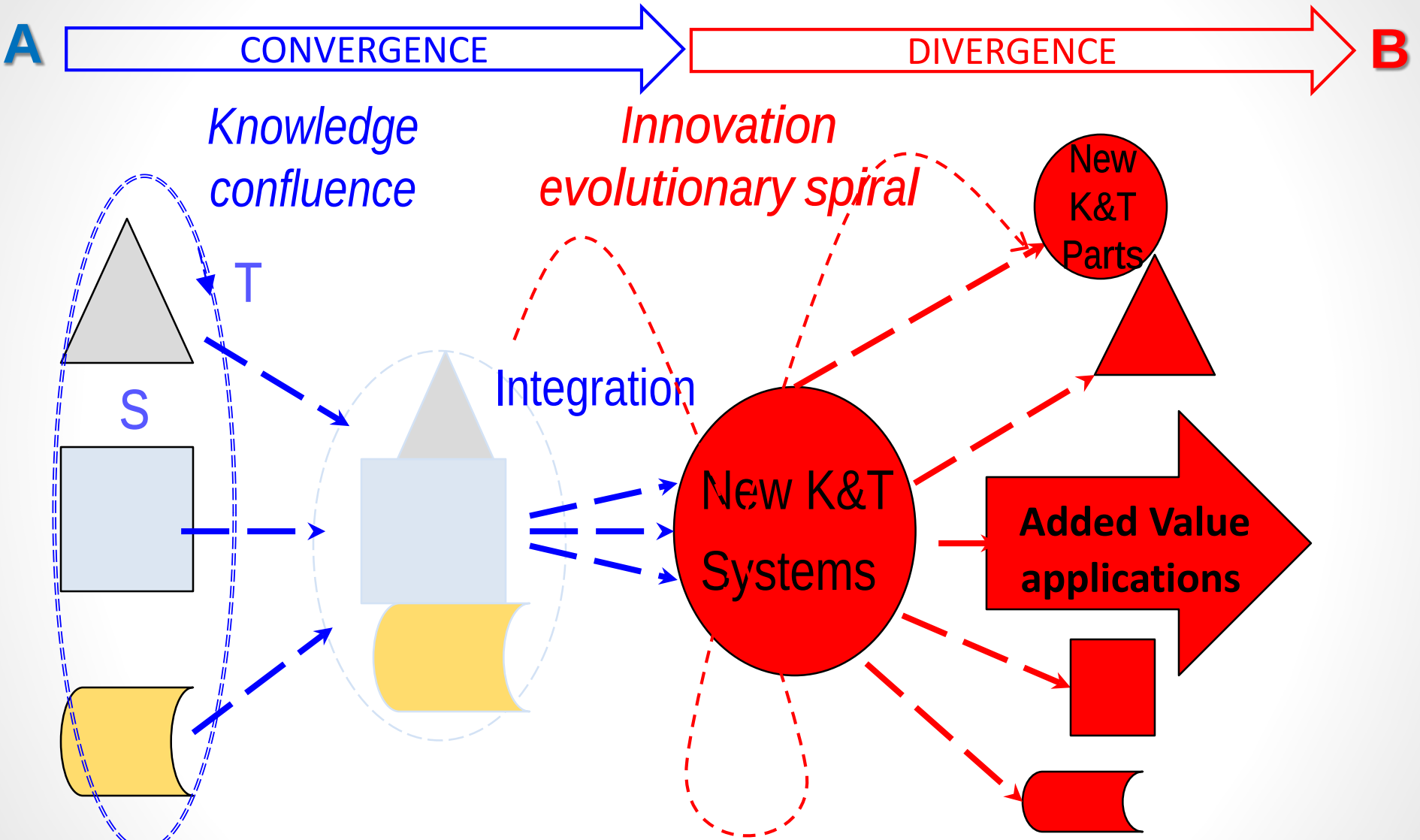
E. Confluence of resources leading to system changes (S curve)

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

PRINCIPLES FOR CONVERGENCE

Ref. 8

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)

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)

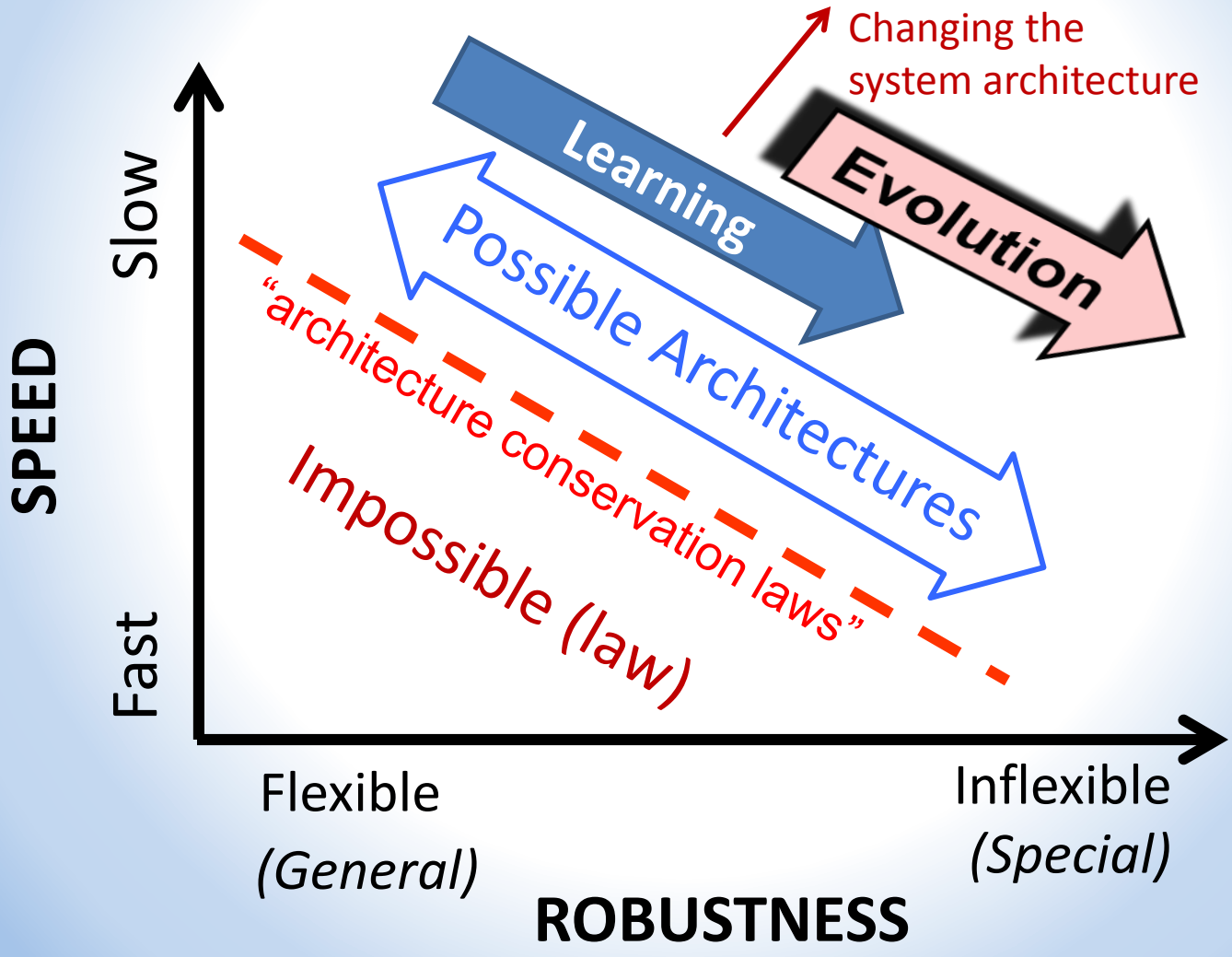
k - coefficient of proportionality (a function of convergence domain S and external context E)

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)

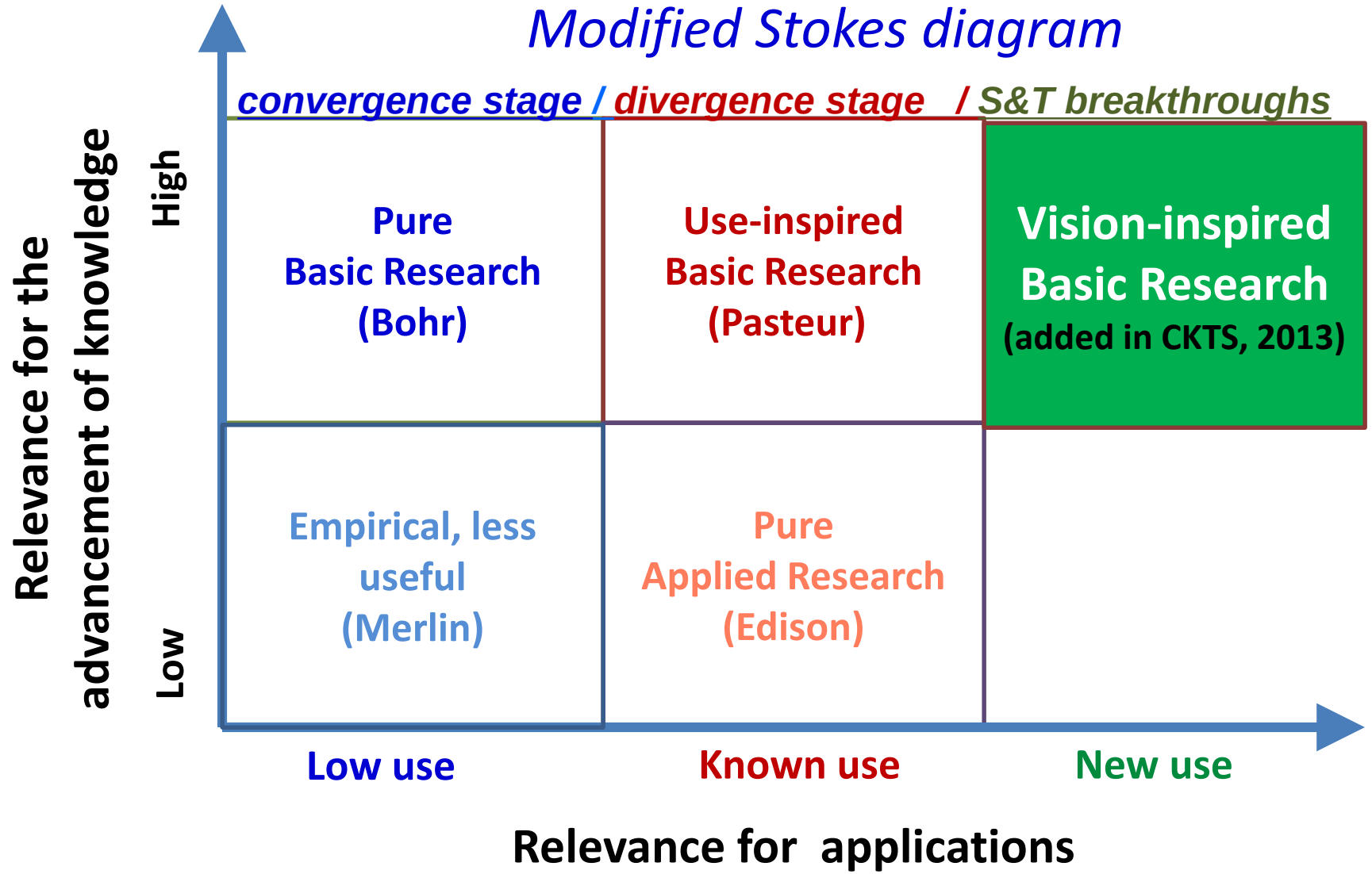
(Ref 6: CKTS Report 2013)

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

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



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)

- Applications -

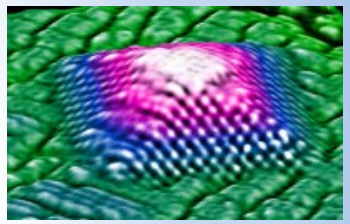
Three implemented stages
of Science/Technology/Innovation Convergence

Three stages of convergence
applied to general-purpose technologies

(Ref 6: CKTS, Springer, 2013)

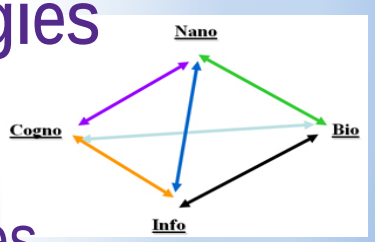
I. Nanoscale Science, Engineering and Technology
"Nanotechnology"

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

I. Nanotechnology programs: S&T divergence

OSTP

DOC/NIST

NASA

HHS/CDC/
NIOSH

DOS

DOTr

DOT

IC/DNI

DOJ

DOC/EDA

DOC/BIS

DHS

CPSC

ITC

DOEd

DOL

DOC/
USPTO

DOI/
USGS

NRC

EPA

USDA/FS

USDA/NIFA
USDA/ARS

HHS/FDA

DOD

NSF

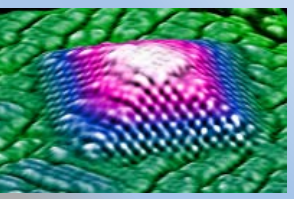
OMB

OSTP

HHS/NIH

DOE

Control of matter at the nanoscale



U.S. National Nanotechnology Initiative, 2000-2030

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

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

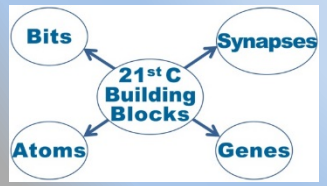
Precision Med

Genome(s) | Microbiome

Architecture, Life, Human-technology

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

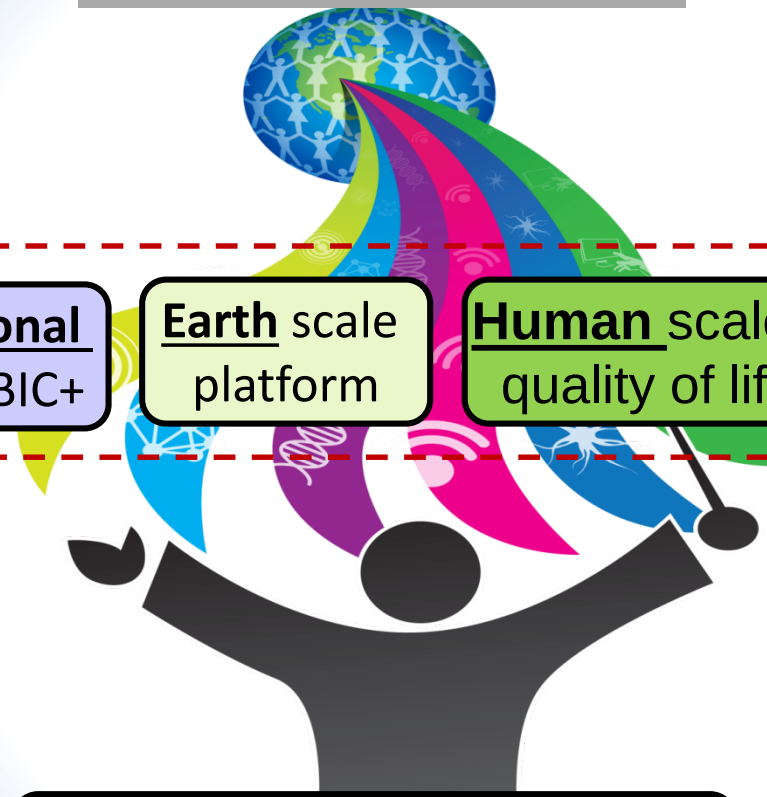
Materials Genome | Photonics | NNI Grand Challenges



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

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

Innovation
WH Office Am. Innovation

SunShot GC (DOE..)

Climate Action Plan

Strategy for Arctic Region

Aging Population

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

Societal

Earth ***Human***

NBIC+

STEAM Education Initiative (NSF, DoEd)

Asteroid GC (NASA..)

Space Station (NASA..)

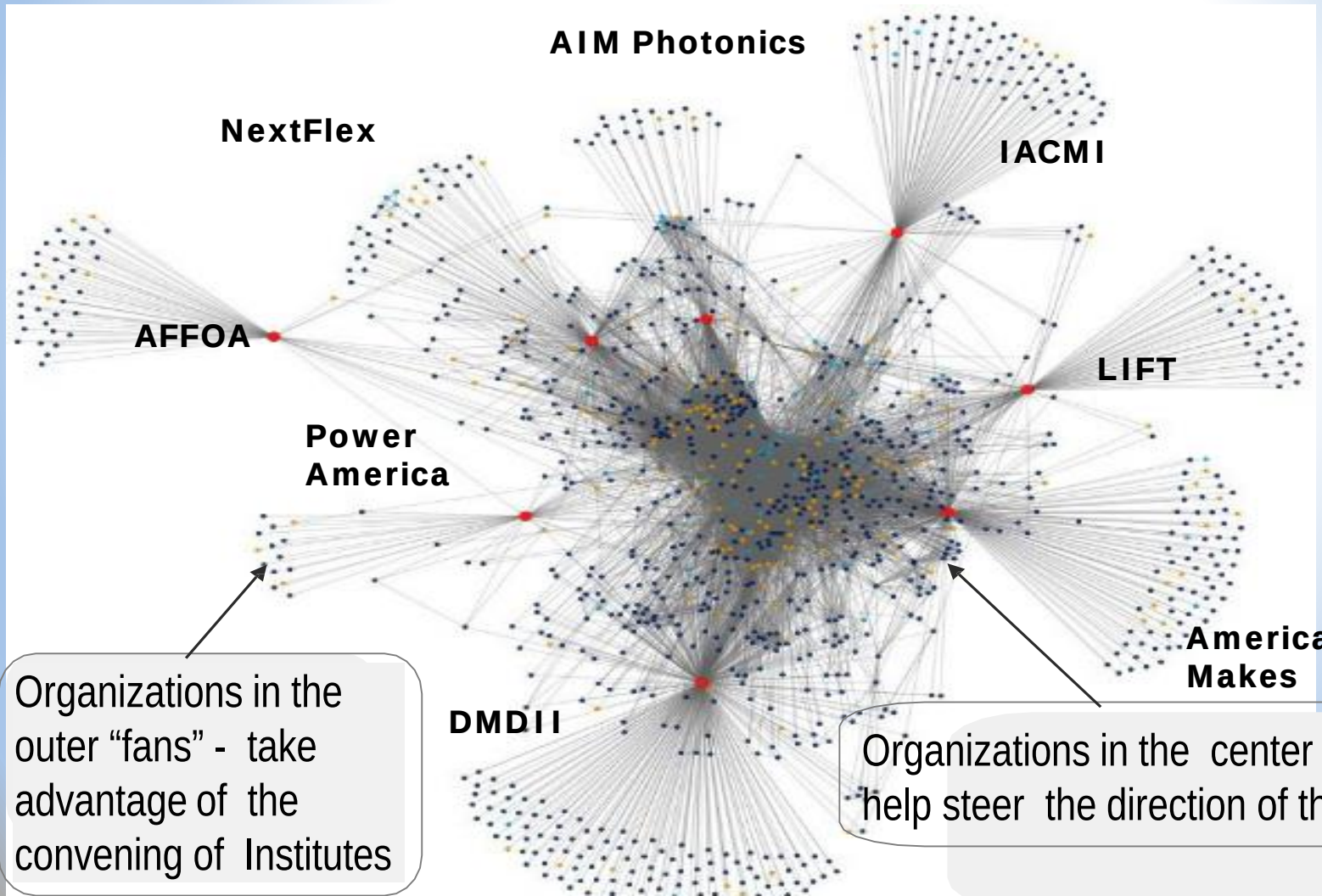
Productivity, Sustainability, Equality, Safety

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

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

III. 14 Manufacturing USA Institutes

Deloitte report: 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.

- Topical applications areas-

Several opportunities for implementation of convergence

- Production process (manu, service, etc.)
- Biomedicine, science and engineering
- Individualized learning

- Research/education for grand challenges
- Intelligent cognitive assistants
- Citizen science

- Governance (local, national, global)
- Sustainability/global change (at NSF)
- Smart communities

Defining convergence for research and education at NSF

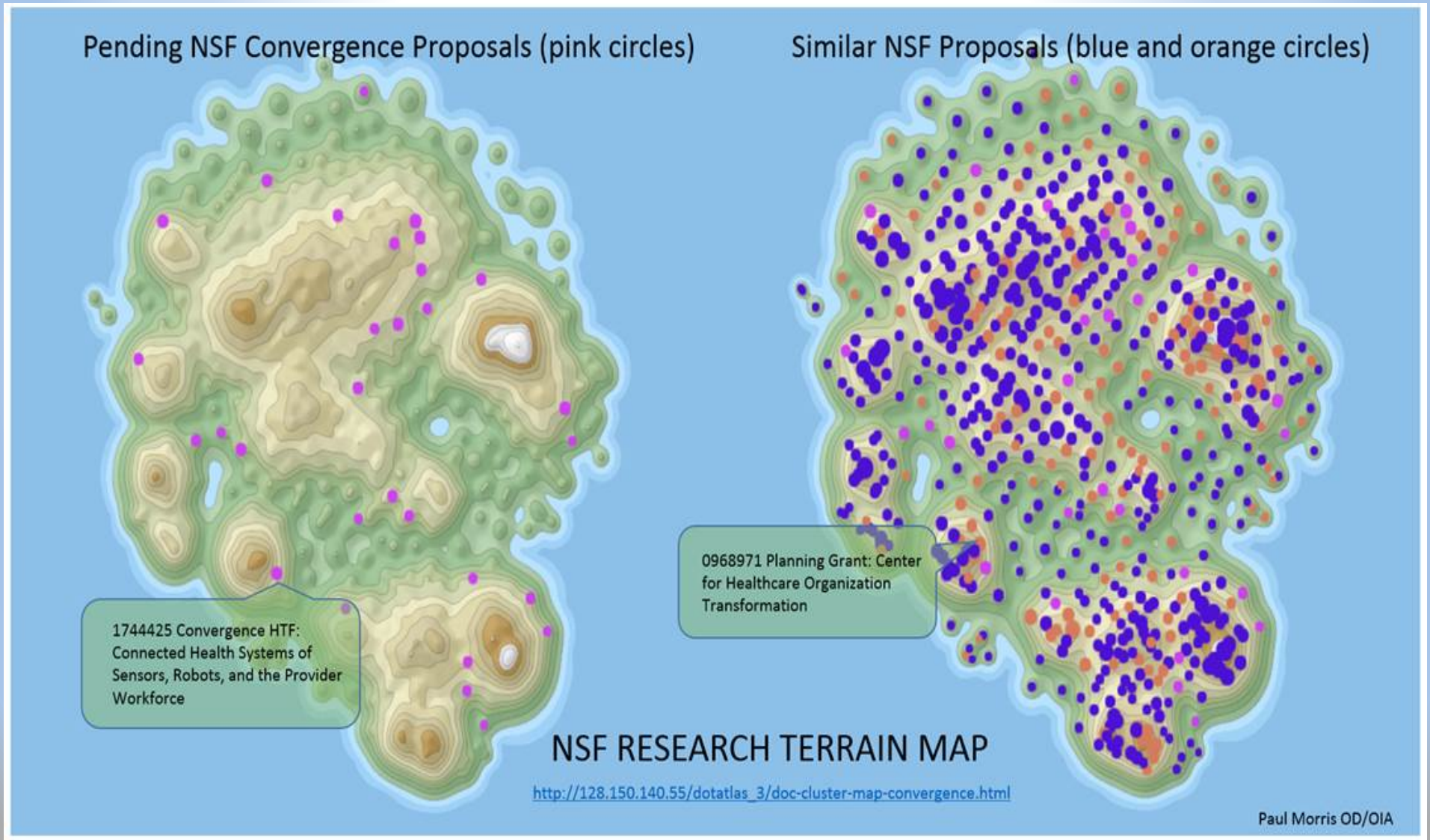
Convergence characterization in research and education (at NSF, 2017)

Convergence is the deep integration of knowledge, techniques, and expertise to form new and expanded frameworks for addressing scientific and societal challenges and opportunities, with two primary characteristics:

1. *Deep integration across disciplines, from which new* 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.

www.nsf.gov/od/oia/convergence/index.jsp

Convergence award topics “in the valleys” between traditional topics



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

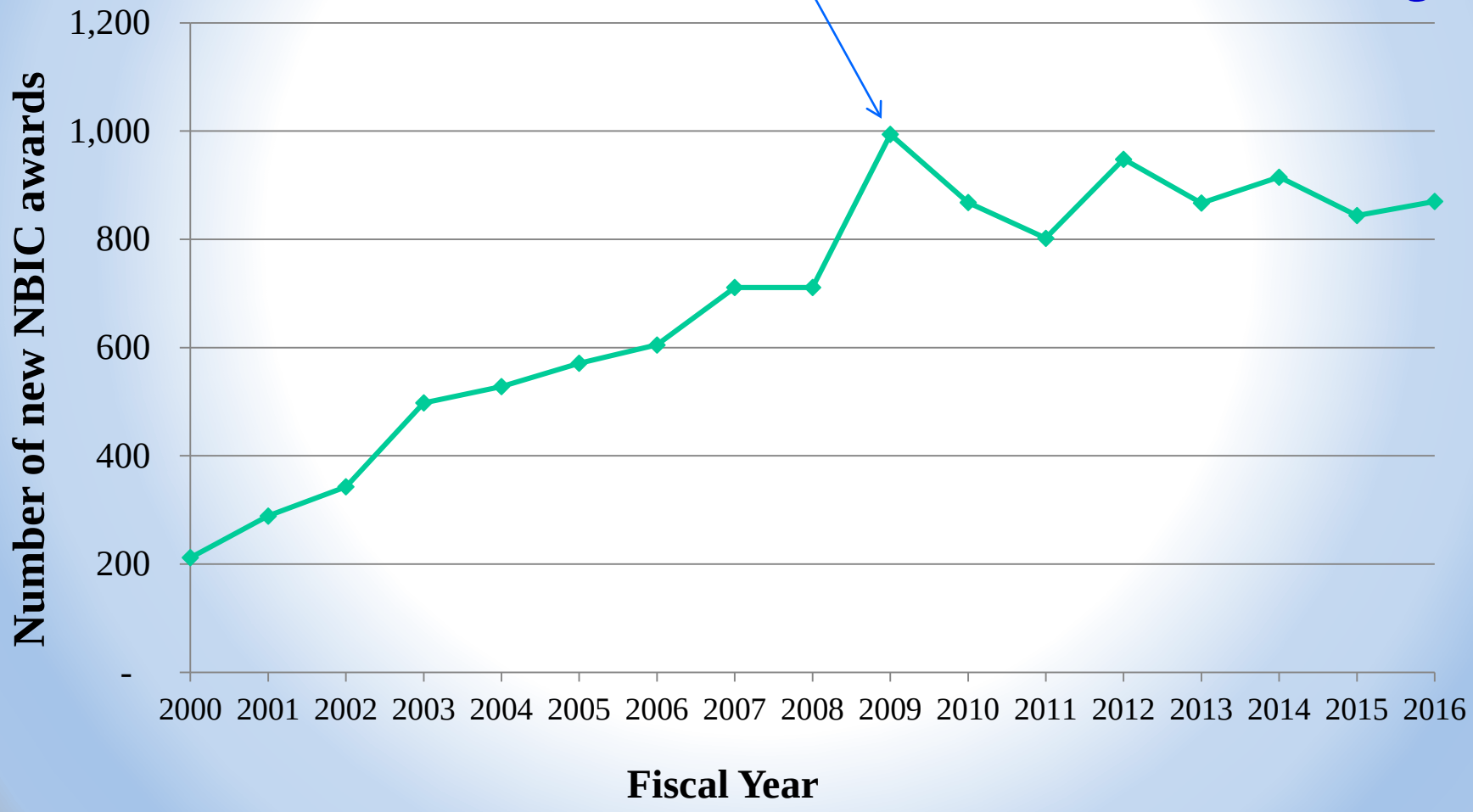
Convergence-Divergence process (downstream): Innovation Corps (I-Corps™)

- 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

Number of NBIC Awards at NSF (2000-2016)

Search by combined keywords

Since 2009, about **5% of total NSF new awards on NBIC**; of which about 1/10 of these focused on NT-IT convergence



Convergence for education

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

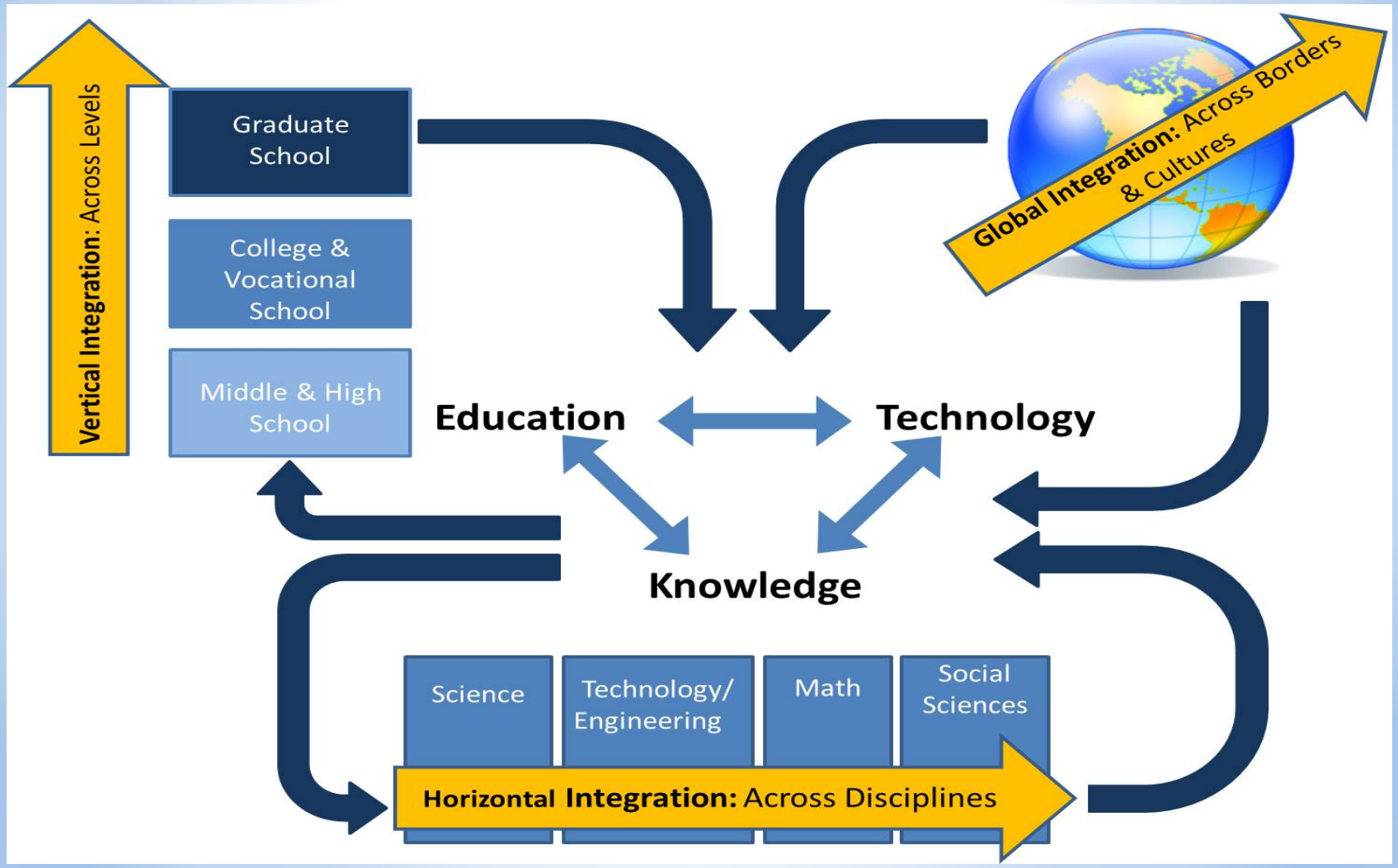
Convergence methods in education (1)

(examples corresponding to convergence principles, as a function of goals)

Ex A. - **Integration** along disciplines, levels, borders and cultures; with benefits for larger domains and faster interactions

- **"Trading zones"** among various areas of relevance
- **Team science** with system view, upstream collaboration plans
- **Circular solution** in science and education
- **Incentives for convergence** in degree accreditation and academic promotion
- Improving **interpersonal and intrapersonal training**
- Revise **organizational structure and regulations** to allow convergence processes to be more effective (IGERT,
- **Confluence of topics** by bringing together: (a) foundational NBIC topics; (b) Feasibility (science & engineering), desirabillity (art & humanistics), and viability (economics & management)

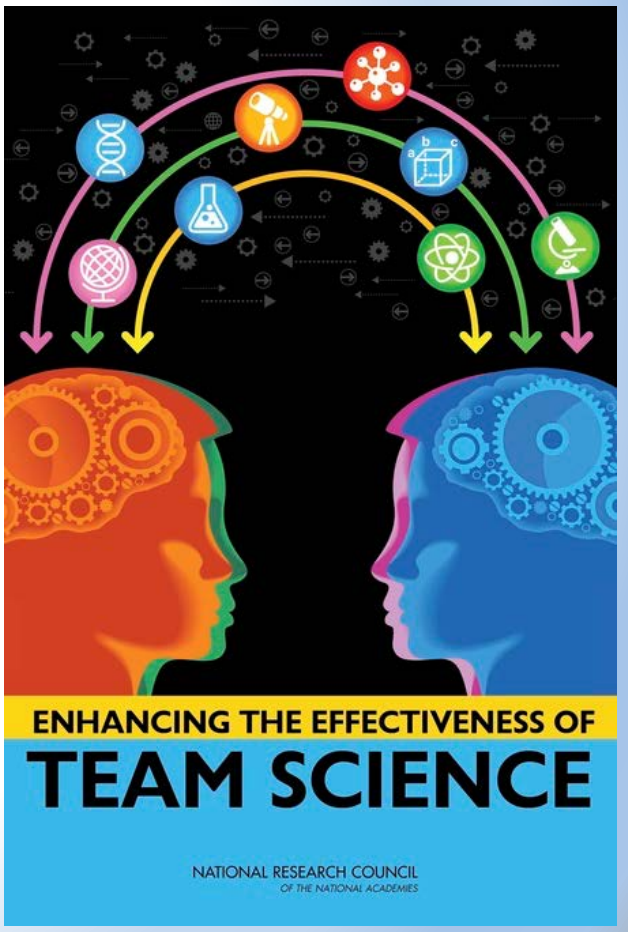
Ex A: Schematic highlighting six axes of integration required for convergence of knowledge & technology to further education



(CKTS 2013, Courtesy R. Chang)

Ex A. TEAM SCIENCE
- A Model Course for Pre-Service Teachers -
University of Delaware

- Designs and implements a first-year, seven-credit multidisciplinary course in science, math, technology, and communication for pre-service high school teachers
- Multidisciplinary team of instructors for the course: research scientists and mathematicians + science and math educators + specialist in writing, teamwork, and communication
- Stresses critical thinking, technology, and communication skills — what future high school science and math teachers will need to know to be effective in the classroom



Ex A. National Convergence Technology Center

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.

Ex A. 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)

Convergence methods in education (2)

(examples corresponding to convergence principles, as a function of goals)

Ex B. Creative assembling of tools for changing the education ecosystem and dissemination. Ex: Virtual reality; digital tutors for students & teachers; modeling and simulations.

Ex C. System-logic deduction: Reversing the pyramid of learning. Learning first unifying concepts of matter / biology/ information systems, and then averaging techniques specific to each discipline

Ex D. Using higher level multi-domain, essential languages. Ex: Mathematics, general modeling and simulation methods, music; “Big Ideas of Nanoscience” (NCLT); More generalists.

Ex E. Confluence of resources for system changes

Convergence methods in education (3)

(examples corresponding to convergence principles, as a function of goals)

Ex. F Vison-inspired education methods:

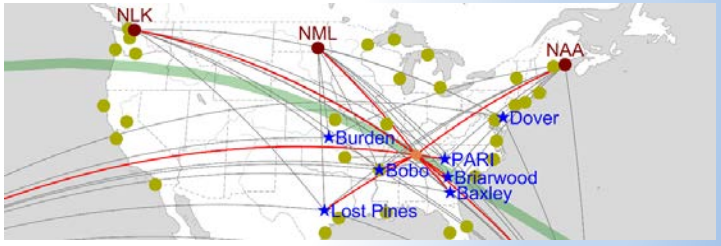
- Forecasting and scenario development: Ex: Long-term planning and management for grand challenges
- Promoting a culture of convergence based on common vision. Ex: Use anticipatory, participatory and adaptive technology assessment to influence culture
- Anticipatory measures for preparing people, tools, organizations, and infrastructure. Ex: Risk analysis of emerging technologies by *Int. Risk Governance Council*
- Reverse mapping and planning.

Ex: NNI goals for ten year intervals (2000s, 2010s) were reversed mapped for funding and investment decisions

Seeding new ideas

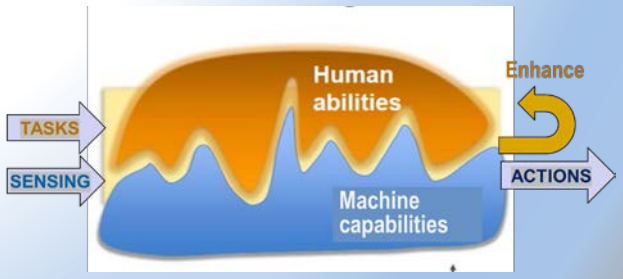
- *Opportunities for future progress: By vision inspired basic research, beginning with selecting earlier scientific changes, identifying the unifying concepts and cross-domain languages, and applying other converge principles.*

- Examples (in 2017):



  - Expansion of citizen S&T,
    and the role of crowdfunding in the STEM ecosystem

  - Intelligent cognitive assistants
    as tutors for personalized education
    (ICA report, SRC-NSF, 2016)



Global Action Possibilities

- An international convergence CKTS network
- Government coordination for: "*science of convergence*" , *"convergence technology platforms" & workforce preparation*
- Manufacturing, cognition-, biomedicine- convergence
- Cross-domain programs in universities & funding agencies
- Principles of convergence for conflict resolution
- Expand role of OECD convergence group to education

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)*

RESERVES

Global Perspectives in Convergence Education

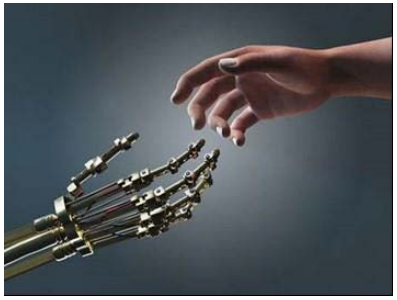
Workshop: NSF / OECD / U.S. National Academies / USC

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

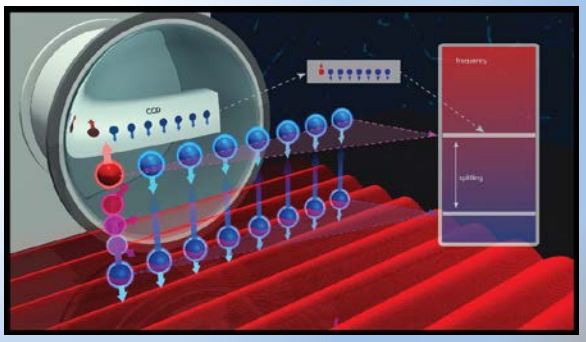
- Identify best-practices for evolving global educational systems facilitated by convergence
- Enhancing the capacity of workers, citizens and society to prepare for converging technologies
- Involve various stakeholder communities around the globe, including in developed and in-development economies

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**