



Principles of convergence in nature and society

with illustration to Converging Technologies

Mihail C. Roco

National Science Foundation and National Nanotechnology Initiative, United States

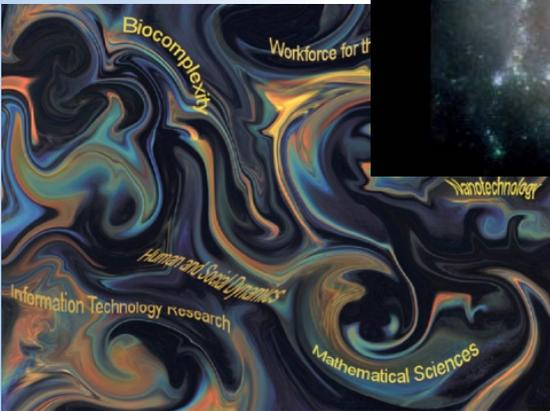
European Academy of Sciences & Arts workshop, Salzburg, March 1, 2019

Principles of Convergence

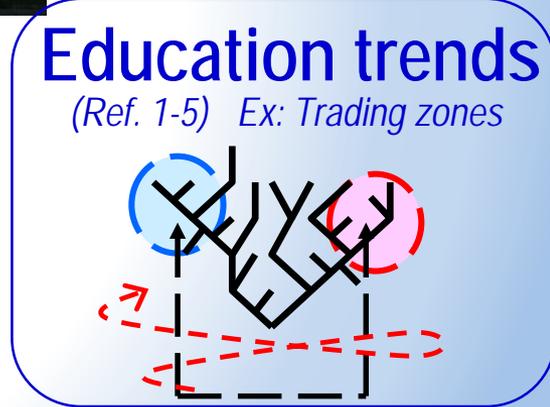
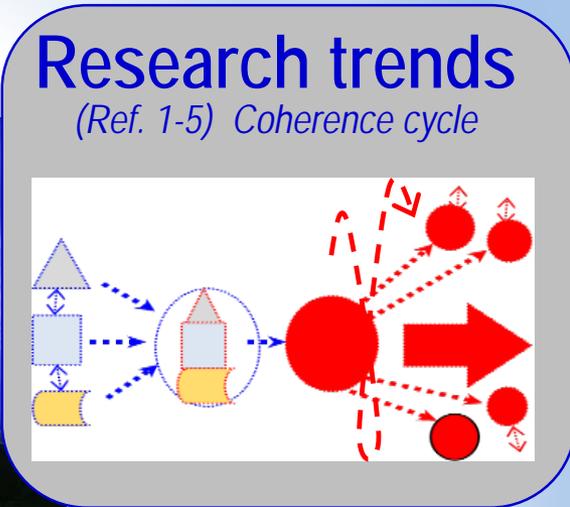
- ✓ Convergence in nature and society
- ✓ Seven convergence principles -
for problem solving in complex systems
- ✓ Relevance to emergence of
foundational technologies - NBICA

Evolution in nature, science, technology and society

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



The resulted ecosystems are too complex for single-domain methods



Convergence is: a problem-solving strategy to holistically understand and transform an ecosystem for reaching a common goal (Roco 2002)



Further defining S&T convergence

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

Convergence approach includes:

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

Convergence science includes:

Underlying theories, principles, and methods – that facilitate convergence toward goals

Definition applied to selected fields:

- **National Academies, 2014 – applied to healthcare**

Convergence is an approach to problem solving that cuts across disciplinary boundaries from health sciences, physical, math, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields. (Priority at Academies 2018-2019)

- **NSF, 2017 – applied to research and education**

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

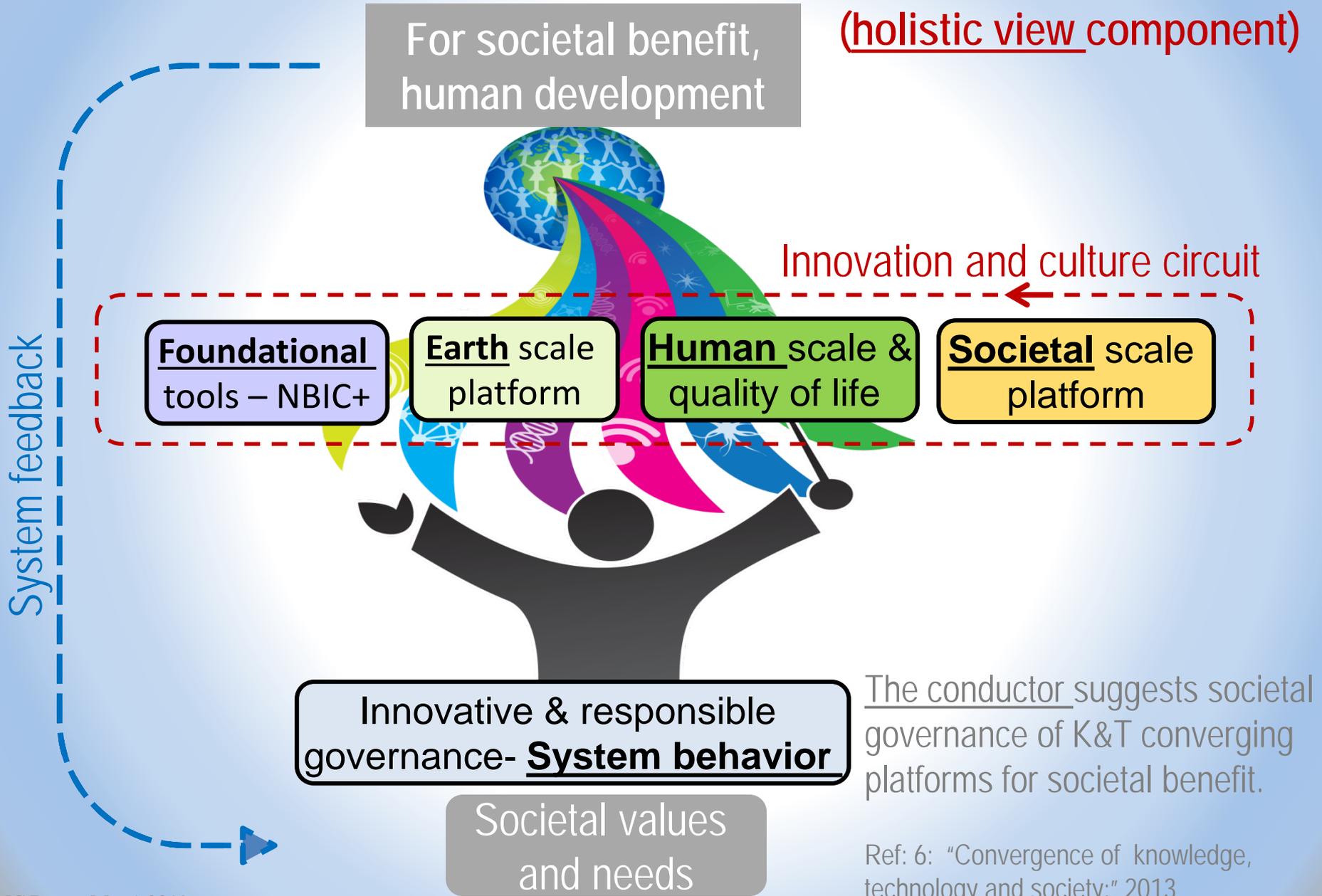
Convergence of knowledge, technology and society is guided by seven principles

- A. **Holistic view** – Interdependence-coherence in nature and society (*find 'unity in diversity'*)
- B. **Common goal** - Vision-inspired basic research for long-term challenges
- C. **Dynamic pattern** - Processes of spiral convergence and divergence
- D. **Unifying actions**- Ecosystem-logic deduction in decisions & problem solving
- E. **Cross-domain** - Higher-level languages
- F. **Multiple pathway dynamics** – Multi-tasking
- G. **Added-value** - Confluence of resources leading to ecosystem changes (*'S curve'*)

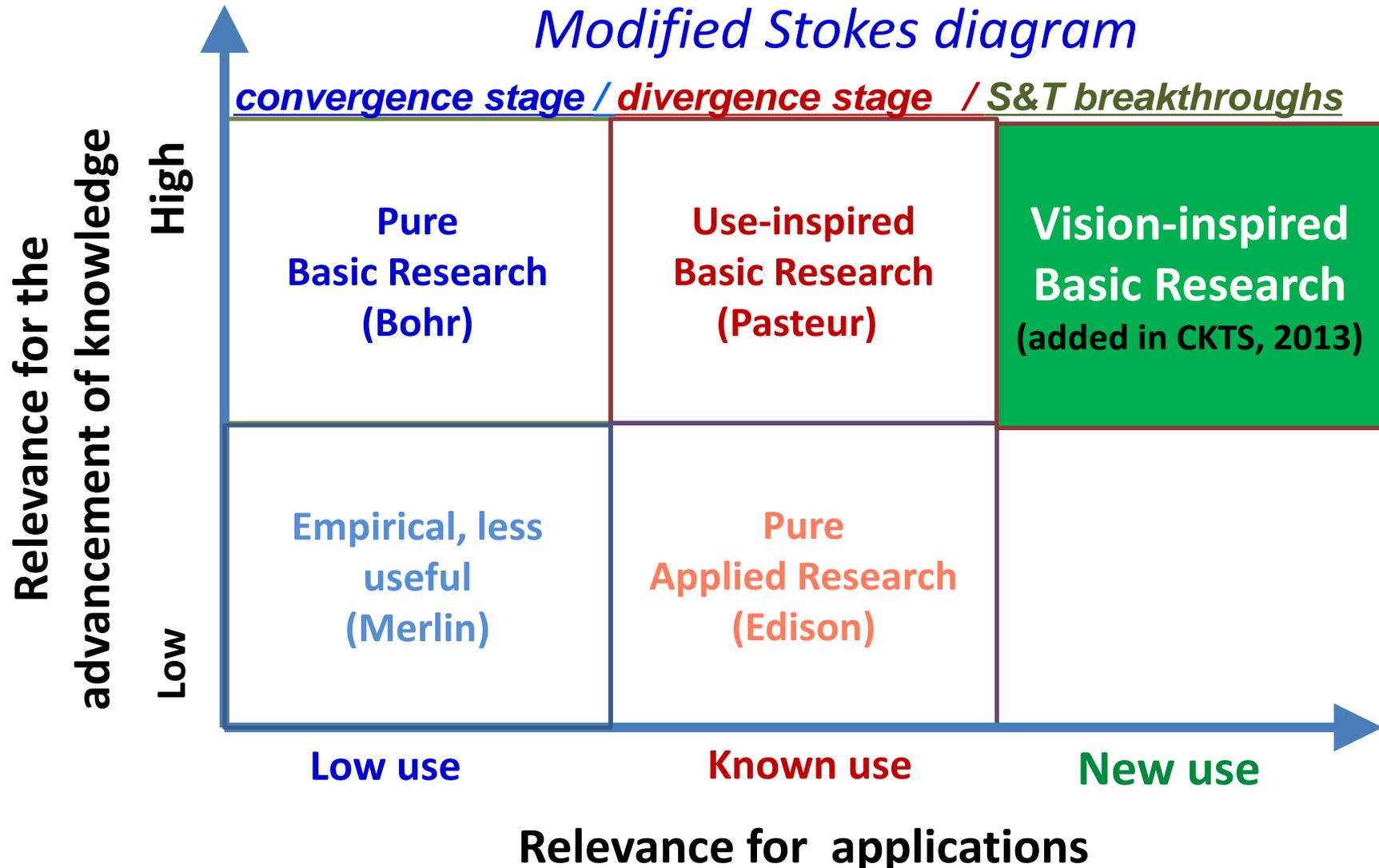
PRINCIPLES FOR CONVERGENCE



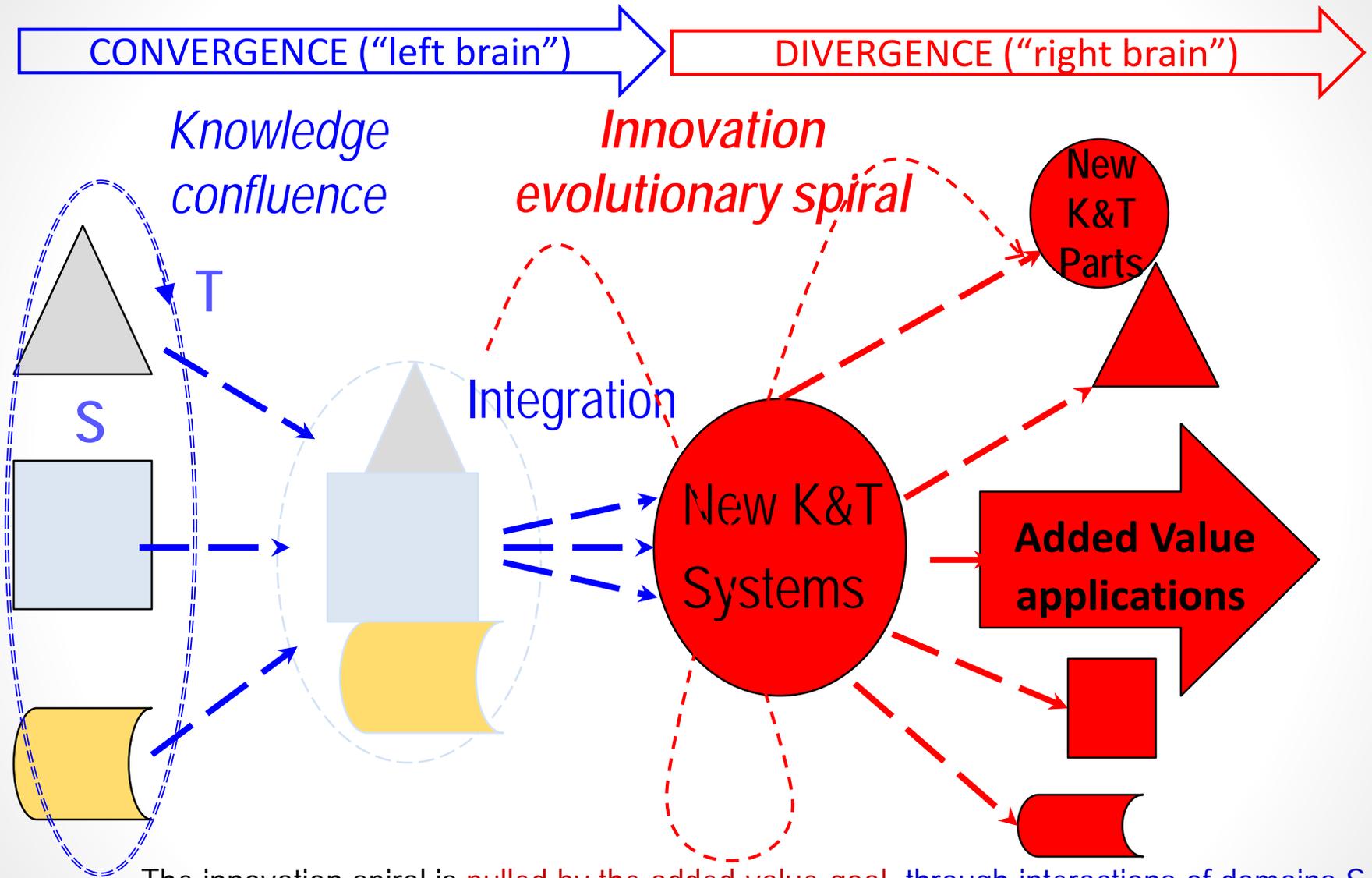
A. Human activity system by convergence platforms



B. Common goal - Vision inspired discovery and inventions are essential for the future of innovation



C. Pattern: Spiral convergence & divergence in S&T



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

ENV

C. Examples of spiral convergence & divergence pattern

- In nature: Various shapes of tornados



- In thinking: Combining computational, directional reasoning ("left brain") and interferential, lateral creativity ("right brain") leads to a spiral pattern
- In general: DNA spiral, bio-evolutionary spiral; innovation evolutionary spiral, stellar spirals . . . : fractals of a higher order principle?



C. Example convergence-divergence opportunities: the cellular phone

Coincidental convergence:



High “innovation index” in
a convergence process

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

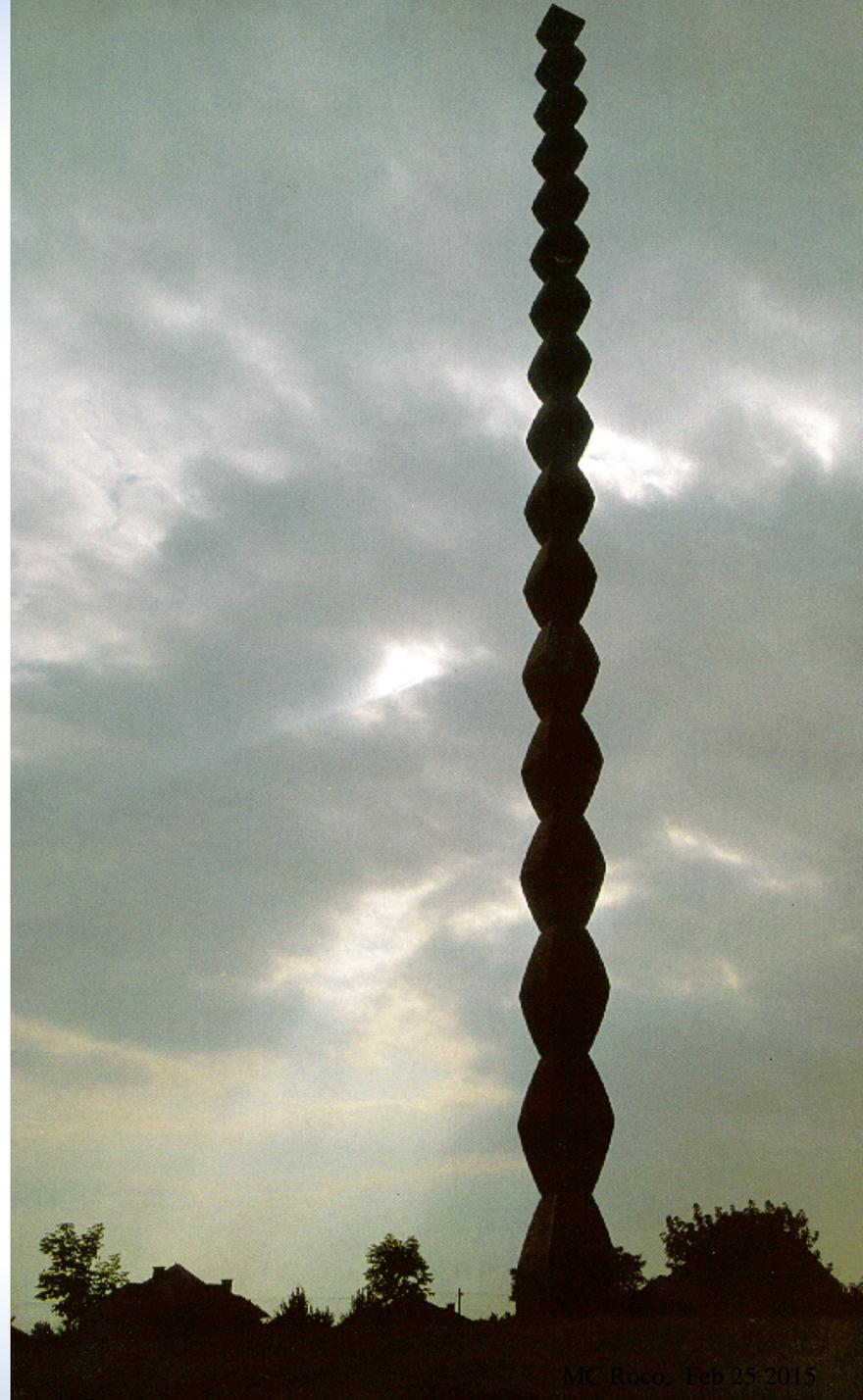
(Ref 6: CKTS Report 2013)

- **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, miniaturized satellites, healthcare and many other examples affecting virtually every aspect of our society.

C. "Endless Column", sculpture by C. Brancusi (1937)

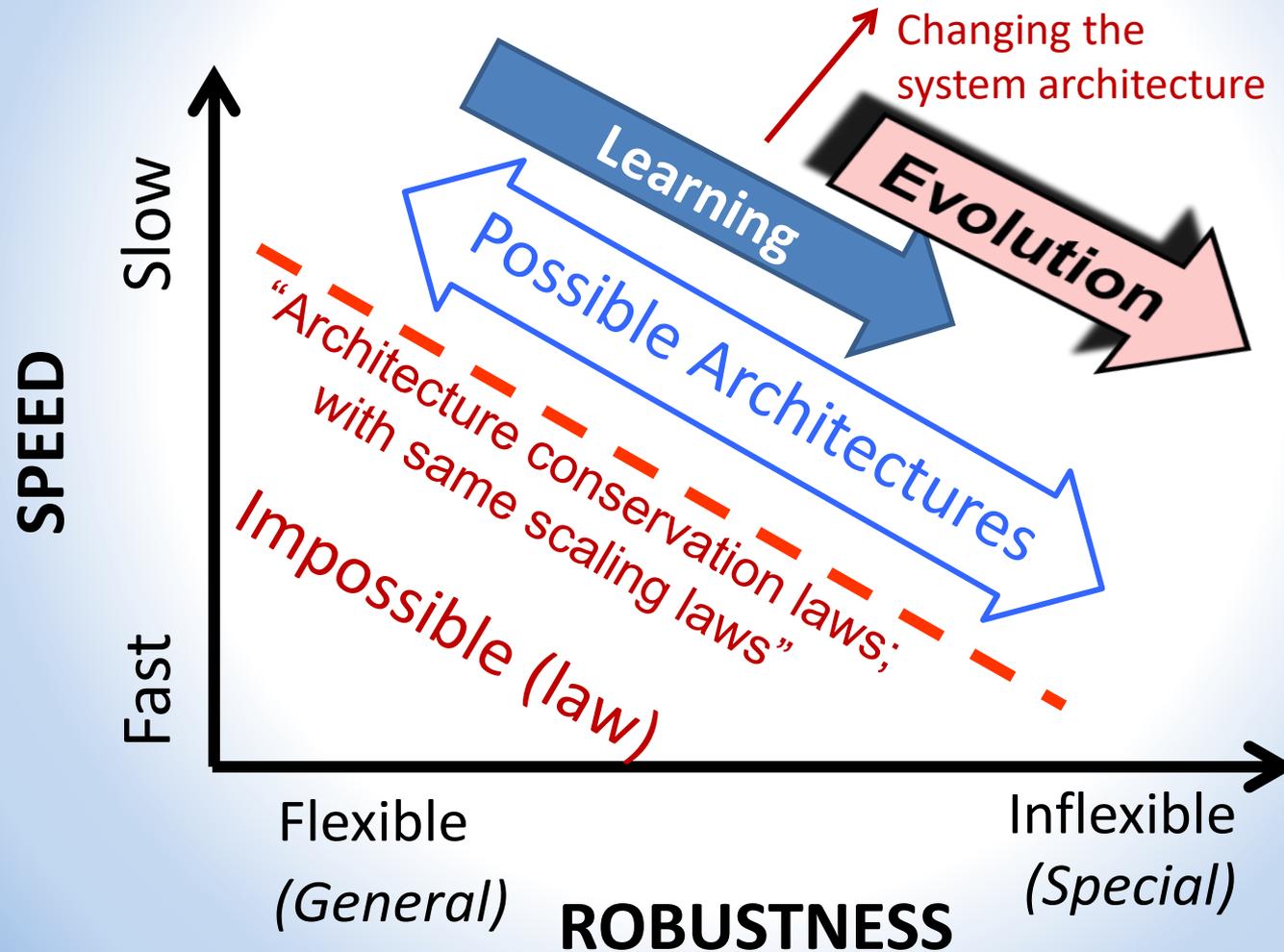


Convergence-divergence elements



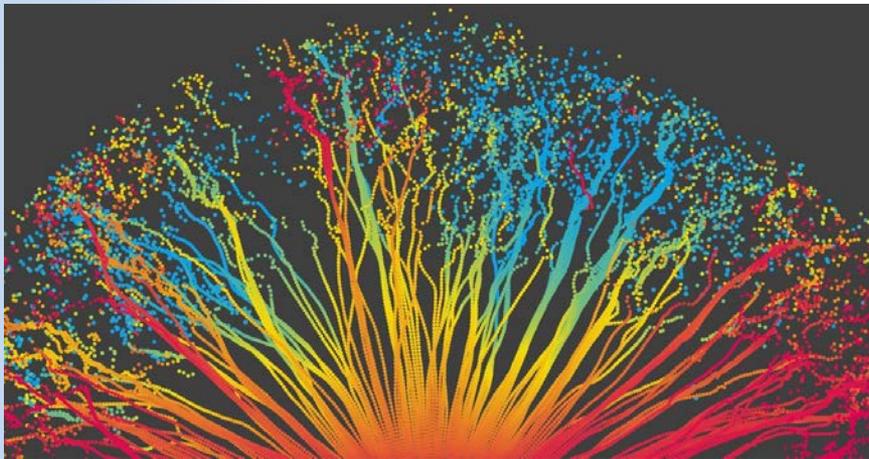
E. Cross-domain: Unifying languages

Universal laws for system architectures: correlations, scaling

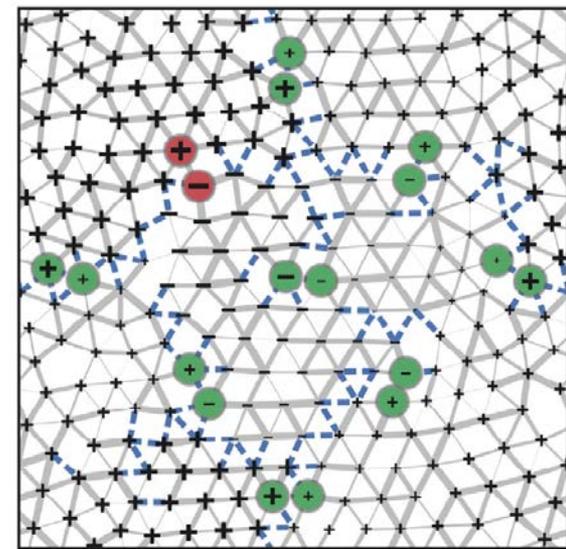


F. Multiple cause-and-effect pathways

Leading to co-evolution of paradigms, requiring multi-tasking, multiple-algorithms in a complex system network



Blood flow in brain



Water flow in water distribution network

Ex: The limits of multi-tasking in biological networks, distribution networks, and other complex systems can be defined (Katifori et al., PNAS, 2019)

CONVERGENCE OF KNOWLEDGE, TECHNOLOGY, AND SOCIETY:

Beyond Convergence of Nano-Bio-Info-Cognitive Technologies

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



INTERNATIONAL BENCHMARKING and APPLICATIONS

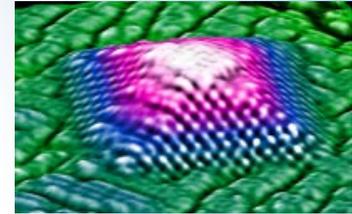


Three stages of convergence

(Ref 6: CKTS, Springer, 2013)

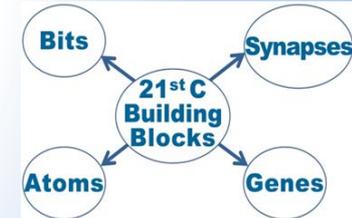
I. Nanoscale Science, Engineering and Technology “Nanotechnology”

Integrates disciplines and knowledge of matter from unifying concepts at the nanoscale



II. Foundational Nano-Bio-Info-Cognitive-AI Converging Techn “NBICA”

Integrates foundational and emerging technologies from unifying - basic elements using similar system architectures and dynamic networking



III. Knowledge, Technology and Society “CKTS”

Integrates the essential platforms of human activity using unifying seven convergence principles



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

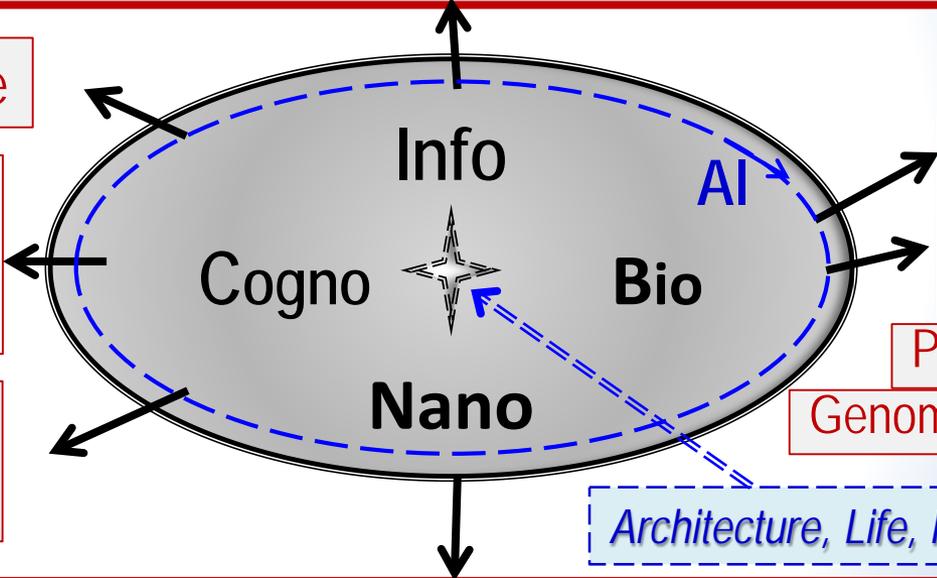
Big Data | National Strategic Computing Initiative | 5G | AI systems

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

Artificial Intelligence

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

National Robotics Initiative



Biology centered

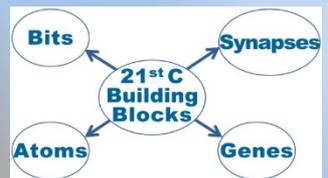
Biomedical / Health focus

Precision Med

Genome(s) | Microbiome

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

Materials Genome | Photonics | Quantum IS | NNI Grand Challenges



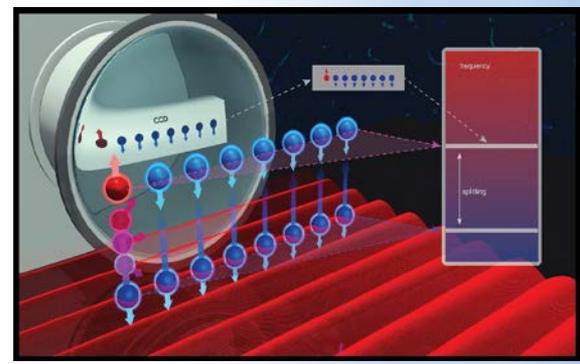
Ref 10: "NBIC", in Handbook of S&T Convergence, 2016

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



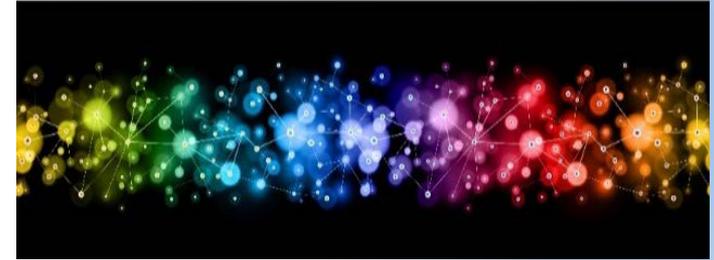
Ex II-III: 2016- NSF 10 Big Ideas (2 research ideas)

- Windows on the Universe: Multi-messenger Astrophysics
- Navigating the New Arctic



Ex 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



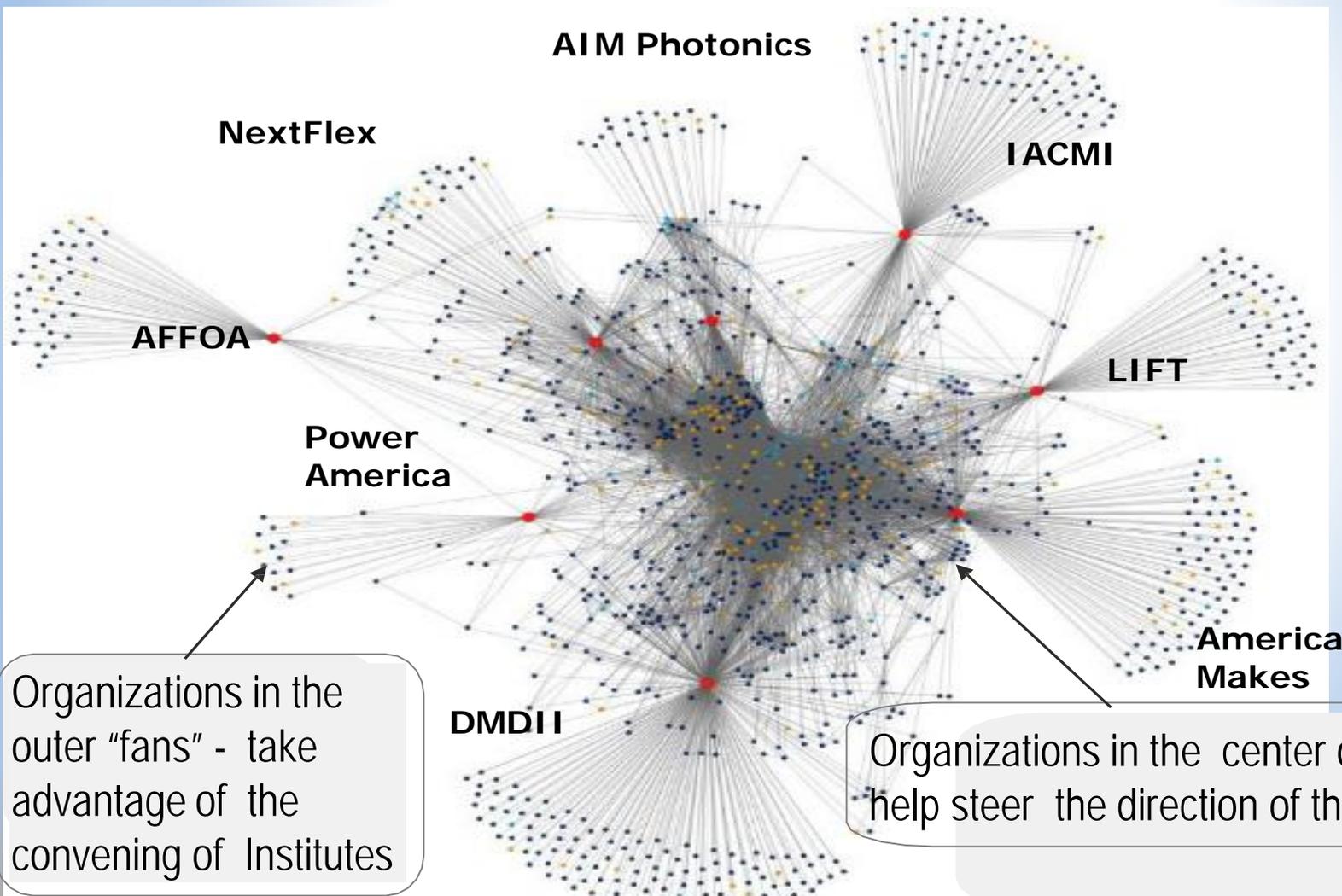
Ex III: 14 Manufacturing USA Institutes

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.

Global Action Possibilities

- Coordination for advancing: *“science of convergence”* & *“convergence technology platforms”*
- Manufacturing, cognition-, biomedicine- convergence – immediate implementation opportunities
- Cross-domain programs - universities, funding agencies
- Principles of convergence **for conflict resolution at personal to international level**
- **OECD committee on Converging Technologies (2014-)**

Related publications

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, Springer Reference, 2016)