



Principles of convergence in nature and society

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National Science Foundation and National Nanotechnology Initiative, United States

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Convergence is seen as a core opportunity for progress in our knowledge society

- ✓ What is convergence in a contextual system and time interval ?
- ✓ Principles to facilitate convergence – for solutions in complex systems
- ✓ Applications and trends: in nature, S&T governance, education, conflict resolution...

Convergence concept

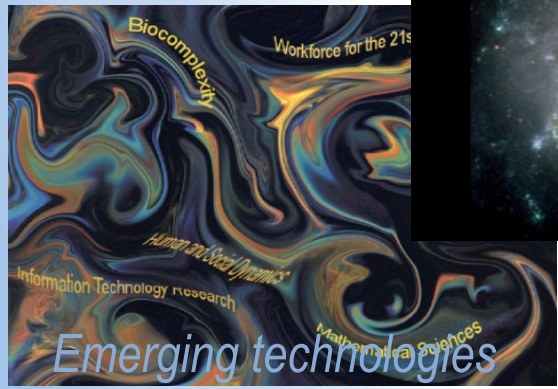
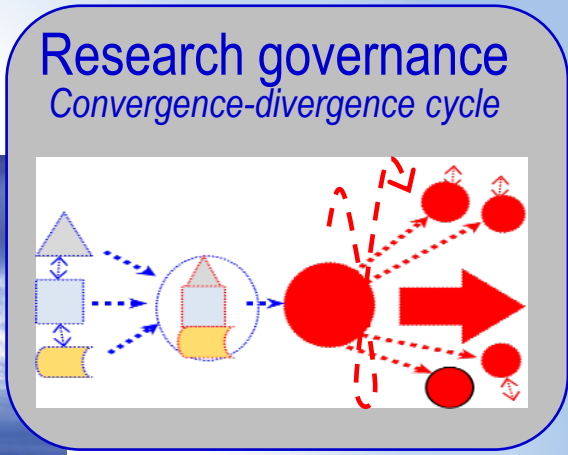
used in many ways as a function of context

- Inherent in human development; Almost all ancient civilizations: concepts of **natural interdependence and unity in nature**
- Western civilization: has shown need of **integrated knowledge in Renaissance in the 15-16th century**; then specialization
- U.S. indigenous Indian culture is guided by a **holistic interaction of nature and society**
- “Convergence” used in many ways in specific domains:
 - from **basic forces in physics & unifying knowledge** (Wilson 1999), to **societal trends** (Kurzweil 1999) & **Grand Ch. (NNI, ...)**

Now: Increased interactions & new role for convergence

Evolution in nature, knowledge, technology, and society

- *Turbulent*
- *Coherent*
- *Cross-domain*
- *Emergent*



The resulted systems are too complex for single-domain methods

Convergence: unifying strategy to reach a shared goal or satisfy a natural law, applicable to all evolving complex systems, modeled as neural networks

[Ref 1,11]

Reaching a shared goal in a system

- simplified vs. evolutive meaning of convergence -

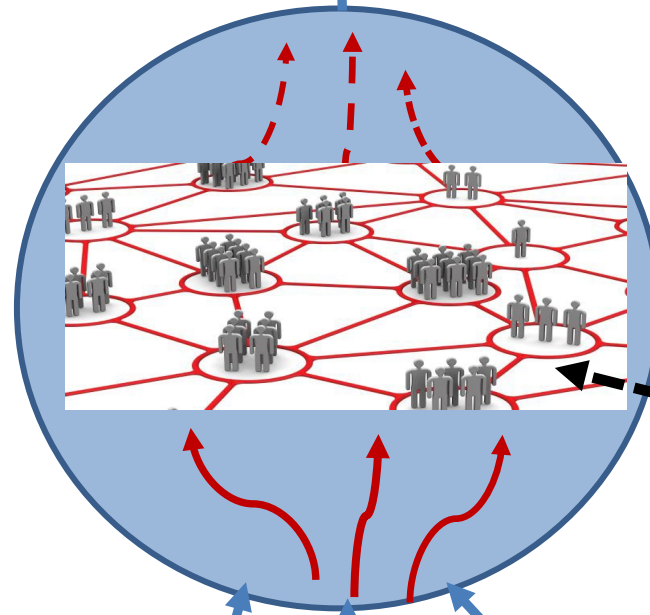
Union
of people, disciplines ...



I

(1) Integration toward union

Common Goal



Ex: Prepare tools, education, manu.. for a technology

Complex networked system

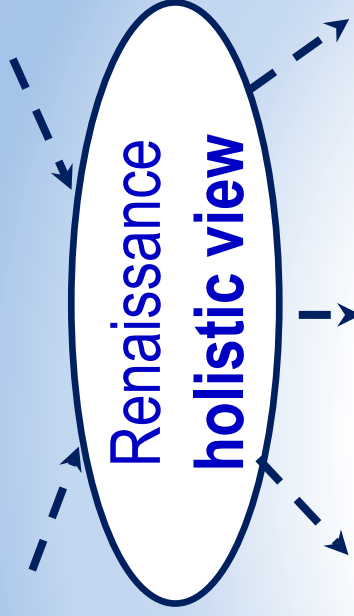
Inputs

(2) Convergence to a goal
by changing the system [Ref 1, 2]

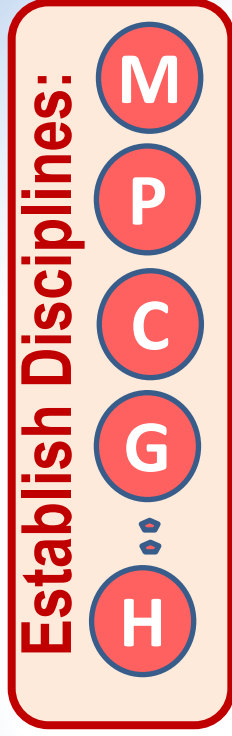
Ex: Advancement of knowledge

through coherent and non-uniform evolution of its system

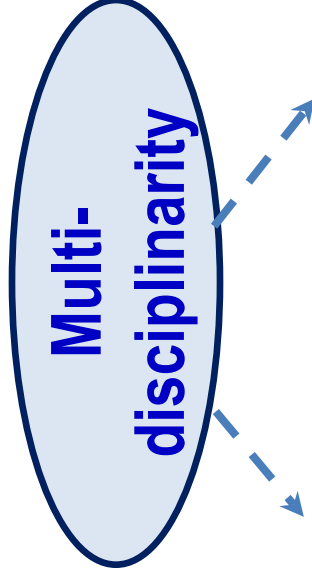
15-16th Century
Integration
of knowledge



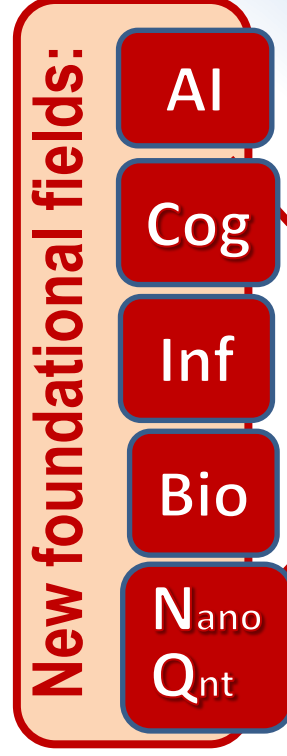
17-20th Century
Divergence
Est. disciplines



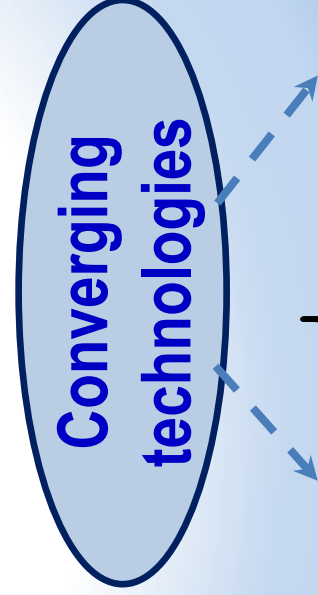
~ 1950-2000
Integration
of S&T disciplines



~ 2000 -
Divergence:
Est. Foundational
fields (N,B,I,C,A)



~ 2010 -
Convergence:
NBICA+ system

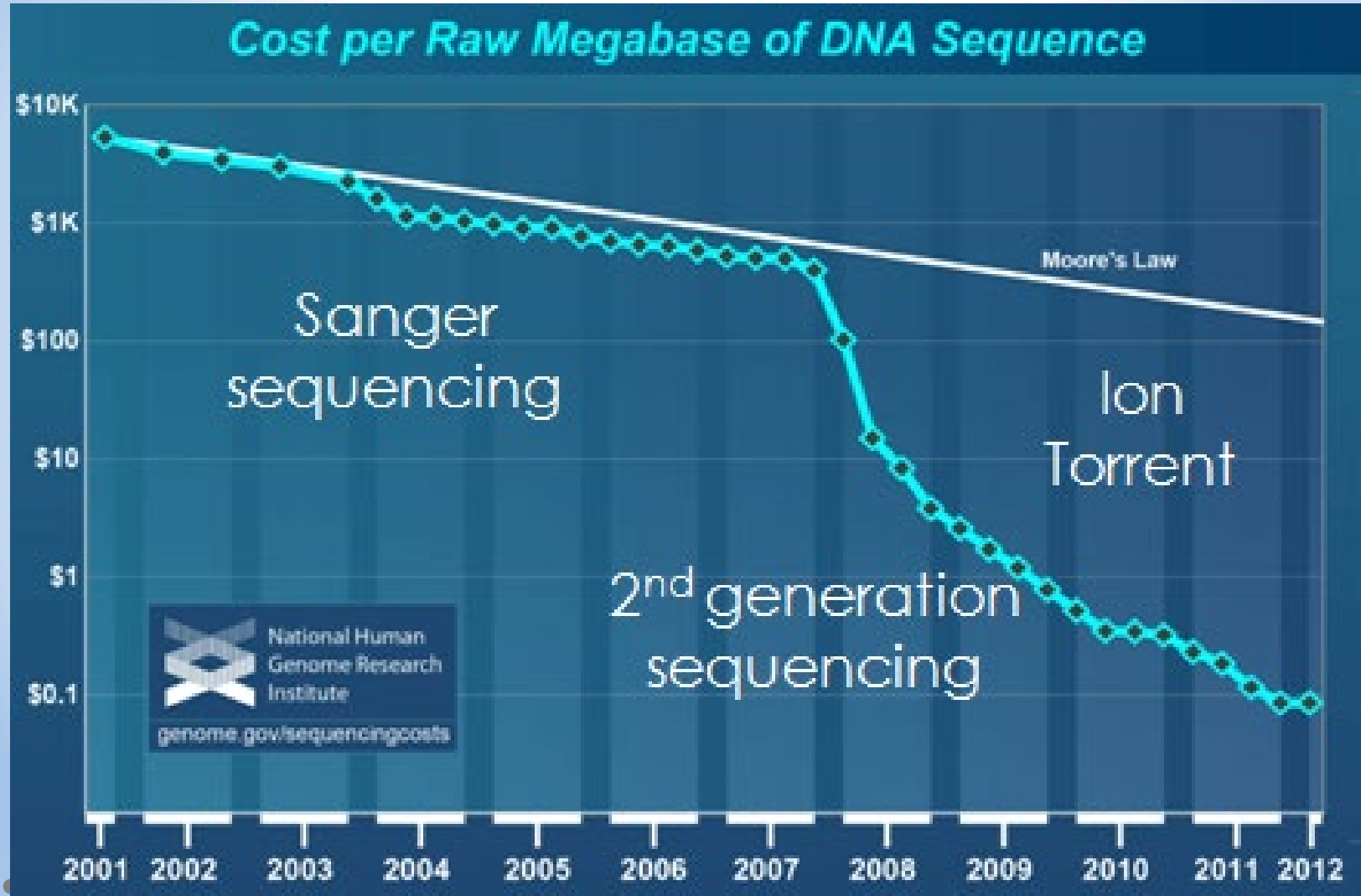


IMPROVING HUMAN CAPABILITIES



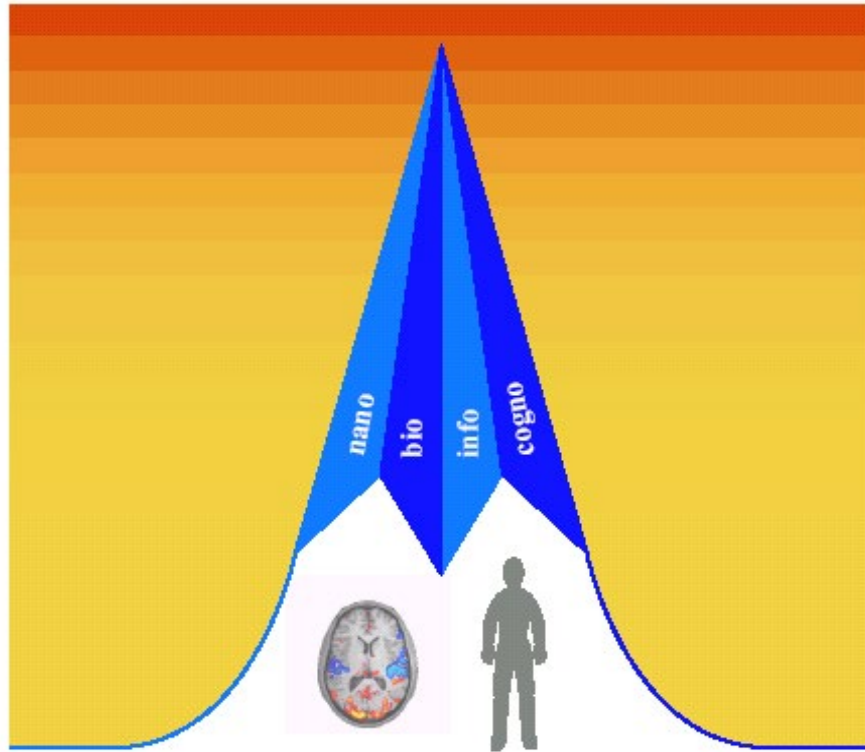
Ex. of added-value: Gene sequencing cost drops after integration with methods from nanoelectronics

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



**Several earlier studies on
knowledge and technology
convergence**

Ref 1. "Coherence and Divergence of Megatrends in Science and Engineering" 2002 (MC Roco, 2000-2002)



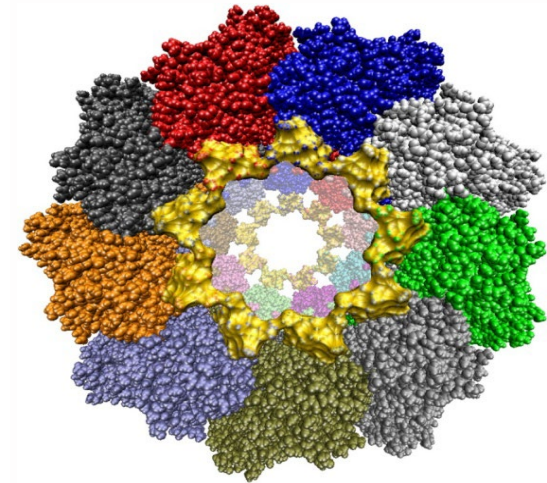
Ref 2. Converging Technologies for Improving Human Performance

**NSF-DOC Report 2002,
Springer 2003**
(MC Roco and WS Bainbridge eds)



Ref 3.

**Coevolution of Human Potential
& Converging New Technologies**

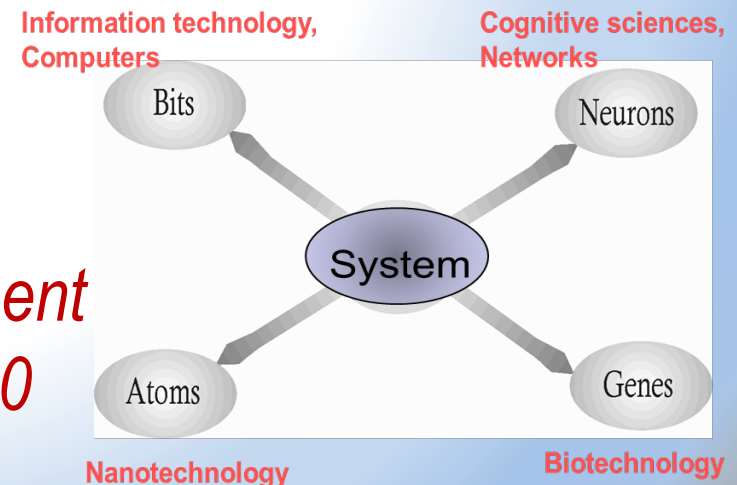


**Annals of the New York,
Academy of Sciences,
Vol. 1013, 2004**

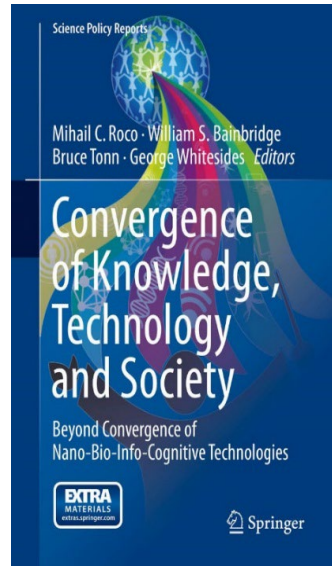
(M.C. Roco and C. Montemagno)

Twelve compelling goals from 2002 NBIC Report that are reality or in development in 2023

- Hierarchically interconnected world – *a reality IT&N by 2015*
- Non intrusive brain-to-brain communication – *accepted, pilots*
- Computer Personal advisor – as laptop or cell – *i-Phone in 2007,..*
- 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 operation*
- 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 after 2010*

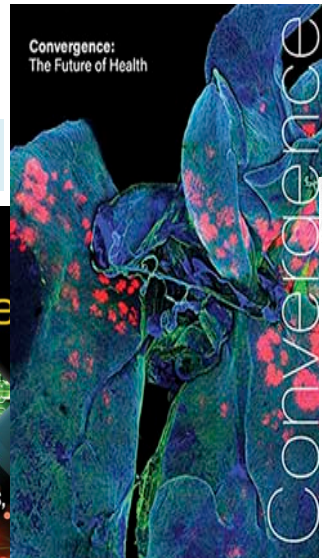
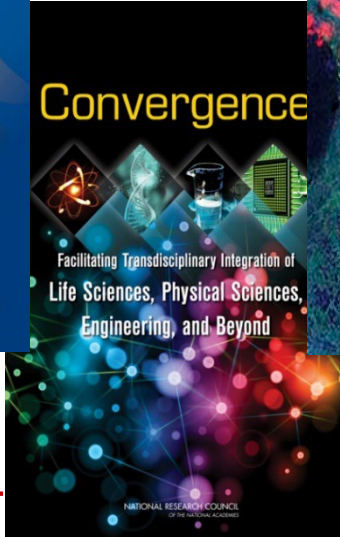


Key convergence reports published between 2013-2019



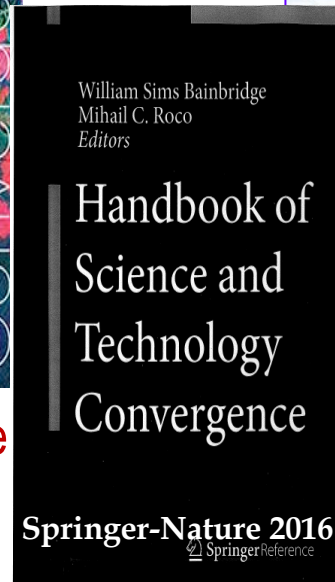
OECD CT

NSF GCR



Convergence of health

2016



Convergence principles and methods

2016



Convergence engineering centers

Convergence Education

2017



Culture of Convergence

2019

International benchmarking

2013

Sponsored NSF & 5 other agencies

Life, physical & engng. sciences convergence

2014



The concept of convergence

Convergence is an integrative, problem-solving strategy to holistically understand and transform a system to reach a compelling common goal or align with shared external constraints

The system may be either in natural, scientific, technological, economic, or societal settings, or their combination.

"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 science

“Convergence of Knowledge, Technology and Society”, 2013 et al [Ref 4, 11]

Convergence science:

Underlying theories

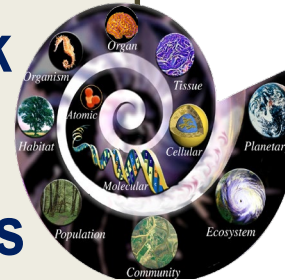
Principles and methods that facilitate convergence

A typical convergence process includes:

- *Deep integration* of knowledge, tools and modes of thinking driven by unifying concepts to a common goal
- *To form* a new framework, paradigm or system
- *From where emerge* novel pathways & opportunities
- reaching the common goal and creating added-value

Underlying theories: Convergence is realized in conjunction with several theories that are applicable to systems in either nature or society

1. Unity of nature
2. Human interaction ecosystem
3. Systems adaptive complexity
4. Economic growth
5. Cluster specialization network
6. Reverse salient drawback
7. Shared fundamental principles
8. The progress asymptote
9. Exogenous revolution
10. Response to social problems



**CONVERGENCE
THEORY SPIRAL**

Seven convergence principles

to facilitate and accelerate progress toward goals

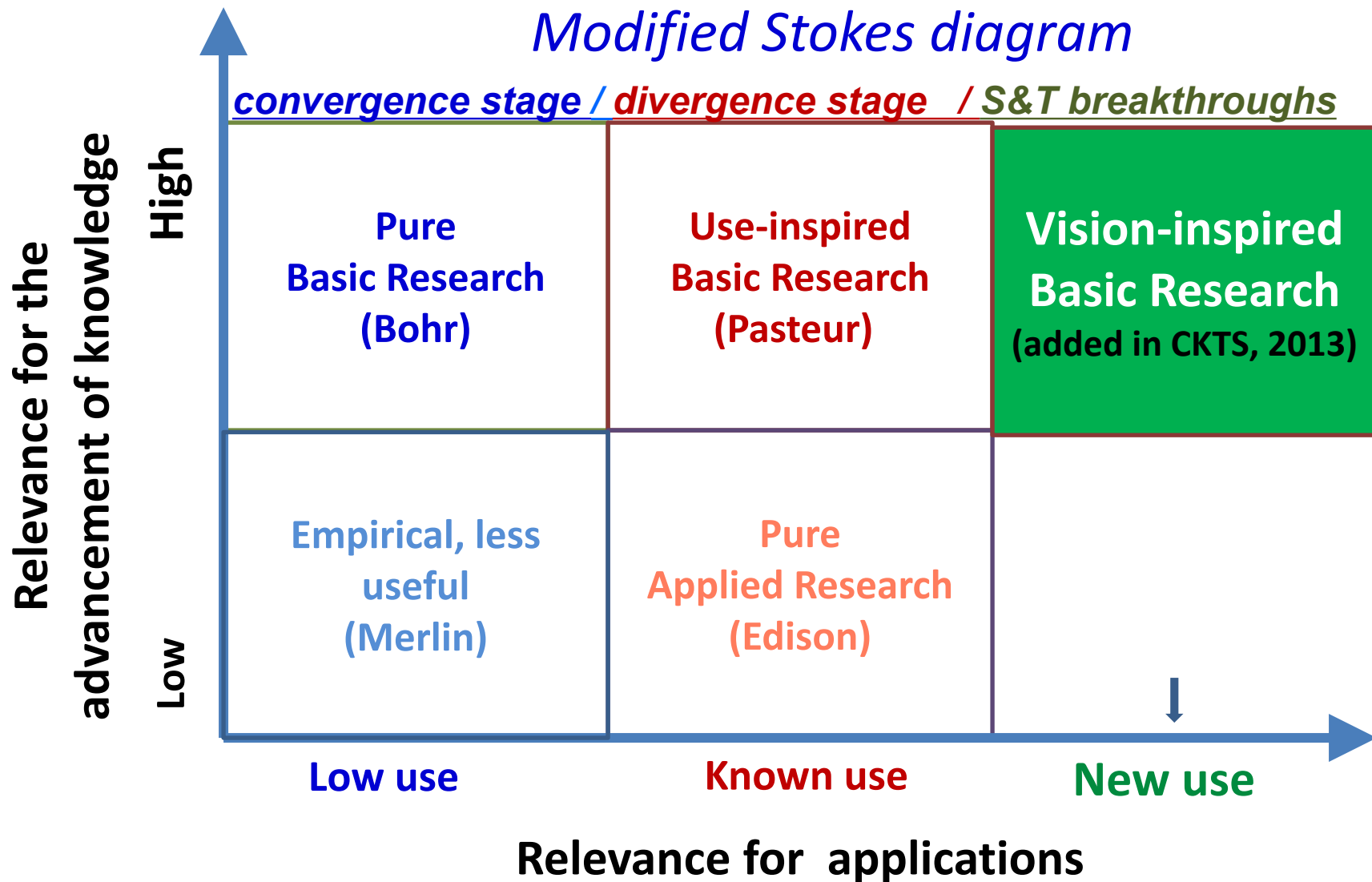
- A. Holistic view** – Interdependence-coherence in nature and society (*find 'unity in diversity'*)
- B. Common goal** - Vision-inspired research for achieving shared challenges or opportunities
- C. Evolution pattern** - Typical *spiral process* of convergence, system change and divergence
- D. Unifying actions**- System-logic deduction in decisions and problem solving
- E. Cross-domain** - Languages, methods, culture
- F. Multi-tasking**– Multiple pathway dynamics
- G. Drive added-value** - Confluence of resources leading to ecosystem changes (*'S curve'*)

PRINCIPLES FOR CONVERGENCE

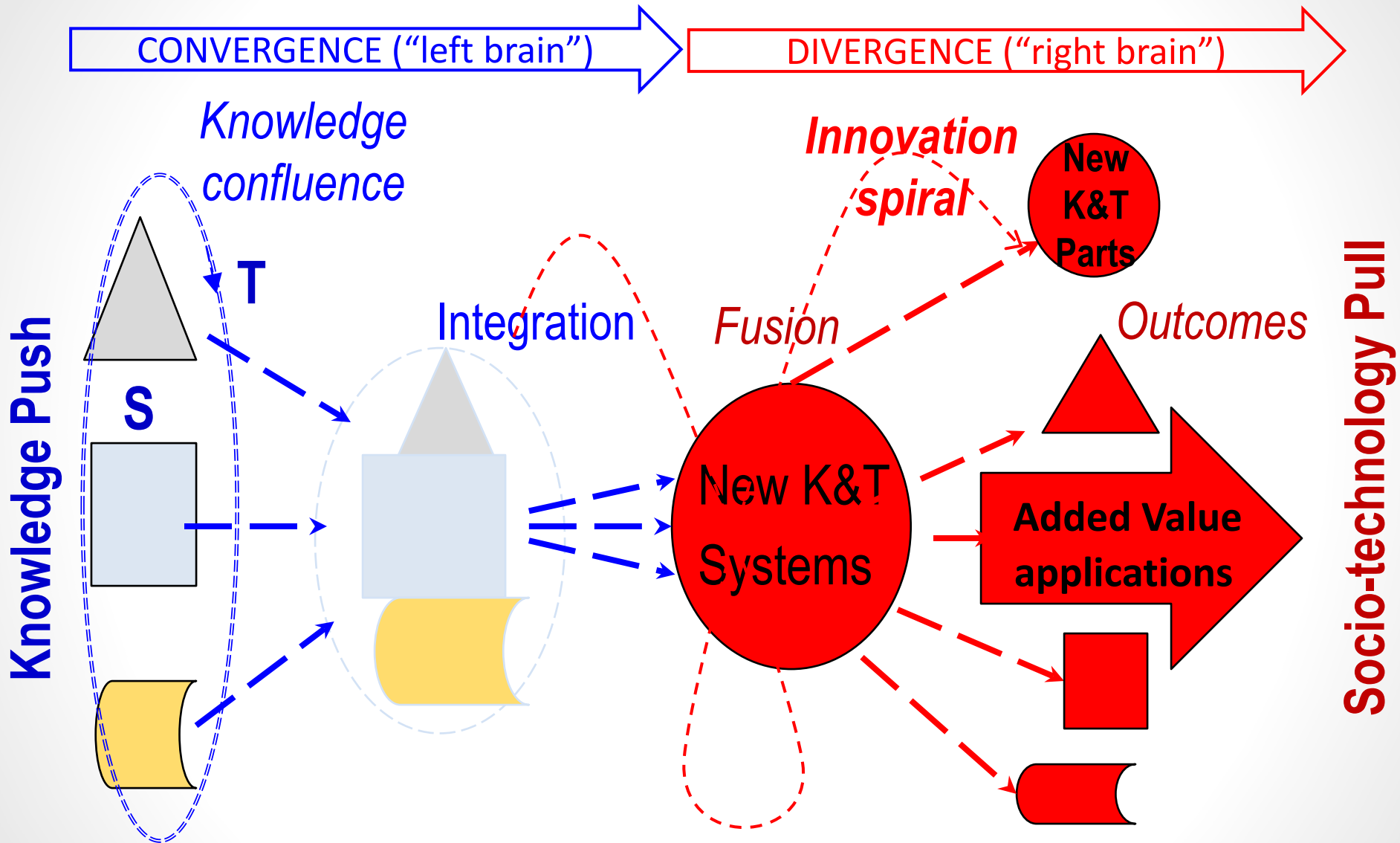


(*applied to a neural network system*)

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



C. Evolution pattern: Spiral convergence-divergence cycle



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



C. Example convergence-divergence cycle with high innovation index: the cellular phone

Coincidental convergence:



- **Confluence 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 platforms, form groups
- **Outcomes, spin-off phase:** Social networks, controlling swarms, miniaturized satellites, healthcare and many other examples affecting virtually every aspect of our society

The “innovation index”

$$I \sim k S^2 O / T^3$$

[Ref 4]

C. NSF Convergence Accelerator

Accelerated integration of research from concept to deliverables in areas of national importance

To augment I-index:
T shorter, S & O up

Main topics in research:



FY 2020 -

- Open Knowledge Networks
- AI-Driven Innovation
- Quantum Technology

FY 2021 -

- Networked Blue Economy
- Trust and Authenticity in Communications Systems

FY 2022 -

- Enhancing Opportunities for Persons with Disabilities
- Food and Nutrition Security
- Sustainable Materials for Global Challenges



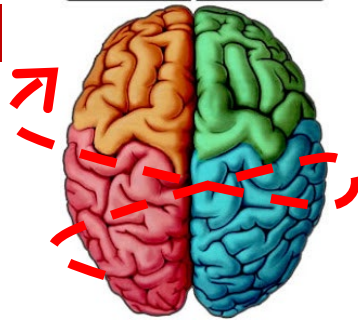
C. Ex. of spiral convergence - divergence cycles

- In nature: Shapes of *tornados*, flow in a *drain*, *stellar spirals*..



- In thinking: Combining computational, directional reasoning ("*left brain*") and interferential, lateral creativity ("*right brain*") leads to a spiral pattern

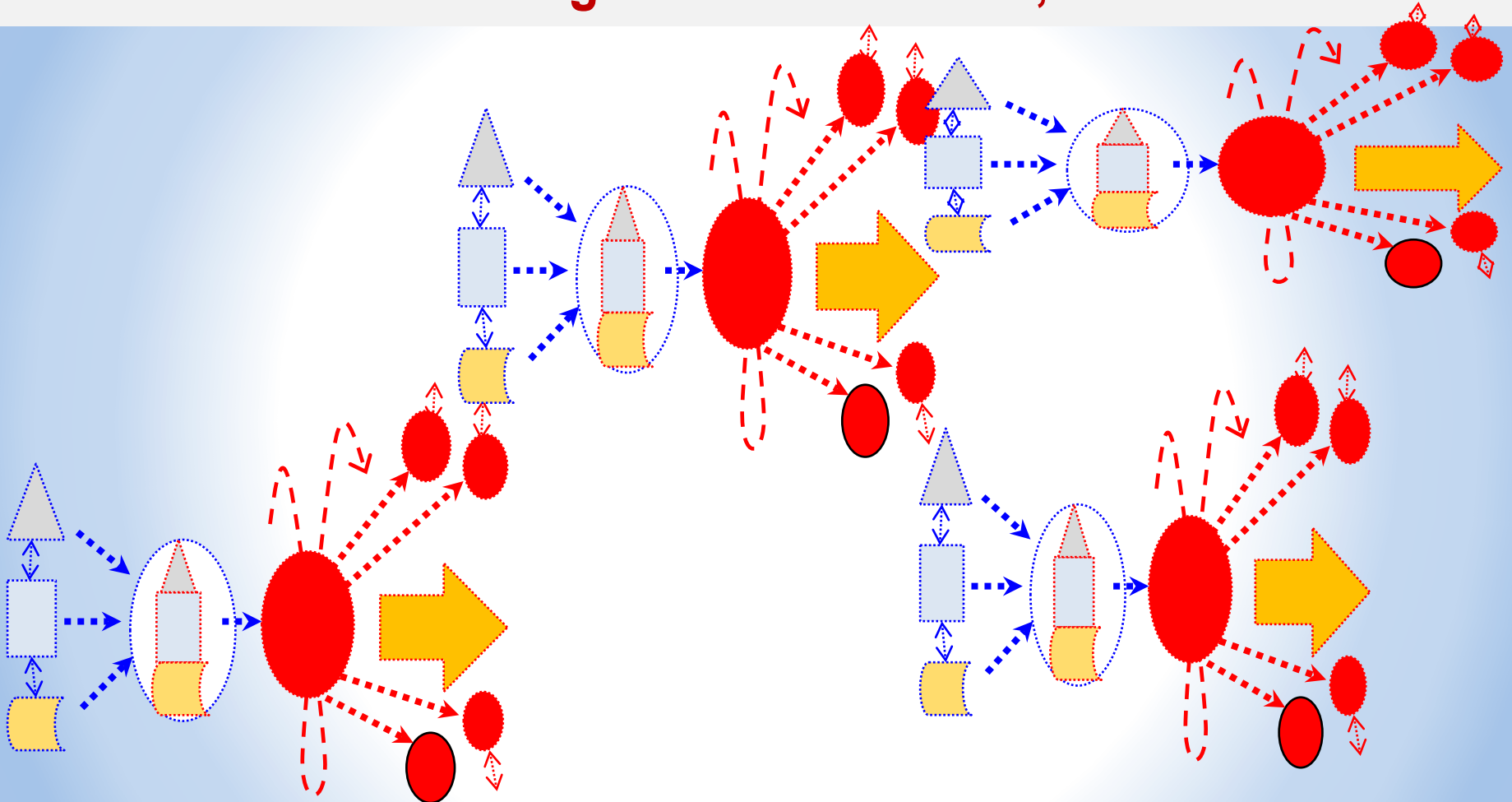
Left Hemisphere Right Hemisphere



- In structures: DNA spiral, nautilus shells: fractals of a higher order principle, minimum energy evolution?



C. Coherent evolution among S&E fields in time with different length and time scales, in cascades

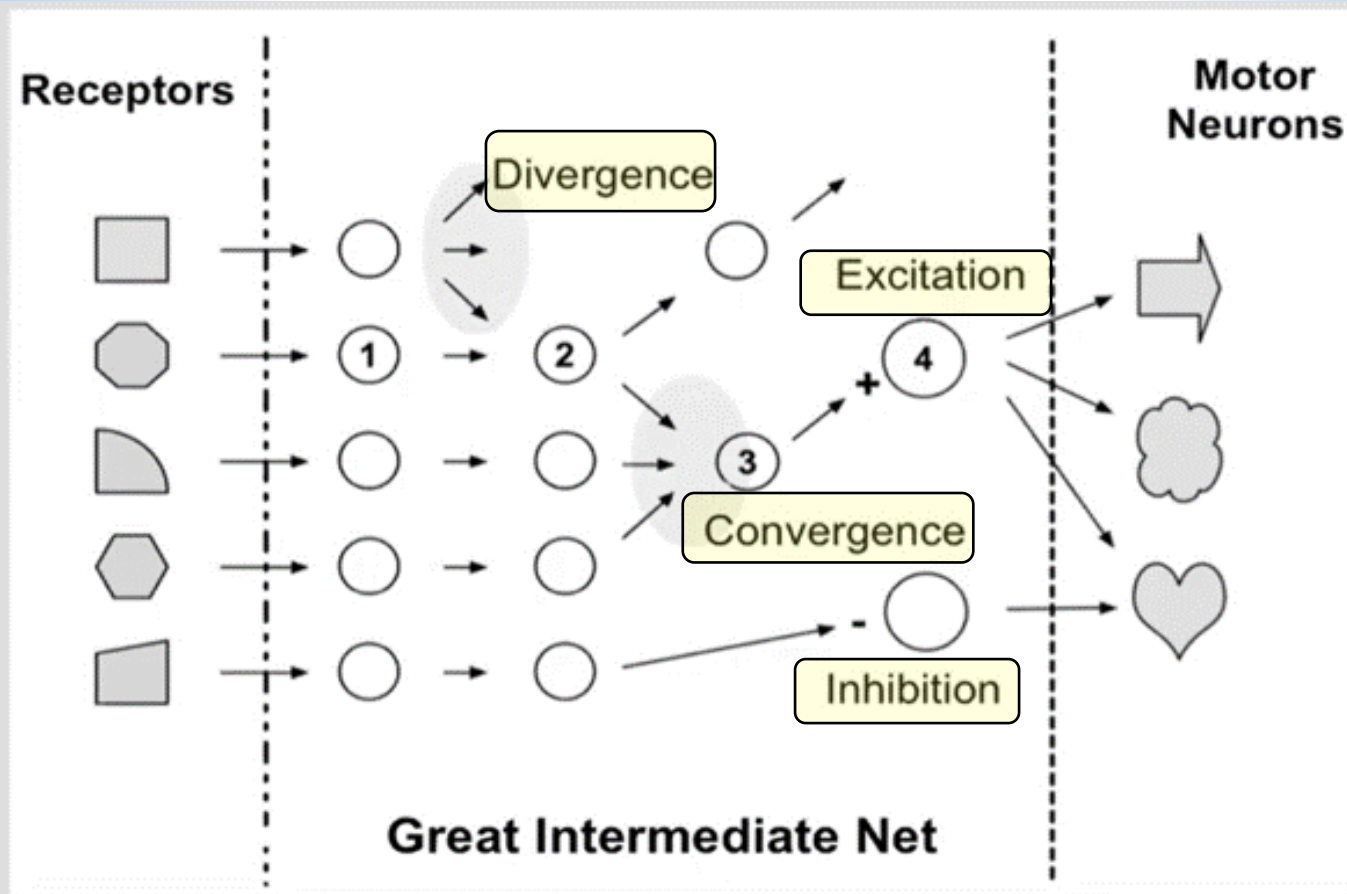


The structure has fractal, pulsatory, spiral behavior.

The convergence-divergence cycle in a dynamic entity: is a universal evolution process

- The world is in a continuing coherent motion that generates **instabilities, which grow and form dynamic entities (excitation stage)**, each for a finite time interval as their surroundings **inhibit them (inhibition stage)**
- The **spiral convergence - divergence cycle** develops within each of those dynamic entities - a universal fractal evolution behavior in nature and society
- Example: NNI

The functions of nervous systems mimic the reality (including the convergence, divergence, excitation, inhibition)

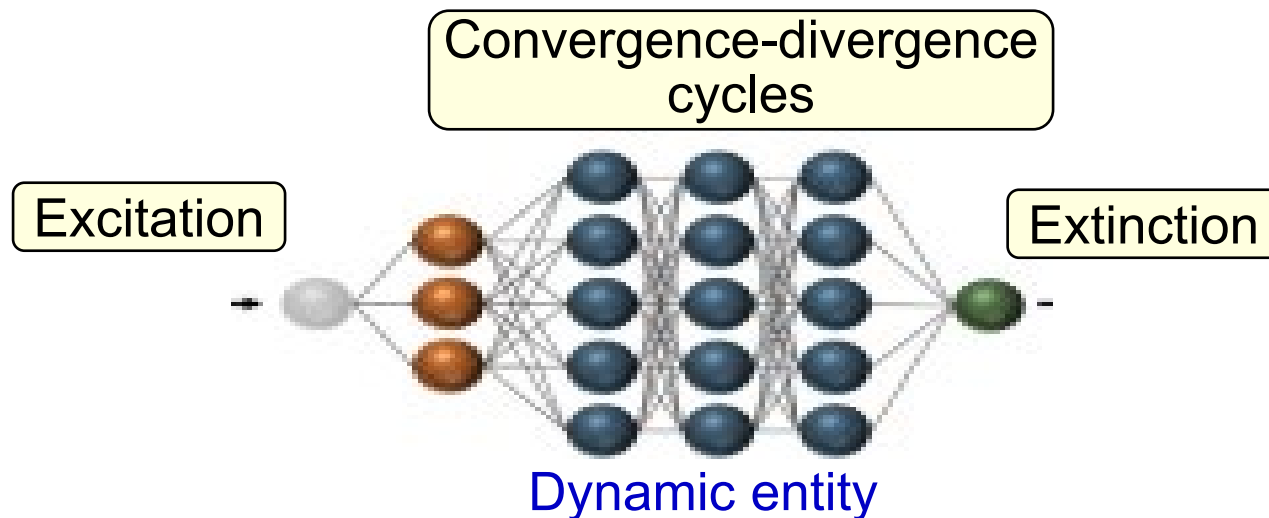


Principle structure of all nervous systems

E. Poeppel, "Science meets art", European Academy of Science and Art, 2021

At their turn, AI algorithms mimic the convergence-divergence cycles from thinking processes

AI systems use 'input layer/hidden layers/output layer' structures and *simplified convergence-divergence cycles* – to simulate the functions of nervous systems

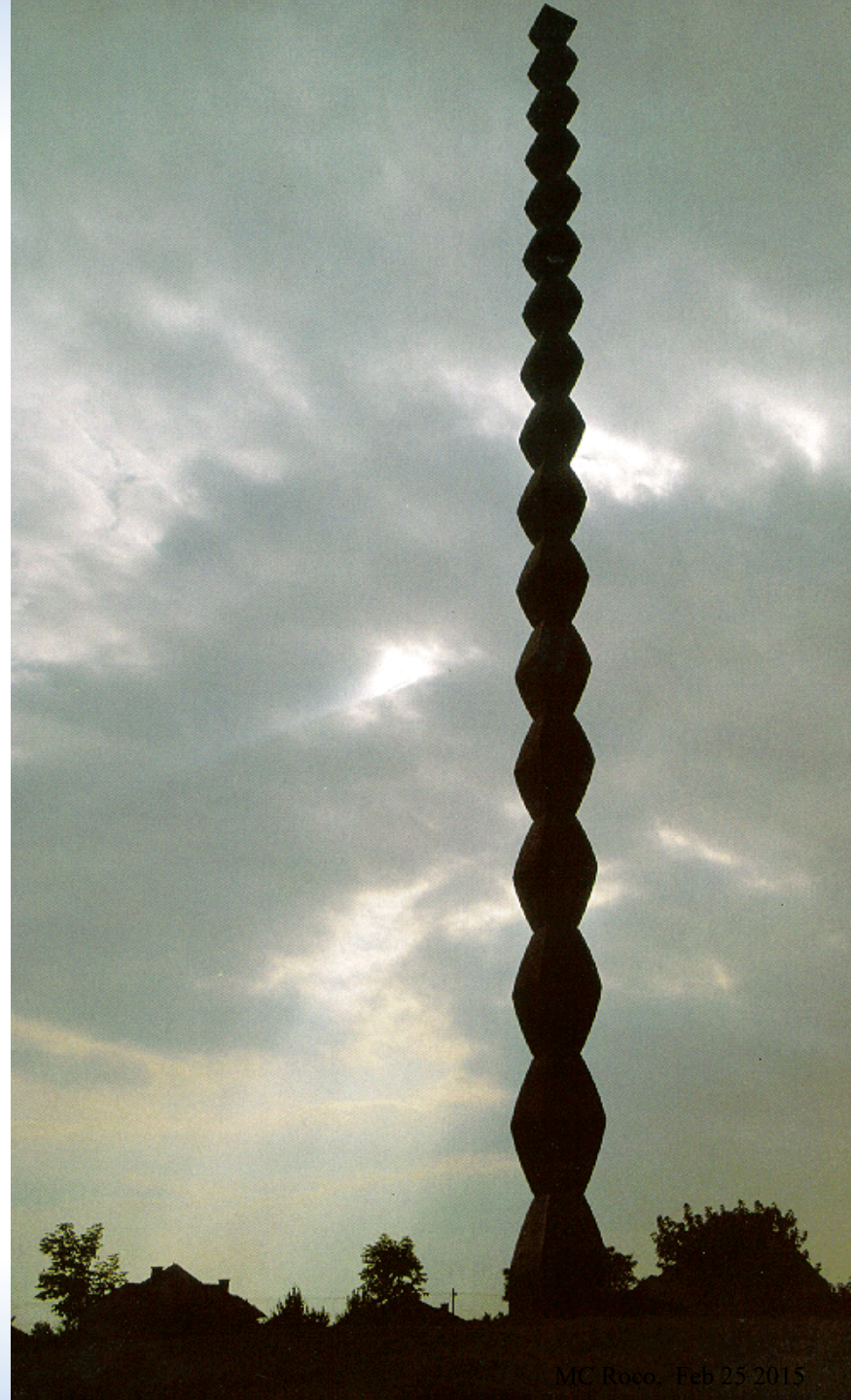


Convergence cycle reflected in art

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



Convergence-divergence elements



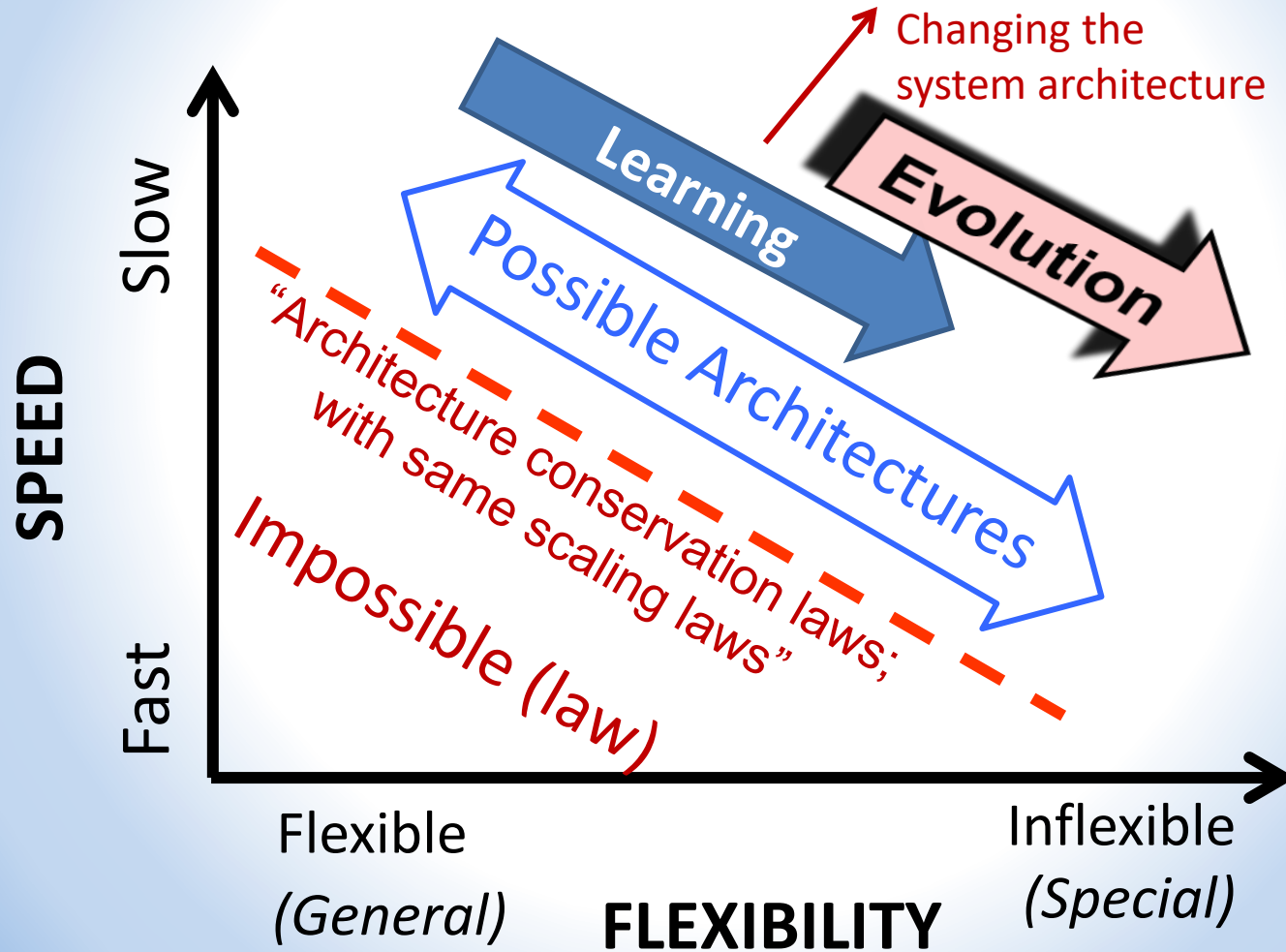
The spiral convergence evolution is an ancient symbol for growth in Asia, Middle East, Latin America ..



Example: The Great Mosque of Samarra (Irak, 852)

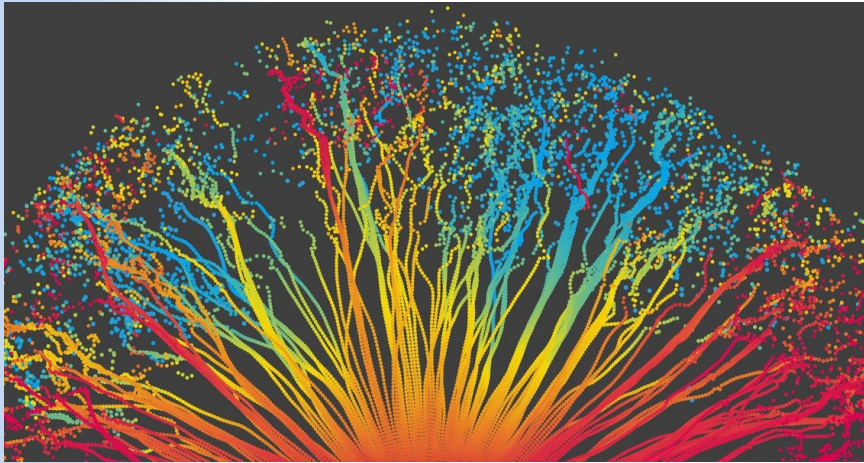
E. Use cross-domain, unifying languages

Generalized laws for similar system architectures; essential scaling; energy minimization for physical systems; collective encoding

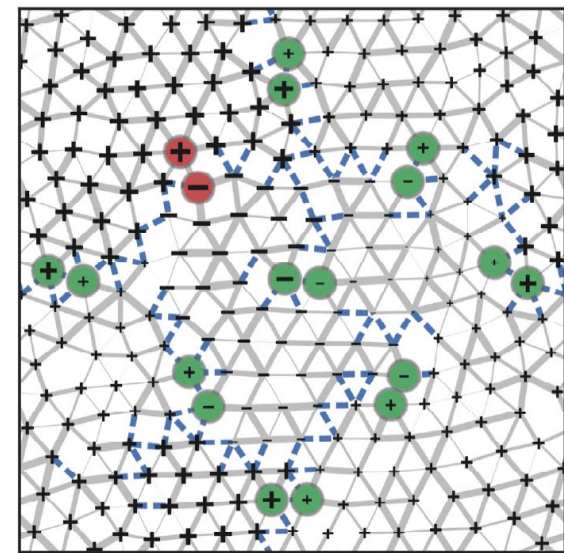


F. Multiple cause-and-effect pathways

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



Blood flow in brain

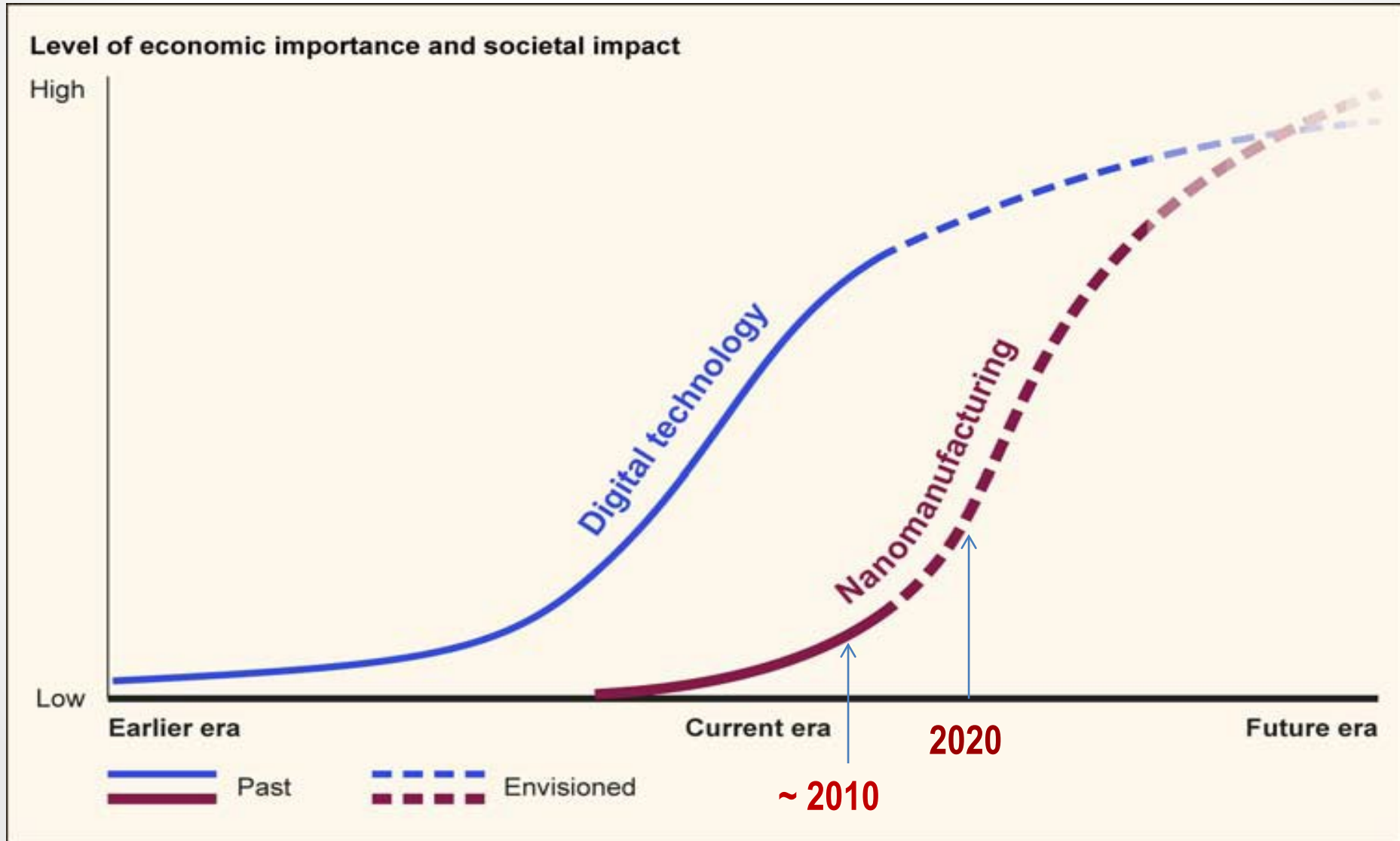


Water flow in water distribution network

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

G. Timely confluence of resources leading to system changes (the S-curve): *Digital, Nano fields*

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





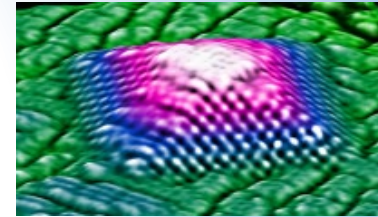
Application of convergence principles: examples

- *Formation of new S&T fields*
- *Improve production, research, education*
- *Governance in society, Conflict resolution*
- *Establishing smart communities*

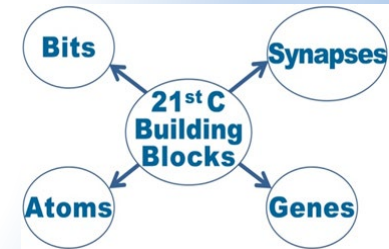
Three stages of S&T convergence creating new fields are under way

(Ref 4: CKTS, Springer, 2013)

- (I) Nanoscale Science, Engineering and Technology**
“Nanotechnology” (Foundational S&T field)
Integrates disciplines, knowledge from atoms/qubits



- (II) Converging foundational S&T fields:**
Nano-Bio-Info-Cognitive-AI “NBICA”
Integrates foundational and emerging technologies
from their basic elements (atoms/qubits, bits,
genes, neurons, logic steps)



- (III) Convergent solutions for**
Knowledge, Technology and Society, “CKTS”
Integrates the essential platforms of human activity



(I) Convergence-Divergence cycle for establishing nanotechnology from 2000 to 2040

Knowledge confluence

Disciplines
Bottom-up
& top-down

Sectors:
Materials
Medical, ..

Tools &
Methods

**Assembly of
interacting parts**

Control of
matter at
the
nanoscale

2020

**New
systems**

Six NT
Generations

**Innovation
spiral**

New nanosystem
architectures

Spin-off disciplines,
technology platforms

New applications,
sectors & business

New Products est
\$30 T (by 2030)

N
B
I
C
A

New expertise (NBIC..)

New governance
methods

**1. Confluence/
basics phase**

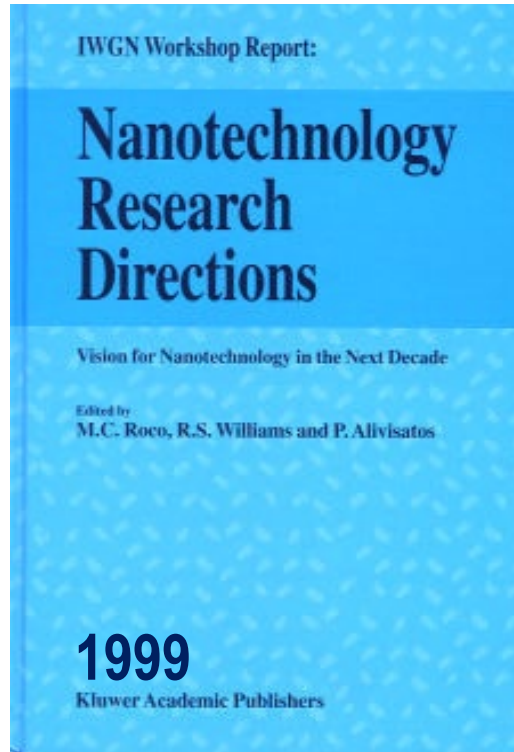
**2. Integration/
Fusion phase**

**3. Innovation/
diver. phase**

**4 Spin-off/ diff.
phase**

Nanotechnology: four vision-setting reports

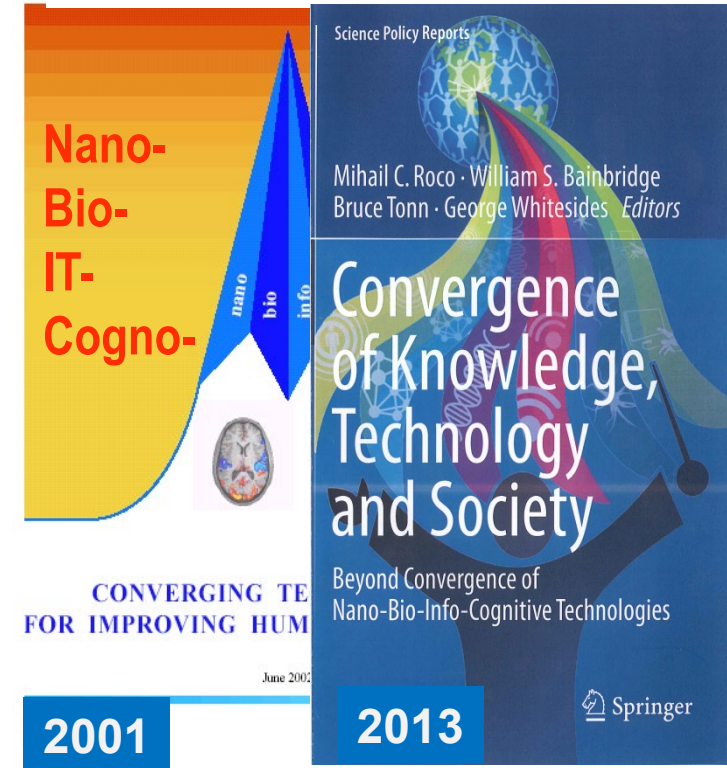
nano1 (2001-2010)



nano2 (2011-2020)



NBIC1&2 (2011-2040)



40-year vision: changing focus and priorities in 4 stages
a. basics, b. system integration, c. divergence, d. diffusion

Input from >40 countries, Used in > 80 countries; Reports on scienceus.org/wtec/ (Ref 2)



Nanotechnology spin-off S&T areas

2000-2020 (top 20 topics) (i)

- **Quantum systems** - *Quantum S&E 2003; expansion NQI 2018*
- **Nano-Environment, EHS & ELSI** 2003 activities, 2005 NNI WG
- **Metamaterials** – 2004
- **Plasmonics** – 2004
- **Nanomedicine** – 2004 (NIH focused program)
- **Synthetic biology** – 2004 (NSF increase of awards)
- **Nanoelectronics Research Initiative** 2005; expansion 2015;
- **Nano antennas and devices for wireless**, 2006
- **Modeling / simulation** - *Materials Genome Initiative 2011*
- **Nanophotonics** - *National Photonics Initiative 2012*

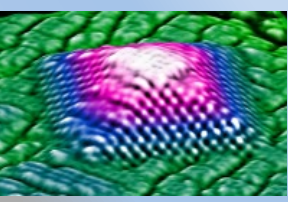


Nanotechnology spin-off areas

2000-2020 (top 20 topics) (ii)

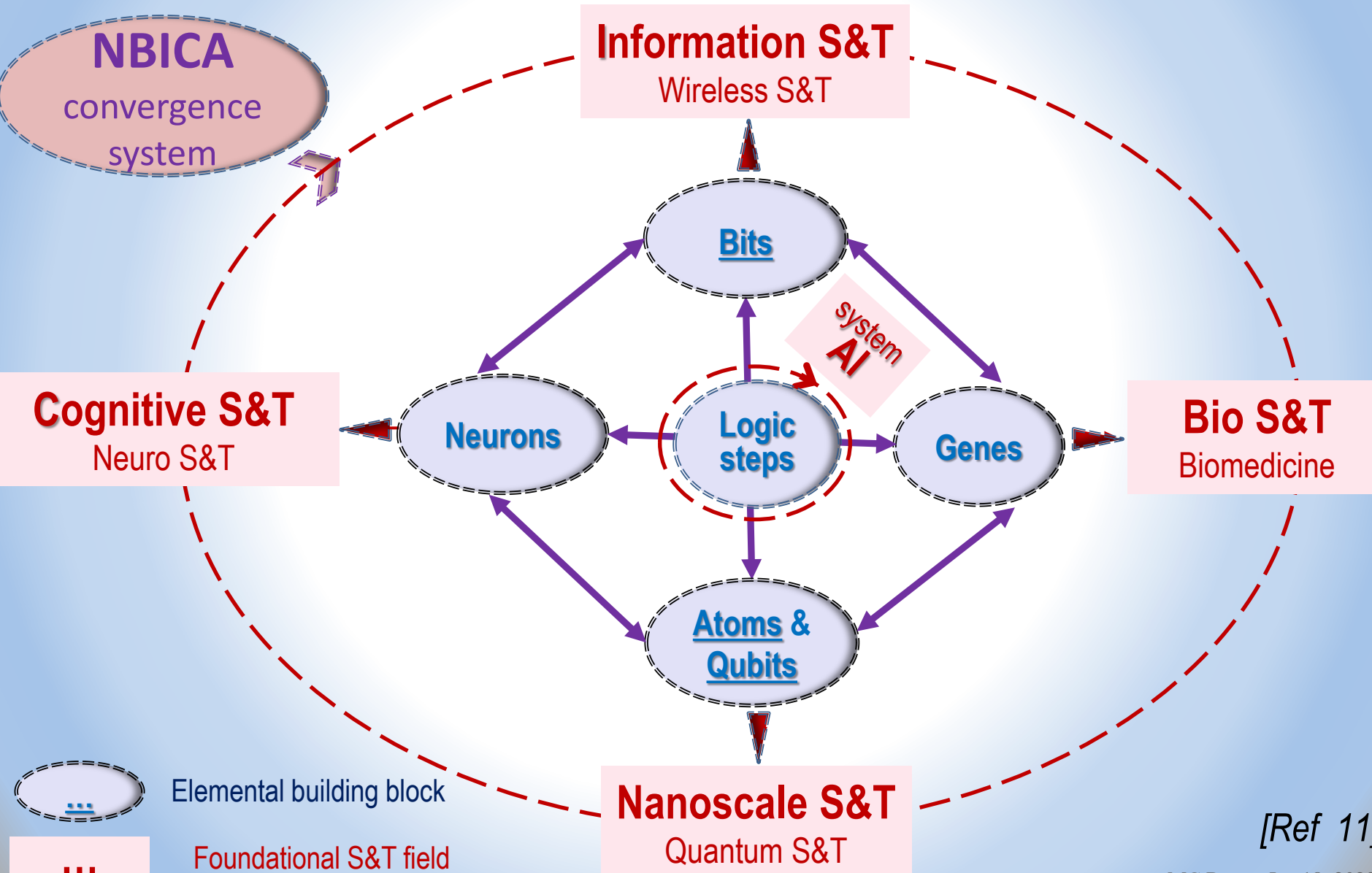
- **Nanofluidics**
- **Carbon electronics**
- **Nano sustainability**
- **Nano wood fibers, nanocellulose**
- **Nano-AI** 2017 steep increase of awards and publications
- **DNA nanotechnology**
- **Protein nanotechnology**
- **Nanosystems-mesoscale**
- **Quantum biology**
- **Nano NEURO Nano in plants**

Nanotechnology programs: S&T divergence



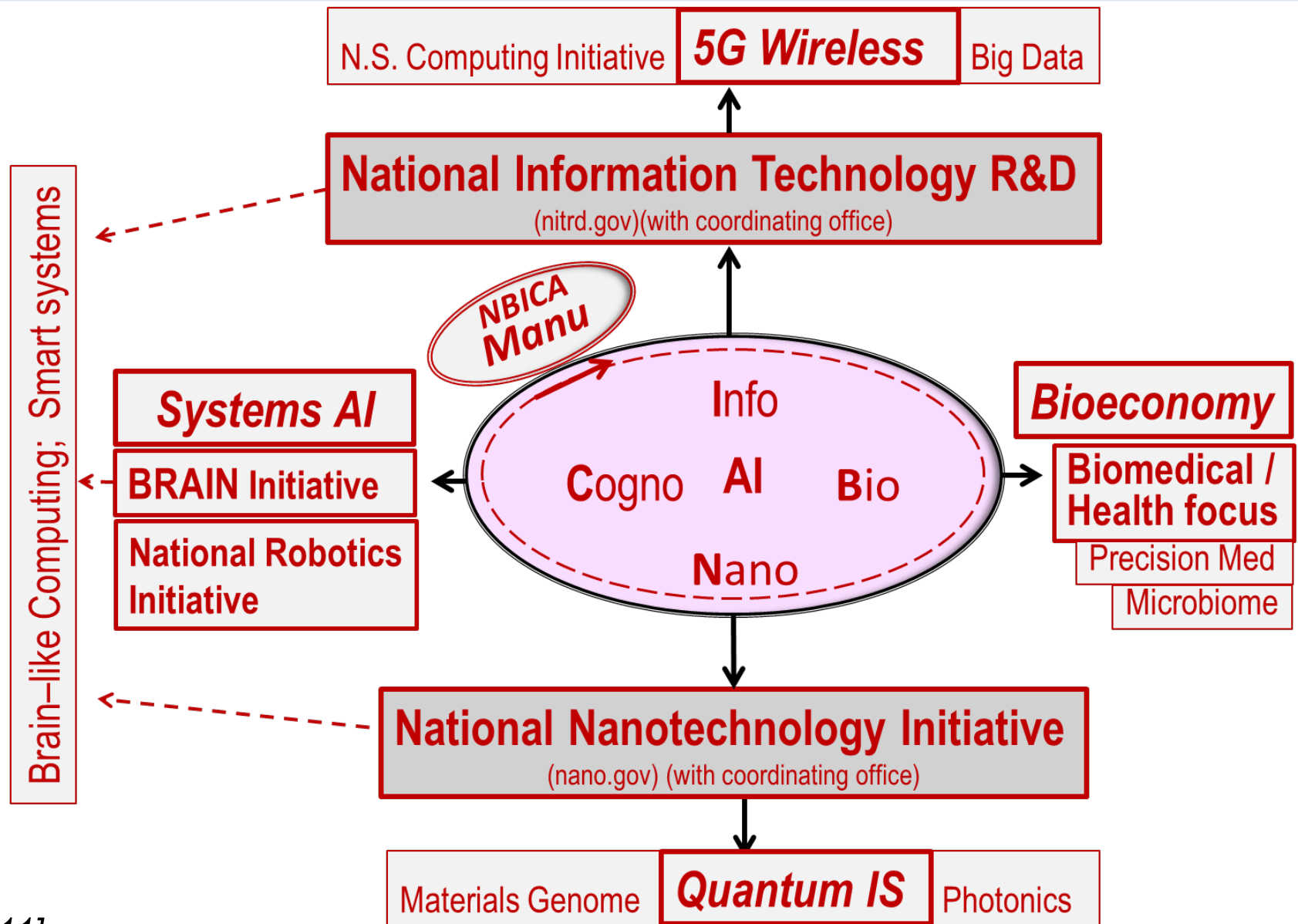
National Nanotechnology Initiative
 32 agencies, R&D \$40 Billion (2001 – 2023)

(II) Convergence S&T system built from 5 elemental building blocks (atoms/qubits, genes, bits, neurons, logic steps)



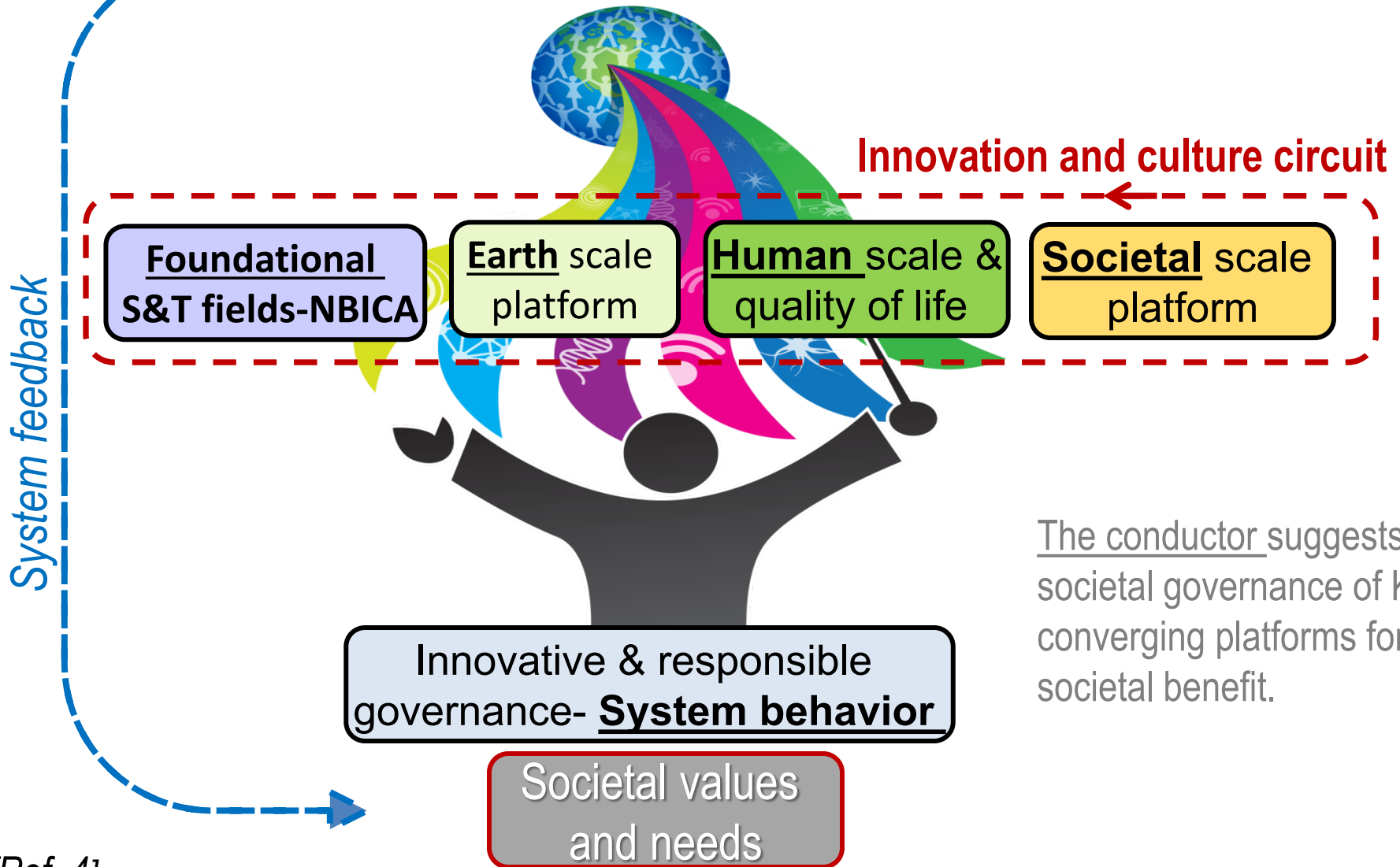
[Ref 11]

(II) Converging foundational S&T fields (NBICA) at the origin of the US emerging S&T initiatives



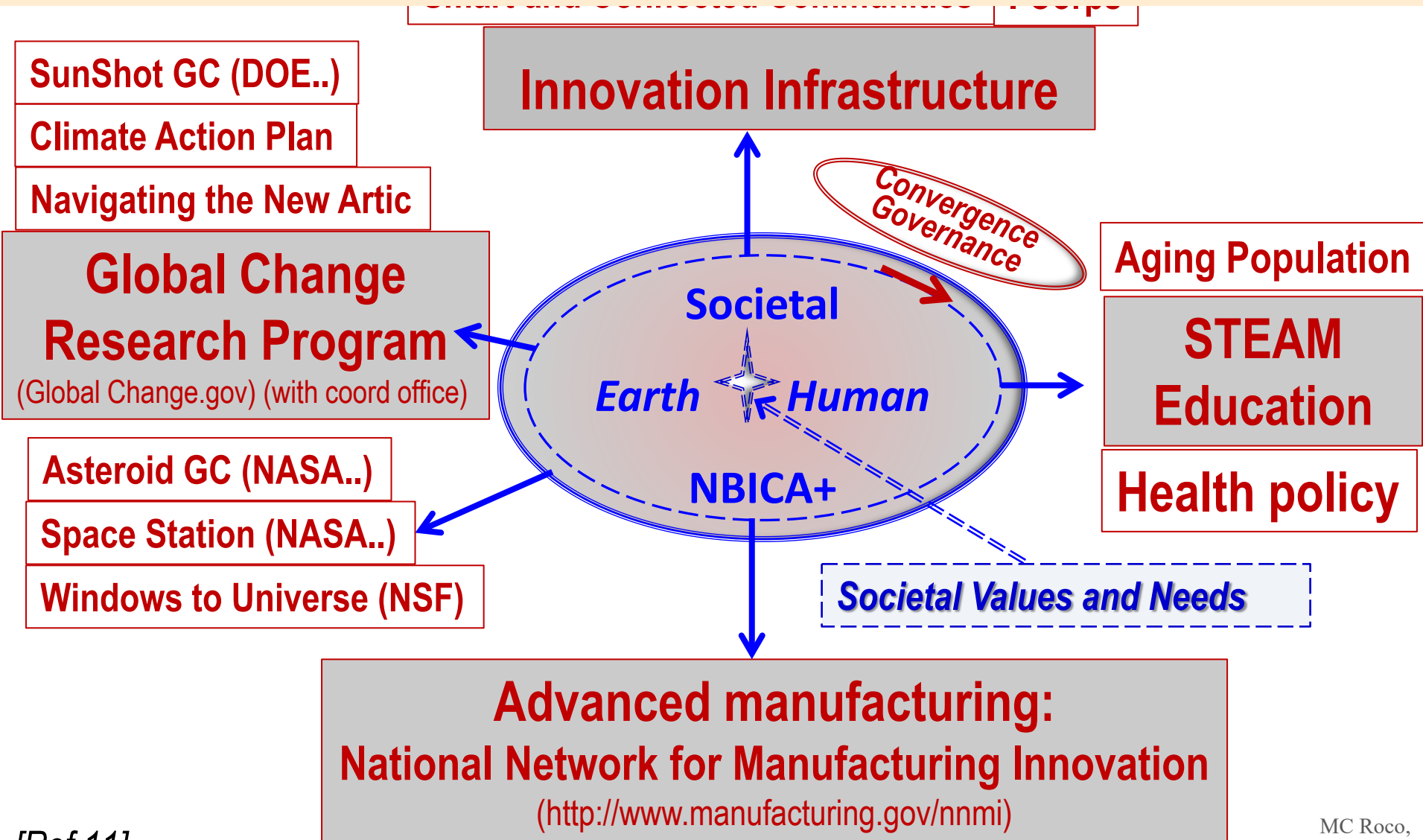
(III) Holistic view for human societal ecosystem

For societal benefit and human development



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

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



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

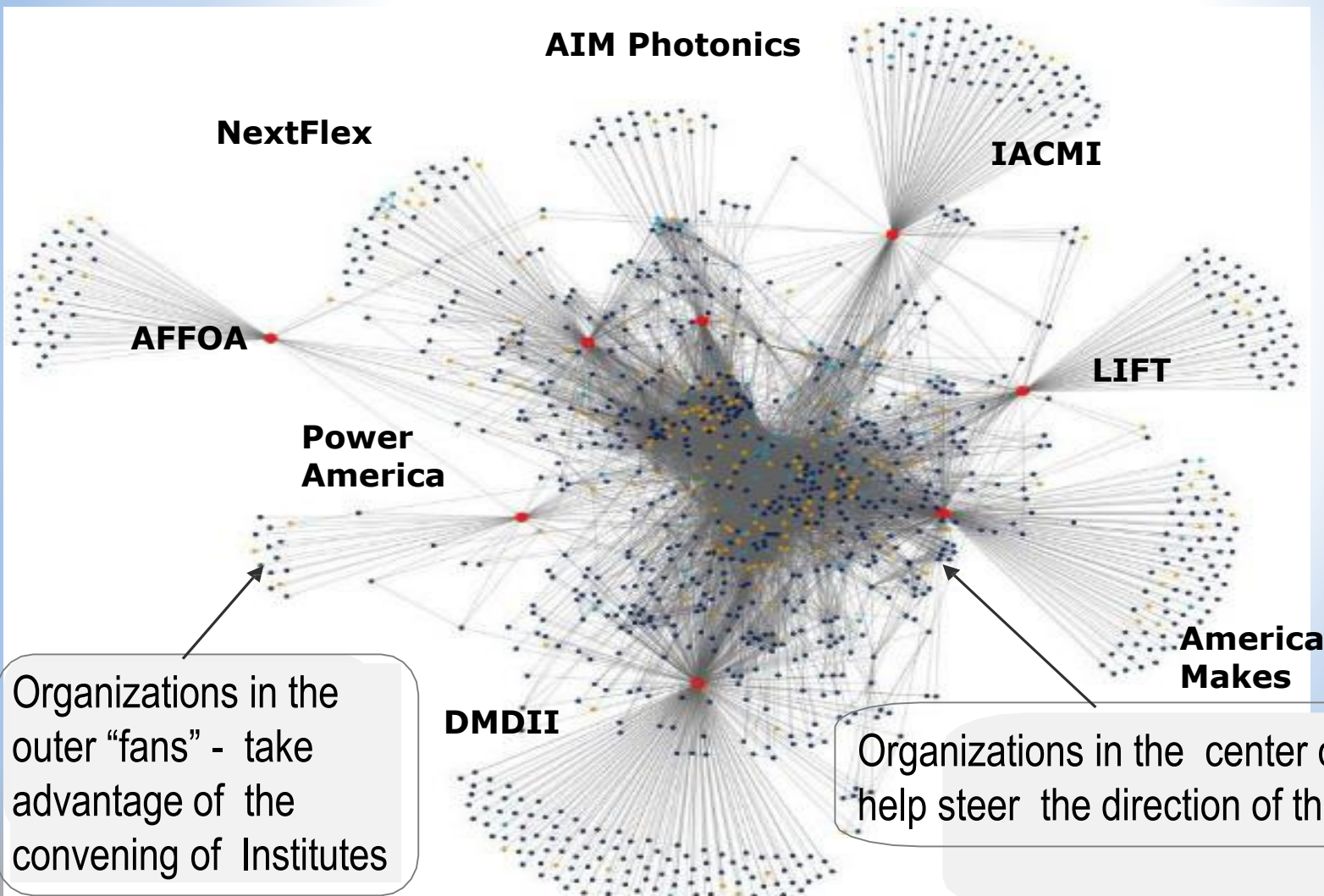
Network

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.

- Topical application areas-

Several opportunities for implementing convergence

- **Production processes**
- **Biomedicine, science and engineering**
- **Individualized learning and improvement**
- **Research and Education**
- **Intelligent cognitive assistants**
- **Citizen science**
- **Governance (university, national, global)**
- **Sustainability/global change**
- **Smart communities, smart individuals**
- **Advancing peace and collaboration**

Examples for:

Convergence in advanced production ⁽¹⁾

- The increased interactions - determines a change to “**cloud**” **production** (distributed growth with the Internet of Things)
- Converging “**supply chains**” from concept to internet, production and use – leads to “**cyber-physical-social**” **production**
- Combined penetration of foundational technologies – leads to **NBICA manufacturing** (nano-, bio-, digital-, cognitive-, AI, and combined 2-4 technologies, including **Modular production**)
- “**Trading zones**” **production**

Examples for:

Convergence methods in research

- **Connecting S&T fields, people & projects; finding unifying & transforming links** – New fields, New platforms, Broader topics for funding & review; Multiple-topic databases & informatics.
- **Expand methods facilitating convergence**
 - Use system approach, cross-domain languages, AI neural networks, and team science, visualization and pattern recognition, open databases/access
- **Changing researchers & faculty recognition system**
 - Credit research at interfaces, cross-domain centers, out-domain collaborations, incentives for degree accreditation, facilitate interactions
- **Revise organizational structures & regulations**
 - To allow the convergence processes to be more effective. Models by OECD's Biotechnology, Nanotechnology and CT Party (2014-)

Examples for:

Convergence methods in education

- **“Trading zones”** among teaching various areas of relevance, and multi-domain courses, departments and libraries
- **Confluence of topics in education:** such as bringing together
 - *Feasibility topics* (science and engineering)
 - *Desirability topics* (art and humanistic)
 - *Viability topics* (economics and management)
- **Use higher level education languages** such as art, music, math, other abstractization tools, improve collective capabilities
- **Use converging technologies** for: virtual reality learning, individualized learning, distributed learning

“Global Perspectives in Convergence Education”, 2017, Report, NSF, OECD, NASEM

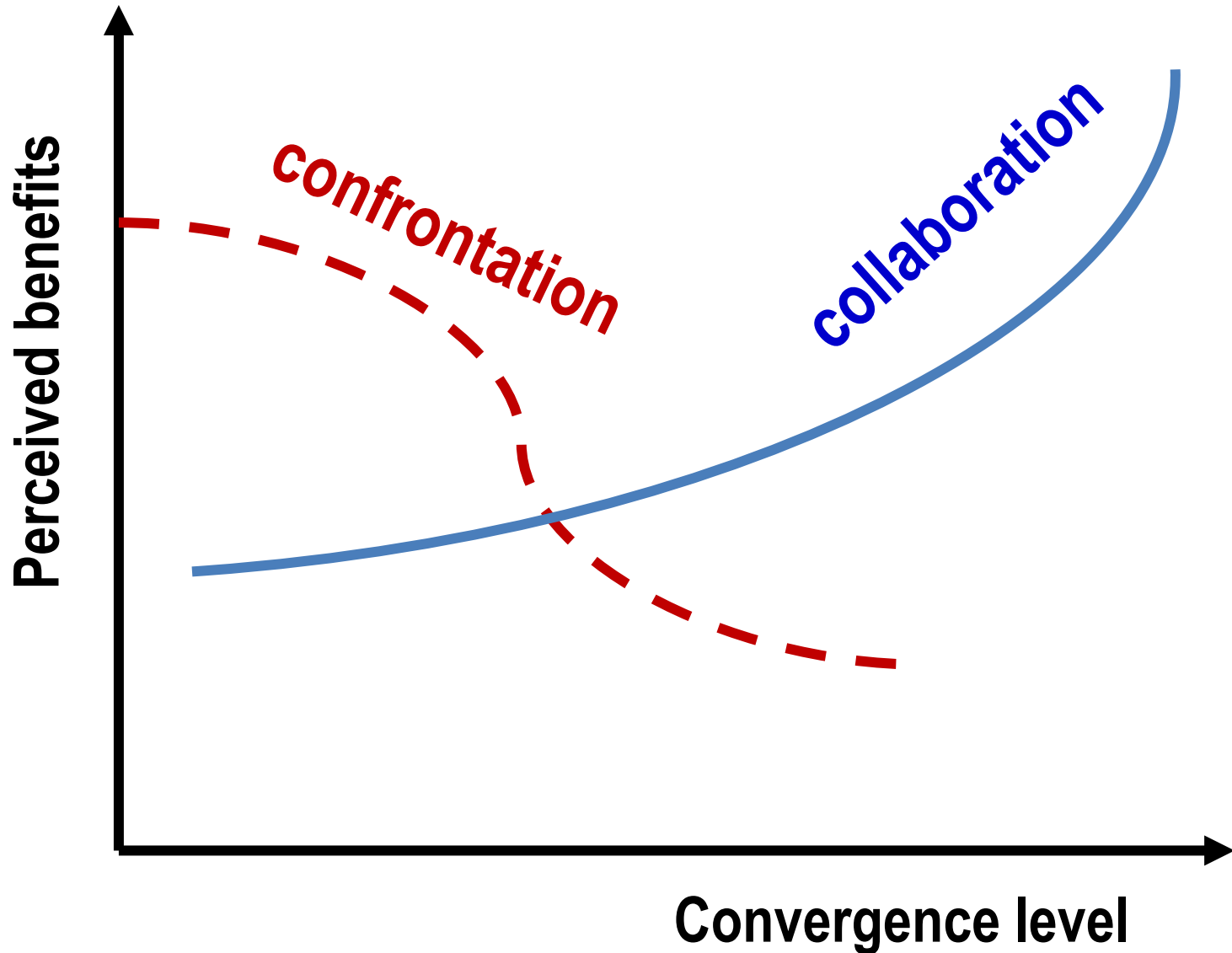
Convergence is transformative: NSF programs in research, education, innovation and translation

Examples of programs in 2023 are:

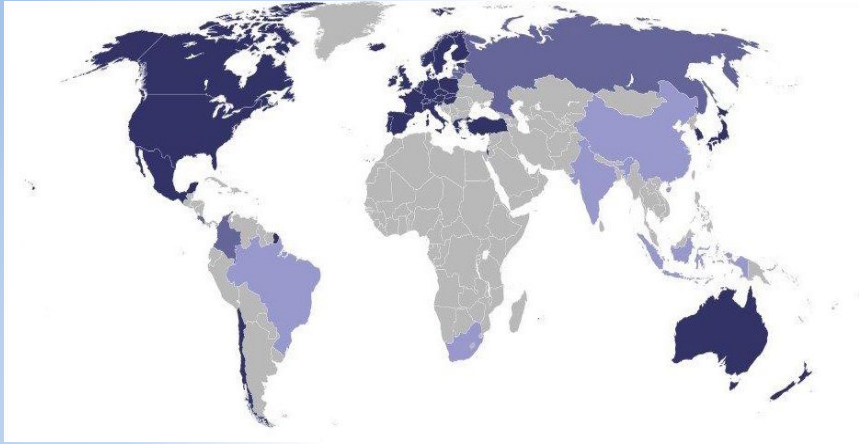
- “***Growing Convergent Research***” (*for new R&D domains*)
- “***Future of Work at Human-Technology Frontiers***”...
- “**Convergence Accelerators**”
- **Core announcements and solicitations**
 - Ex.: the “***National Convergence Technology Center***”
 - Upstream: ***Germination***; Downstream: ***Innovation Corps***

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

Conflict resolution: Perceived change of balance of benefits from confrontation to collaboration through convergence



2014-2023: *International OECD Working Party on Bio- Nano- and Converging Technologies (BNCT)*



Organisation for Economic Cooperation and Development (OECD) - 37 member countries

BNCT considers policy issues related to: innovation; standards and regulations; ethical, legal, and societal issues; public engagement; research, education, skills, and training

Examples of BNCT activities: Harnessing Conv. Technologies for the Next Production Revolution; Gene Editing, Converging platforms for emerging technologies; Circular bioeconomy

Global Action Possibilities

- Convergence-divergence cycles are building blocks of evolution and progress. **Convergence transformation is a fundamental process in nature, society, thinking.**
- International collaboration is needed for: ***science of convergence, convergence technology platforms, and evaluating holistic trends in society***
- There are immediate opportunities in: **NBICA manufacturing, enhancing cognition, biomedicine, governance, research and education**

Convergence is an evolutionary strategy to improve and accelerate outcomes in complex systems.

*Evolution is never finished.
Each convergence event **is finite.***

A talk is never finished.

Selected convergence related publications

1. **“Coherence and Divergence of Megatrends in Science and Engineering”** (Roco, Swiss Academy Of Sciences 2000; and JNR, 2002)
2. **NBIC Report: “Converging technologies for improving human performance: nano-bio-info-cognition”** (NSF-DOC, 2002; and Springer, 2003, 468p)
3. **“Nanotechnology: Convergence with Modern Biology and Medicine”**, (Roco, Current Opinion in Biotechnology, 2003)
4. **CKTS Report: “Convergence of knowledge, technology and society: Beyond NBIC”** (Springer, 604p, 2013b)
5. **The new world of discovery, invention, and innovation: convergence of knowledge, technology and society** (Roco and Bainbridge, JNR 2013a, 15)
6. **“Convergence - facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond”** (NASEM, 2014, Wash., D.C.)
7. **Enhancing the effectiveness of team science.** (NASEM, 2015, Wash., DC)
8. **“Handbook of Science and Technology Convergence”** (Springer, 1154p, 2016)
9. **Convergence: The Future of Health** (MIT, 80p, June 2016, Cambridge, MA)
10. **Fostering the culture of convergence in research: proceedings of a workshop.** The National Academies Press, NASEM (2019, Wash., DC)
11. **Principles of convergence in nature and society and their application: from nanoscale, digits, and logic steps to global progress.** (Roco, JNR, 2020, 321)