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Convergence Research for Universal Processes

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Abstract
Convergence patterns are inherent in knowledge and human development, and they have evolved into a cycle of increased interaction, coherence, transformation, and then emergence in the respective systems. Convergence is an integrative strategy to holistically understand and change a system to reach a shared goal or satisfy a natural law. The strategy typically begins with deep integration of previously separated disciplines, communities, and modes of thinking, leading to a new framework, paradigm, or system, from where solutions diverge to previously unattainable applications and outcomes. Such a transformative convergence–divergence pattern is universal in nature and society as well as in thinking. The pattern applies to all complex systems simulated as evolving neural networks. Principles and methods to facilitate convergence are presented. Their application is illustrated for knowledge creation, emerging technologies, and governance in society. Convergence of foundational science and technology fields has led to major outcomes and national initiatives. Convergence creates a framework for decision-making and problem-solving not only for science and technology, but also for business and humanities.

Keywords: Convergence science, Neural networks, Convergence-divergence cycle, Universal evolution pattern, Emerging technologies, Transcended outcomes

Introduction

Affirmation of convergence in science, technology, and society has been a major research trend in the last two decades. Convergence is today a core strategy in our knowledge society for progress that addresses solutions for complex challenges and opportunities. It provides an efficient approach to enhance creativity, innovation, and outcomes. This entry presents basic concepts, principles, and methods to facilitate convergence to reach a goal or satisfy a natural law in an evolutive system. They apply in society and natural systems, including biological systems. The outcomes obtained through converging technologies and improving human capabilities are prevalent.

The concept of convergence

Civilizations throughout history have included concepts of natural interdependence and unity with nature. Indigenous cultures in the Americas have a holistic view of nature and society. In the 15th-16th centuries, the Renaissance highlighted the need for integrated knowledge in Western civilization. More recently, researchers have integrated disciplines for understanding basic phenomena and addressing multidisciplinary problems. Convergence essentially means bringing together components toward union. A more general meaning of convergence is the evolutive, transformative confluence toward reaching a common goal or satisfying a bounding constraint in the system, where assembling of stakeholders, disciplines, and fields of relevance toward union is just a first step. Evolutive convergence further implies deep integration of components and change of the respective system to enable new capabilities toward reaching the goal. The evolution in nature, knowledge, technology, and society is increasingly coherent, cross-domain, turbulent, and emergent. This is true, for instance, in the affirmation of emerging technologies, governance of society, and weather predictions. Such systems are too complex for the usual single-domain, single-approach methods. In order to include system complexity, as well as the transformative and emerging processes in the respective evolutive systems, we have advanced the concept of *convergence to a goal* (Roco, 2002; Roco, 2020). Convergence to a goal is an integrative, problem-solving strategy to holistically understand and transform a system to reach a compelling common goal or align it with shared external constraints such as natural laws and bounding conditions. It is a unifying strategy applicable to all evolving complex systems modeled by dynamic neural-like networks. External constraints may include natural laws (such as minimum energy dissipation, minimum entropy creation, natural selection-survival of the fittest) in the physical world, economic laws and human development requirements in society, and various bounding conditions. The strategy is applicable to knowledge, technology, societal, and humanistic goals.

A typical convergence process includes:

- Formulating the vision and decision pathway for reaching a compelling common goal;
- Bringing together previously separated knowledge domains, tools, stakeholders, and modes of thinking, driven by unifying concepts and shared purpose;
- Deep integration of the respective components to collectively form a new framework, paradigm, field of study, or system;
- From where emerge new pathways and opportunities (competencies, capabilities, governance) for reaching the respective goal and creating added-value.

Convergence science includes:

- Underlying theories, such as human interaction ecosystem and adaptive complexity;
- Principles and methods that facilitate convergence, such as holistic view and convergence-divergence evolutionary cycle;
- Measuring the level of convergence and its impact, such as number of outcomes and speed of the process.

Convergence implementation initially was assessed for two major goals of societal interest: (a) Advancing emerging, converging technologies, and identifying new science and technology fields outgrowing from them (Roco, 2002), and (b) Improving human capabilities by using nano-bio-info-cognitive converging technologies (Roco & Bainbridge, 2002). In the second report, a long-term vision was formulated for: the potential of converging technologies; expanding human cognition and communication; improving human health and physical capabilities; enhancing group and societal outcomes; safety and security; and unifying science and education. About thirty visionary ideas looking 20-30 years ahead were identified based on convergence principles; the visionary topics included a hierarchically interconnected world, brain-machine and brain-to-brain interactions, and personal advisors or brokers (which evolved later to smart phones and AI systems). Other visions were paths from brain physics/chemistry to mind and intellectual coherence in education, intelligent environments, and regenerative medicine with 3D printing. Two decades later, most of these ideas are in development now or have become reality. The corresponding National Science Foundation (NSF)-Department of Commerce (DOC) report (Roco and Bainbridge eds., 2003) concluded that converging science and technologies integrated from the nanoscale could determine a tremendous improvement in human capabilities and societal outcomes. Advances in many of these visionary ideas were achieved because, during the interval 2002–2007, the strategy of convergence was adopted in science, medicine, and technology initiatives in the US, Europe, Japan, China, and South Korea, and successively it was accepted in various organizations as a transformative strategy for compelling goals. After a benchmarking study in 2013 in over sixty countries on various areas of convergence (e.g., Urban, et al., 2013, p.185 for biomedicine), convergence became an overall priority in programs at NSF (e.g., "10 Big Ideas") and National Institute of Health, for the National Academies of Sciences, Engineering, and Medicine (NASEM), and various academic institutions and organizations. Convergence research strategy has led to truly major advances in healthcare, fighting cancer and infectious diseases (Sharp et al., 2016). "It integrates knowledge and tools from life and health sciences, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges'' (NRC, National Research Council of National Academies, 2014, p. 1). OECD has organized activities and a working group on Biotechnology, Nanotechnology, and other Converging Technologies since 2014 (OECD, 2014).

Principles to facilitate convergence to solutions in complex systems

The scientific foundation for convergence relies on several key underlying theories: (i) *unity in nature* (a unified set of principles and laws could explain world events); (ii) *human interaction ecosystem* (all biological and human systems have tendencies to interact, assemble, and evolve collectively); and (iii) *system adaptive complexity* (complex systems survive through adaption and a natural selection process) (Roco, 2020).

On this foundation, seven principles to facilitate or accelerate converge to a goal or satisfy a natural law in complex systems have been formulated:

A. **Holistic view**. Convergence exploits the unity and interdependence found in nature and society. Yet a challenge is finding unity in diversity: what are the essential patterns, processes, and unifying concepts? How does interdependence determine the structure and coherent evolution? Available investigative tools are mathematics, fractal pattern recognition, frequency distributions functions for mapping the system and its synthetic representation, and neural-like network modeling. Convergence can be facilitated by integrating originally distinct domains and databases, establishing open access knowledge systems, and adopting 'universal scaling laws' for system representation (e.g., West, 2017). The goals may be reached by supporting system science and team science, changing local interactions for guided self-organization, and advancing cross-domain networking as well as interpersonal and intrapersonal education. Dynamic system analysis is useful for identifying the instabilities that trigger new dynamic entities and new convergence processes.

B. **Vision-inspired common goal**. Long-term vision is essential for addressing challenges and capturing transcendent opportunities. Setting long-term visionary targets beyond the known concepts and applications needs to be done at the beginning of a convergence process. A vision-inspired goal may be realized via one or successive convergence processes. While "Use-inspired basic research" Pasteur's quadrant in the Stokes's knowledge-relevance diagram (Stokes, 1997) applies to known uses and applications, the "Vision-inspired basic research" relates to new uses and applications unknown at the beginning of research. Methods to implement this principle include scenario development and forecasting, anticipatory planning, and reverse mapping in planning (working backward from the vision to establish the intermediate research steps and approaches). Sufficient time to imagine and define the vision needs to be dedicated before working on a solution. Promoting a culture of convergence based on common goals is essential.

C. **Convergence–divergence cycle.** The transformation pattern of an evolving system includes convergence (confluence of upstream components and their integration), system transformation (to form a new system), and divergence (to various outcomes and reaching the goal) (Figure 1). A domain- and time-crossing spiral of information exchange and innovation is created by the system's interactions with its surroundings. This convergence–divergence cycle is triggered by upstream "excitation" of the process and completed by its downstream "extinction." Understanding and optimizing the convergence–divergence cycle leads to improved outcomes.

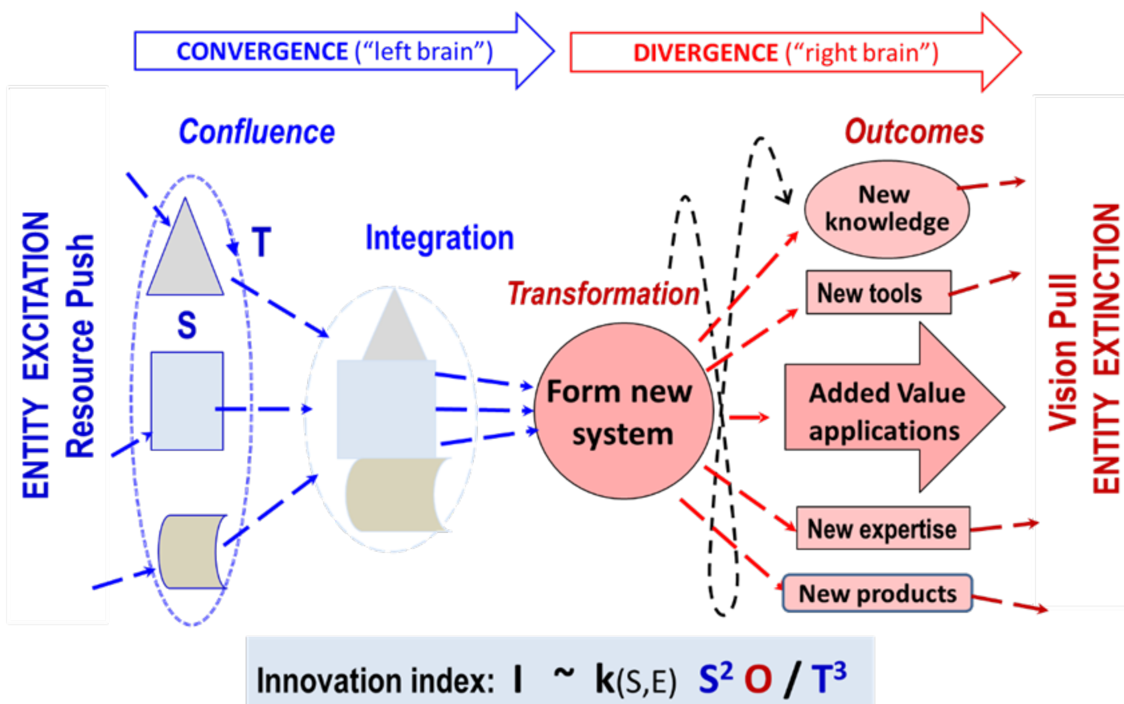

Figure 1. Convergence-divergence cycle: dynamic pattern from "excitation" to "extinction" in a transformative system or entity

The innovation index (I) in a convergence process has been introduced to evaluate the efficiency of the process (Figure 1) (Roco [2020], p.10). The index is proportional to the size or the number of confluent components S at power two and divergence opening O (number of opportunities created after system transformation) at power one, and is inversely proportional with power three of the time interval T of the convergence–divergence cycle, where k is the coefficient of proportionality as a function of confluent components S and external context E. The formula underlines the importance of a larger confluent domain S and of accelerating the convergence process (smaller T of execution) for improved outcomes. Several models for convergence accelerators have been established in industry (Intel, Semiconductor Research Corporation, others) and government programs (e.g., at NSF and Air Force Office of Scientific Research).

Other principles to facilitate convergence are:

D. **Unifying actions.** Making system-logic decisions and actions leads to better system integration and reaching the common goal. One needs to consider the evolution of the entire system when addressing local and time-dependent problems. The transformative goal is better realized if it is aligned with contextual trends such as natural laws, economic and social requirements.

E. **Cross-domain approaches**. Creating and implementing cross-domain languages formed by shared concepts, social customs, and methods improves outcomes. This facilitates sharing of essential ideas and techniques across the entire system and promotes synergistic and transcendent solutions of the convergence process. It may change the culture and encourage the use of mathematical and artistic abstraction, general system architectures, general-purpose databases, benchmarking, and generalized scaling laws (West, 2017).

F. **Multi-tasking.** Coordinating tasks for simultaneous cause-and-effect pathways encountered in a complex system improves outcomes. A challenge is managing the co-evolution of different paradigms and non-linear interdependences of multi-algorithms required by various tasks. Actions may include co-design, co-production, and co-management.

G. **Added value.** Timely and synergistic confluence of resources may generate added value and increase return on investment. A key challenge is proper concurrence and staggering of resources to achieve the transformative effect of the system. A desired effect is the steep increase in the return-versus-effort diagram that is frequently recognized as the “S-curve”. Timely staggering of decisions from basic research to implementation is illustrated by NSF’s Convergence Accelerators program.

Convergence–divergence cycle : Universal evolution pattern

Implementing convergence enables improved outcomes in applications. In addition, evolutionary convergence brings a philosophical perspective in understanding transformation in nature and society. The universe is in continuing and coherent motion and transformation, from subatomic quantum levels to biosystems and astronomic ‘Big Bang’ expansion. Bounding conditions, dynamic gradients, and inherent non-uniform structure create motion instabilities and small-scale fluctuations that, in suitable conditions, can grow ("*excitation*" stage) to form larger scale dynamic entities or systems. Each dynamic entity has a finite lifetime under the constraints imposed by surrounding conditions and energy dissipation, which both force the entity's "*inhibition*". Transformation processes within each dynamic entity typically follow a convergence–divergence cycle ("*transformative cycle*") under the internal and external effects according to the convergence–divergence cycle principle (listed above and in Figure 1). Fractal transformative cycles with pulsatory excitation-to-extinction behavior develop at various length and time scales (Figure 2). The dynamic entities may be either physical systems, disciplines, or something else as a function of the context. Collectively, the interacting dynamic entities represent a universal fractal behavior of change in nature and society.

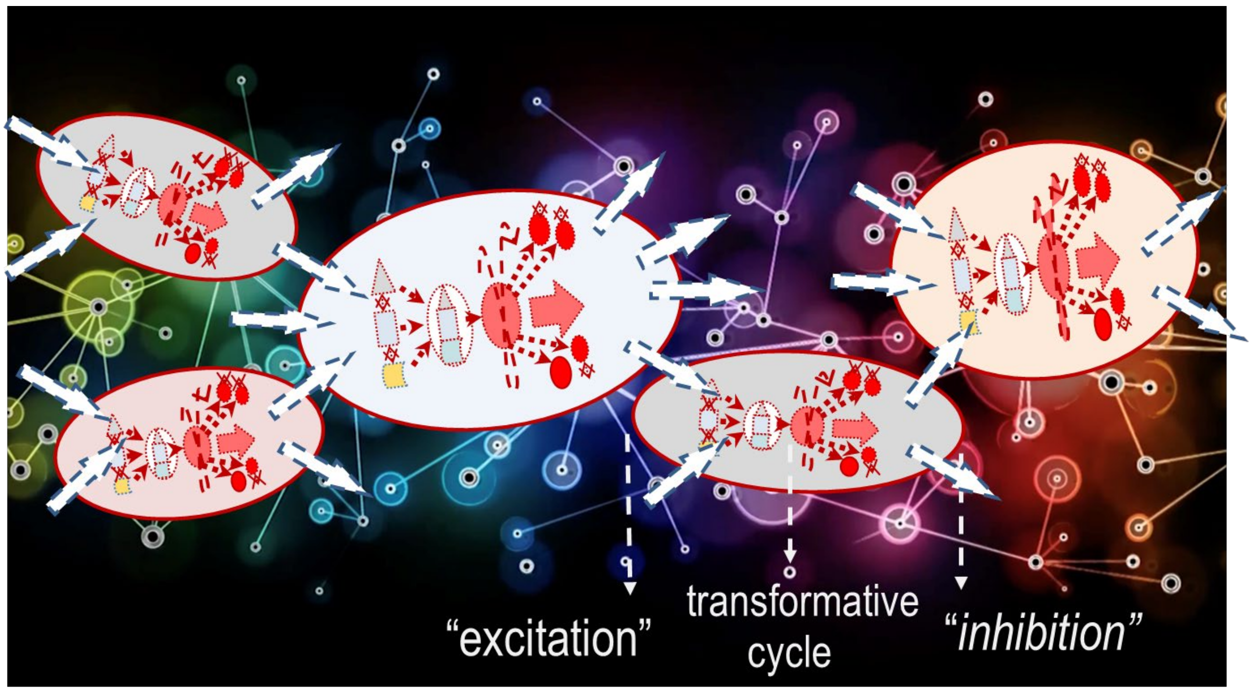

Figure 2. Coherent transformation of systems or entities, each characterized by a convergence-divergence cycle (universal evolution pattern)

An example in physics is turbulent flow with growing-dissipating cycle of fluid vortices. An example in biology is the cell growing-division lifecycle. The development of nanotechnology, and its governance through NNI, is another example. Nanotechnology was dominated during 2000–2020 by the convergence of disciplines and the creation of new technology platforms; since 2020 it has been dominated by divergent use of earlier results in many S&T areas. Hierarchical evolution (for example, from DNA to tissues in biological assembling) would involve several successive convergence–divergence transformative cycles (for example, from DNA to RNA, from RNA to proteins, and from proteins to tissue).

While the overall evolution or transformation in nature and society continues in time, each evolution or transformation cycle is finite. While fluid flow in atmosphere continues in time, the cycle of each component turbulent fluid vortex is finite. While the life of a species continues, the life span of each individual is finite. The transformative cycles and the respective systems evolve in time in response to the individual interactions with the surrounding context. The *system information content and complexity tend to increase with the convergence-divergence cycles* as the divergence stages create more features and functions.

The behavior of nervous systems tends to mimic natural and societal reality**,** including the convergence-divergence cycle. It begins with "excitation" of neurons in response to an upstream action or event; then, convergence of neural signals from several thousand neurons to those dedicated for that type of action; leading to change of the state of dedicated neurons; followed by divergence of neural signals from those neurons to other thousand neurons at different length scales; and finally, "inhibition" of the respective event. Neural events reflected in thinking processes, like natural events in physical systems, have limitations because of the partial exposure of neurons to external events and the limited neuronal capacity to absorb and keep the information.

In turn, artificial intelligence (AI) deep learning algorithms mimic the convergence–divergence cycles from thinking processes**,** reflecting implicit evolution of physical systems. However, compared to thinking processes in human brains, AI has several limitations: (i) brains use chemical, electrical and other signals, while AI relies on electrical signals alone; (ii) AI networks are smaller and simpler so far; and (iii) AI is based on given input instructions and data and does not have "common sense" directly from the physical world. Current research tries to address these limitations.

The convergence–divergence cycle also has been reflected in art**.** The "Endless Column" is a sculpture modeled by C. Brancusi in Paris (see Pompidou Center) and built at large scale in the Carpathian Mountains (Târgu Jiu, 1938). The column has a succession of vertical convergence–divergence elements suggesting the human thought process. In another example, the spiral, like convergence evolution, is an ancient intuitive symbol for growth in Asia, the Middle East, and Latin America, and several monumental building such as the Great Mosque of Samarra (Irak, 852) have a spiral shape similar to the spiral of information and innovation in a typical transformative cycle.

Application areas

Applications of convergence principles in the last two decades have influenced knowledge creation, advancements in emerging technologies, and various societal activities by expanding from components to a holistic view, focusing on compelling goals, and creating divergent fields of activity. This progress has been served by new tools such as neural-like network modeling, open-source digitization, mapping large data sets, and artificial intelligence.

The convergence–divergence process of knowledge systems has played a key role in the emergence *of five foundational S&T fields* — nanoscale, information, modern biology, modern cognition, and artificial intelligence — each built from their essential elements (atoms/qubits, bits, genes, neurons, and respective logic steps) by hierarchical assembly to address global challenges and opportunities (Roco, 2020).

Convergence between two or more disciplines or application areas have resulted in *new S&T domains*, such as bioinformatics, nanobiomedicine, synthetic biology, cyber-physical-social systems, and brain-machine interactions.

Areas where convergence already has brought profound transformations are advanced manufacturing (e.g., the Manufacturing USA Institutes, distributed manufacturing), synergistic research (e.g., nanomedicine, synthetic biology), seeding novel research domains (e.g., intelligent cognitive assistants, cyber-physical-social systems), new approaches in research, personalized learning (e.g., virtual reality environment, from brain to cognition and learning), and collective societal actions (e.g., citizen science, team work approach, creation of national investment coordination centers) (NRC, 2014; Roco & Bainbridge, 2002; Sharp et al., 2016; Urban et al., 2013). Measuring convergence in such applications has improved the convergence process itself. An exploratory area of research is prediction of convergent adaptive evolution during the transformative cycles, such as genomic structural variations with human culture or plant replicated evolution in same environment.

Some promising, timely opportunities for implementation of convergence principles are advancement of the global S&T system, realizing sustainable society in planetary boundaries, convergence of medicine with science and engineering, fostering convergence in organizations, and social convergence including conflict resolution (NRC, 2014; OECD, 2014; Roco, 2020; West, 2017).

Conclusion

Evolutionary convergence is a strategy to improve and accelerate outcomes in complex systems. It can catalyze transformations with smaller costs or investments as compared to using disciplinary or sector specific methods. It may generate transcendent outcomes that are not possible otherwise. Convergence of knowledge and technology for the benefit of society is a core opportunity for progress in our knowledge society. The intentional implementation of transformative convergence to a goal is a new approach that needs a new cultural framework. Convergence principles facilitate advances in discovery, innovation, production, and humanities. They best serve individuals or groups with broad responsibilities in organizations addressing complex problems and multidomain challenges. Convergence can accelerate the integration of science, technology, and applications.

Convergence in manufacturing, biomedicine, and cognitive technologies appears to bring societal benefits more quickly compared to other approaches. Cross-domain programs in universities and funding agencies also have shown improvements. Investments in convergence strategies were beneficial in research initiatives (e.g., U.S. National Nanotechnology Initiative and EC long term R&D strategy), funding agency programs (e.g., NSF's Growing Convergence Research, NSF's Future of Work at the Human–Technology Frontier, and Convergence Accelerators), national coordination centers (e.g., The Korea National Industrial Convergence Center), and international partnerships (e.g., in OECD). International collaboration is essential for the development of convergence science and convergent technology platforms.

Convergence concepts have been inherent to human development. Convergence–divergence cycles in nature and society are fractal components of a universal evolution pattern. Furthermore, human thinking processes and AI's deep learning algorithms follow similar patterns characterized by convergence-divergence cycles.

All systems in nature and society are evolving together. Confluent upstream factors act on each system leading to its transformation through convergence–divergence cycles. At a personal level, each individual is subject to confluent multisource teaching particularly in childhood, reaches integrative achievements at maturity, and then diverges into areas of strength and to new generations based on experience before the end of the cycle. Each cycle event is different and finite. Collective evolution is never finished and determines trends in nature and society.

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