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PERSPECTIVES

Principles of convergence in nature and society and their application: from nanoscale, digits, and logic steps to global progress

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Abstract Knowledge, technology, and society as well as natural systems are increasingly coherent and complex, and new systems are continuously formed at their interfaces. Convergence is a problem-solving strategy to holistically understand, create, and transform a system for reaching a common goal, such as advancing an emerging technology in society. The systems may be either in natural, scientific, technological, economic, or societal settings. Convergence offers a unifying strategy applicable to all systems that can be modeled as evolving neural-like networks. The paper presents an overview of the convergence science including underlying theories, principles, and methods and illustrates its implementation in key areas of application. The convergence approach begins with deep integration of previously separated fields, communities, and modes of thinking, to form and improve a new system, from where solutions divergence to previously unattainable applications and outcomes. The worldwide science and technology (S&T) landscape is changing at the beginning of the twenty-first century because of convergence. First, there is the affirmation of three transdisciplinary general-purpose technologies—nanotechnology, digital technology, and artificial intelligence (AI). A second main characteristics is the deep integration of five foundational science and technology fields (NBICA: nanoscale, modern biology, information, cognition, and artificial intelligence) from their basic elements—atoms, genes, bits, neurons, and logic steps and their collective action—to address global challenges and opportunities. The affirmation of nanotechnology at the confluence of disciplines toward systematic control of matter at the nanoscale has been an enabling inspiration and foundation for other S&T fields, emerging industries, and convergence solutions in society. Several future opportunities for implementation of convergence principles are the global S&T system, realizing sustainable society, advancing human capabilities, and conflict resolution.

Keywords Convergence science · Principles and methods for convergence · Complex systems · Neural-like network · Convergence–divergence cycle · Nanotechnology · Societal sustainability · Knowledge and technology trends

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Introduction

Defining convergence

In the early decades of the twenty-first century, with the growth of knowledge societies, progress in emerging technologies, and increased complexity of societal systems, convergence has reached a special significance. It has become a means of harnessing the fundamentally new and rapid scientific and technological advances of our time. Convergence has various meanings in literature as a function of the domains that are subject of integration and how they are brought together. In this paper, convergence refers to a strategy for reaching a shared goal in a system. The principles guiding convergence and their implementation will be outlined.

Progress in science and technology is accelerating, increasingly interdependent and emergent. At the same time, society is becoming more populous and more dynamically networked, with longer-term and more intense interactions. An increasing number of research areas, such as the study of universe, require dealing with a higher level of complexity with limited information. Such systems and topics of study are too complex to be adequately evaluated and managed using single-domain approaches. Problem-solving must go beyond a single application field, discipline, or pathway. A general problem-solving strategy for all these cases is convergence.

Convergence strategy aims to holistically understand and transform a knowledge, technology, or society system for reaching shared goals or align with shared external constrains (Roco 2002; Roco and Bainbridge 2003, 2013; NASEM 2014, 2019). Most such systems can be modeled as neural-like networks with dynamic or complex behavior. Such networks are systems composed of artificial neurons and artificial neural links whose structure and functions may be simulated in a similar manner as the biological neural networks or circuits of neurons linked via synapsis as found in brain. Seven principles to facilitate convergence have been formulated reflecting the unifying behavior of the neural-like networks describing the respective systems. Using convergence principles, multidomain knowledge databases, digitization, and artificial intelligence are tools for bridging diverse fields together toward a holistic comprehension. Illustrations of shared goals are research toward realizing an emerging technology, satisfying the environmental planetary boundaries, and better decision-making in research funding organizations. Understanding the evolution of natural ecosystems is driven by astro-geo-physics-bio convergence principles within the nature bounding constrains.

Convergence processes not only connect across domains of human activity but also along evolution in time and across types of behavior, architectures, and actions. A convergence process is evolutionary and transformative achieving mutual compatibility, synergism, and integration of seemingly different disciplines, technologies, and communities to create added-value transformations for shared goals. Convergence is a way of thinking that requires a specific culture. Convergence is a process that advances creativity, invention, and innovation. Convergence in society ultimately leads to finding better solutions in daily tasks at work, for learning, aging with dignity, and physical and cognitive wellness.

This is a conceptual shift from the focus on studying the components of a system to managing both the components and the overall system. How will convergence change society and how can individuals and groups adjust and take advantage of this? Convergence for reaching a common goal in a system, or in brief “convergence,” offers a framework for philosophical concepts and culture that connect nature and society.

Convergence may begin with setting together multidisciplinary teams or integrating multiple disciplines, and it continues with several essential phases such as creating a new system from where divergence to new competencies and applications take place to reach the desired goals. Convergence is not described just “by coincidental links” or “multiple nodes” in a networked system—but it is an interactive, purpose-driven strategy and process. Promoting links alone may lead to “info silos” or “eco chambers.” Convergence does not imply “top-down governing” in an ecosystem—but convergence governance is dominated by horizontal links and self-organization principles.

Convergence science

Convergence science includes the underlying theories, principles, and corresponding specific methods that facilitate convergence, as presented later in this paper. Ten theories underpin the origin and relevance of convergence beginning with unity of nature and human interaction ecosystem. At the core of transforming features, there are seven convergence principles and corresponding methods, beginning with the holistic view of a system and closing with the confluence of resources to transform the system.

All ecosystems in nature and society are guided by similar bottom-up principles and patterns, originating from similar dynamic behavior of their neural-like networks even if they have different domains of application (social, production, or biological networking) and different system architectures (linear, hierarchical, others). This is true for societal interactions including for areas such as semantic systems and religious beliefs (Bainbridge 1995, 2004). The tools of the digital economy, IT, and AI facilitate the establishment and operation of a global neural-like network with heterogeneous composition.

Similar dynamic patterns can be found in the spiral space-time evolution of natural processes (e.g., tornado and stellar system; see Fig. 1), the spiral of innovation describing the evolution of smart phone technology platform (crossing in time multiple S&T fields such as materials, cognition, electronics, energy, personalized learning, and packaging, with the same common goal; Roco et al. 2013), and the spiral of multidisciplinary approach to advance unifying educational programs (teaching similar foundational S&T modules by rotation in different disciplinary fields/courses; Roco and Bainbridge 2003). The spiral convergence pattern also is a characteristic of the growing Internet of Things (IoT) progressing in time across multiple fields. The global IoT in 2017 had more than 5 billion components and an extended network of 50 billion things, poles, and processes, plus others affected by the network. For the first time in history, most human activities are linked in a unifying world network.

Observing and controlling convergence in complex systems

To identify the essential and unifying characteristics in large dynamic systems, one needs observations and analysis based on abstraction (to see what is essential), system view (holistic understanding, see what are the unifying characteristics), generalization (across domains), and simplicity (eliminate non relevant details to avoid system noise). The reductionism to essential features does not means reduction to individual components. There is an increase use of general-purpose mathematics, nanotechnology, digitization, artificial intelligence and the so-called universality concepts as tools of implementing convergence. Control of convergence in complex systems can be done by changing the system boundary conditions, controlling the rules for interaction links between nodes or of a subset of essential nodes, and guiding information and energy distribution. A trend in observing complex systems is the increase use of system AI.

Possible benefits

Several possible benefits from implementing convergence are:

- Creating generalizations in understanding of systems ("unity in diversity") and new ideas in research and production at the confluence of fields, which are achievable with relatively small added effort or investment. Identifying general theories or "universality" in reaching a goal in complex adaptive systems is one of science's and society's main challenges.
- Realizing compelling goals in complex systems, which are difficult to reach with other strategies.
- Addressing emerging topics that could not be identified and addressed well otherwise. Illustrations include confluence of general-purpose AI and societal trends including human rights, emerging technologies for biomedical breakthroughs, and connecting quantum theories to manufacturing and space exploration.
- Improving human behavior and capabilities, teamwork methods, and outcomes.

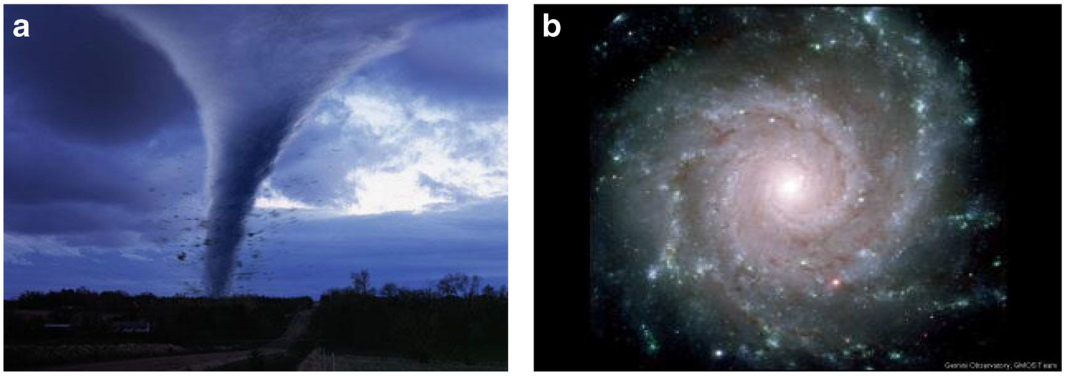


Fig. 1 Spiral patterns of convergence structures in nature: **a** tornado (credit Real Tornado, Google) and **b** stellar system (credit Perfect Spiral Galaxy, Gemini Observatory)

– Creating convergence culture as a framework of mind for individual and groups, to improve results and overall human development, with potential relevance to all areas of human activity (NASEM 2019).
– Implementing convergence principles in several areas of multidisciplinary research, education, biomedicine, and production, to be discussed later in this paper will bring immediate returns that are low-hanging fruit.

This paper outlines the basic concepts for convergence science (underlying theories, principles, and methods of convergence) and illustrates its implementation in key societal activities, with a focus on nanoscale-inspired converging technologies. This is explained from the perspective of evolving neural-like network describing most complex systems. This paper makes the case that convergence, as defined here, is a key transformative approach to improve societal outcomes that is expected only to increase in importance as societal interactions grow and convergence methods improve.

Earlier studies on science and technology convergence

It is well-known that "natural interdependence" has been prevalent in native Indian culture in North America. Unity of nature and society was at the core of the Renaissance ideas in Europe in the fifteenth century. Earlier signs of convergence concepts may be identified in China and India traditions. At the end of the twentieth century, "unifying knowledge" leading to a holistic approach has been advanced in several academic circles at Harvard University (Wilson 1999) and technology-driven projects (Kurzweil 1999).

The report on "Converging technologies for improving human performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science" (Roco and Bainbridge 2003) was followed by two complementary books on coevolution of human potential and converging technologies (Roco and Montemagno 2004) and managing nano-bio-info-cogno innovations (Bainbridge and Roco 2006a). The 2003 report aimed at visionary targets to 20 to 50 years into the future.

An international benchmarking survey in over 30 countries on decision-making and problem-solving has shown that knowledge, technology, and society convergence are prevalent, even if not always explicitly recognized and methodically applied (Roco et al. 2013). Seventy-five case studies on the application of convergence to advance science and engineering have been illustrated in a handbook (Bainbridge and Roco 2016a). Relatively recent reports on convergence as applied to various areas of relevance (such as health, research and education

Fig. 2 Key convergence reports published between 2013 and 2019

centers, and culture) are shown in Fig. 2 (Roco et al. 2013; NASEM 2014; MIT Press 2016; Bainbridge and Roco 2016a; NASEM 2017, 2019).

The National Academies of Science, Engineering, and Medicine (NASEM 2014) report marked the broader acceptance by the science and technology (S&T) community of the convergence approach. After 2016, NSF implemented this approach in about half of the new program announcements, with the term "convergence" being in either the project title or abstract. After 2017, convergence became a priority in The Academies (NAS, NAE, NIM), as highlighted in the report "Fostering the Culture of Convergence" (NASEM 2019).

Diverse international communities aim at specific convergence approaches in reaching their goals of satisfying the needs and aspirations of people in society. The United Nations, Organization for Economic Co-operation and Development (OECD), G7, various Academies, and other organizations have created such frameworks for reaching visions on sustainable human and societal development (e.g., United Nations 2019; NAE 2008).

Key underlying theories

Convergence has ten key underlying theories, outlined below (Fig. 3) (Bainbridge and Roco 2016b). The first three theories—unity of nature, human interaction ecosystem, and systems adaptive complexity—are essential for convergence systems. The remaining theories provide the context for convergence.

The unity of nature theory

Since antiquity, people have explored whether a unified set of principles and corresponding coherent set of laws could explain world events. In the scientific realm, mathematics, fractals, and frequency distributions functions of events in physics, evolutionary concepts from biology to social sciences, and more recently "neural networks" and "universal scaling laws" (West 2017; Danielmeyer and Martinetz 2015) representations have strengthened the support for this theory. Unifying concepts and holistic perspectives, such as the integral philosophy of creative transformation (Tanaka 2018), have generated a theoretical foundation for applying convergence to societal systems. In another example, nanotechnology provides unifying structures, phenomena, processes, and methods across disciplines for both the material and biological worlds (Roco et al. 2000).

The human interaction ecosystem theory

All material, biological, and societal systems have natural tendencies to interact at their interfaces, assemble, and act and evolve collectively. Their interdependence affects their evolution and long-term transformation. Hierarchical, self-regulating large systems seem to have developed as a result (Lovelock and Margulis 1974). This theory provides a foundation for the system-based strategies in convergence. For illustration, a cell's evolution is determined by its interactions with other cells in the respective tissue, organ, and overall living system. A human group's effectiveness is affected by the connectivity between its individual members across diverse backgrounds technical expertise and moral beliefs.

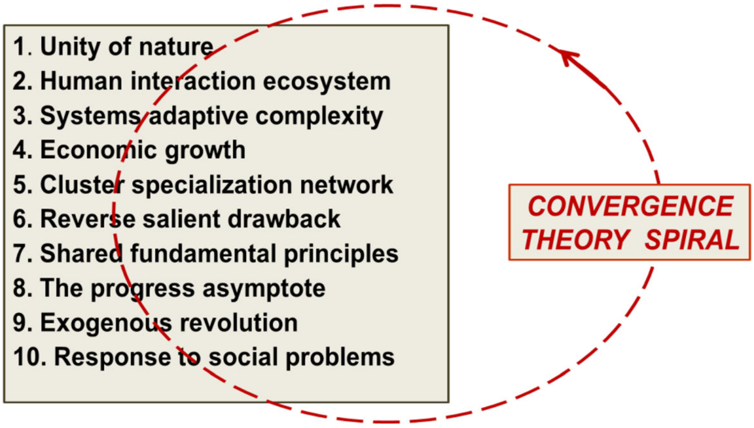


Fig. 3 Convergence is realized in conjunction with ten interconnected theories that are applicable to systems in either nature, knowledge, technology, or society

The systems adaptive complexity theory

Most natural and human systems are large and heterogeneous, and they may be described by nonlinear interaction networks and hierarchical architectures that evolve under external constrains at various spatial and temporal scales. They often reach emergent behavior. Such complex systems may survive through adaption and a natural selection process akin to biological evolution (Levin 2005). Understanding such systems is limited if using disconnected disciplinary approaches. Full system understanding and transformations may require convergence of science and technology. For example, changing an internal interaction mechanism or the type of links between nodes in a neural-like network may determine changes in the overall system properties and functions.

The economic growth theory

Modern society is prosperous enough to afford research and development projects that ensure that growth continues. Faster economic growth is made possible by concurrence of knowledge areas and investment efforts to introduce new technologies and products. This suggests the possibility of funding coordinated societal efforts to realize a compelling goal. For instance, significant financial efforts worldwide have sustained development of the semiconductor industry following the Moore's Law, and NSF funding of more than one billion dollars led to the detection of gravitational waves in only several decades after the initial decision, both allowing further progress in society.

The cluster specialization network theory

The dynamics of teams or communities change as the number of their members increase, and the same is true for the proliferation of subdisciplines that must cooperate with each other (Massey 2002). The theorized effects are enhanced by convergence processes of smaller groups. The results from many specialized networks within a system are generally superior to that from larger groups or individuals in the same system (Galesic et al. 2018). This underlines the importance of suitable clustering structuring of a convergence system to improve outcomes. For example, structuring of materials into nanoscale clusters significantly change the properties of those materials.

The reverse salient drawback theory

If science and technology advance all along the front, except for a stall in one sector, that is, a reverse salient, the histories of the electric power and appliance industries (Hughes 1983) have shown that the reverse salient is a critical drawback for the field. If disciplines of science and technology are advancing without much convergence between them, some areas between disciplines ("salients") will fail to advance, and the overall field will suffer. This theory underlines the importance of coherent development of disciplines and fields of relevance. For example, when safety or ethical issues are neglected, all other technical achievements may lose their recognition in an emerging technology.

The shared fundamental principles theory

This theory postulates that phenomena and processes have essential laws and fundamental principles that may cross various domains of knowledge and applications. It has relevance to the higher-level multidomain languages needed in convergence. For example, concepts from one field of science and technology can be applied to other fields, and data and methods of investigation and transformation may be integrated over larger knowledge and application domains.

The progress asymptote theory

This theory postulates that there exist natural limits to what can be discovered by science and created by engineering. This is important in setting the vision and goals of convergent processes. If indeed we are approaching the natural limits of science and technology in a specific field, then the last few advances may require unusually great investment not only of money but also of diversity of technical expertise in that field. An example is the increase expertise and investment needed to realize semiconductors with nanoscale features close to molecular and atomic levels.

The exogenous revolution theory

Science and engineering are societal institutions, and a radical transformation elsewhere in human institutions can trigger transformations in technical fields. Convergence processes among initially distinct domains become important. Societal shifts, such as economic changes favoring growth in a new industry, or unexpected developments in an adjacent field can break the stasis into which one discipline has frozen, thus liberating it to achieve new progress through an unexpected convergence from outside forces. For illustration, the nanotechnology and nano-bio-info-cogno technology convergences have reached recognition and societal support in the past 15 to 20 years and led to significant progress in science, medicine, electronics, environment, energy, space, and other areas.

The response to social problems theory

Science and technology are occasionally enlisted in a public response to an acute social problem, such as war, epidemic disease, or economic depression, and each problem may require a specific new partnership among disciplines that had not already converged. For instance, it is easy to think of convergent examples from the Second World War that contributed to subsequent peaceful technologies, such as civilian nuclear power and rockets to launch satellites. A more recent example is the coordinated response of science (e.g., virology and structural biology/chemistry, virus transmission models), engineering (e.g., vaccine biomanufacturing and environmental engineering of virus transmission by contact and aerosols), and social and behavioral sciences (e.g. implementation of social distancing measures, mask coverings, and vaccine acceptance) to address and control the Covid-19 pandemic.

Principles and methods to facilitate convergence

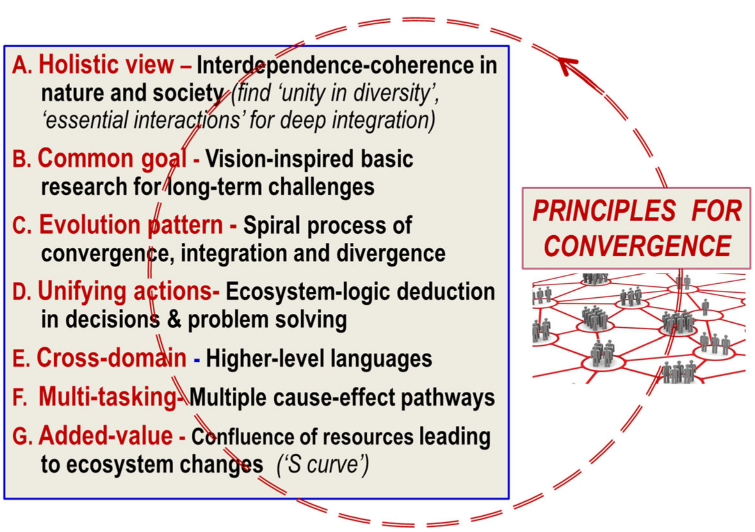
We have identified seven principles guiding convergence of knowledge, technology, and society (Roco 2016), as listed in Fig. 4. They are applicable to a general case of systems that can be modeled as neural-like networks. Each principle leads to corresponding methods for facilitating convergence.

Holistic view (Fig. 5): exploiting the interdependence and unity in nature and society

The behavior of a system is a function of its components and interactions between those components. Identifying the holistic characteristics for the respective system including its essential and unifying features and the systemic interdependencies (D'Agostino and Scala 2016) is a challenge. This can be facilitated by system science, team science, and interpersonal and intrapersonal education. Convergence methods associated with this principle include integrating originally distinct information systems and changing local interactions and inter-domain connectivity characteristics to change the system outcomes. A holistic view of human activity ecosystem is given in Fig. 5. Each converge platform (foundational S&T fields, Earth-scale, human-scale and societal-scale) is characterized by a set of concepts, group of participants, and specific investigative tools (Roco and Bainbridge 2013).

For illustration, nanomanufacturing enterprise changes from vertical and concentrated production to a more distributed and specialized enterprise because of

Fig. 4 Principles to facilitate convergence



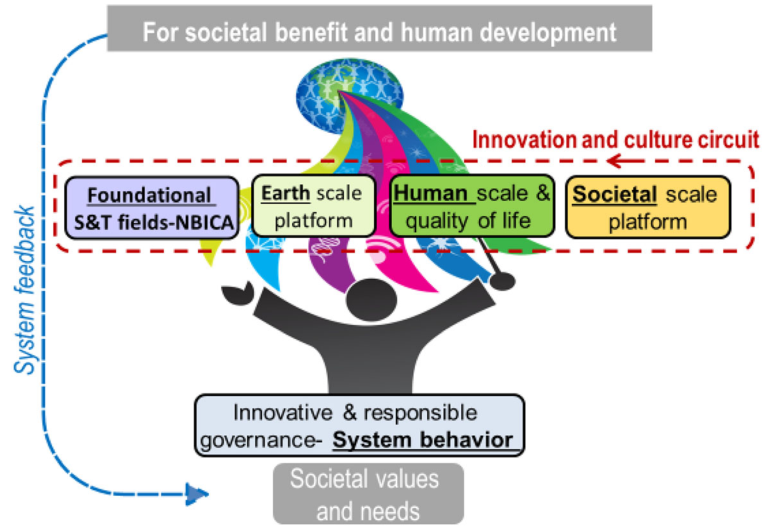


Fig. 5 Holistic view of human activity ecosystem (modified after Roco and Bainbridge 2013)

changes made in local interactions, node characteristics, and improved connectivity (Roco et al. 2013). In another example, advancing "teamwork" leads to increased interactions and group efficiency in an ecosystem (NASEM 2015). One way to facilitate information exchange for cross-field interactions is creating a "general-purpose database" or an "open knowledge network" for many types of information, ideas, and applications (Roco et al. 2013; NSF 2019).

Common goal (Fig. 6): using vision-inspired basic research and innovation to address common system challenges

Identifying and reaching visionary goals beyond the known concepts and applications ("New use" in Fig. 6) is a main objective. Convergence methods associated with this principle include forecasting and scenario development and anticipatory measures for preparing people, tools, organizations, and infrastructure for the future technologies and relationships. A recommended approach is reverse-mapping and planning, to work backward from the vision to investigate the intermediate research steps and approaches. Sufficient time to imagine and define the vision needs to be dedicated before working a solution.

For illustration, the National Nanotechnology Initiative (NNI, www.nano.gov) was proposed based on a 20–30-year vision of systematic control of matter at nanoscale for societal benefits (Roco et al. 2000; Roco 2011). The core concept was formulated in 1995–1996, the supporting technical studies were completed in 1997

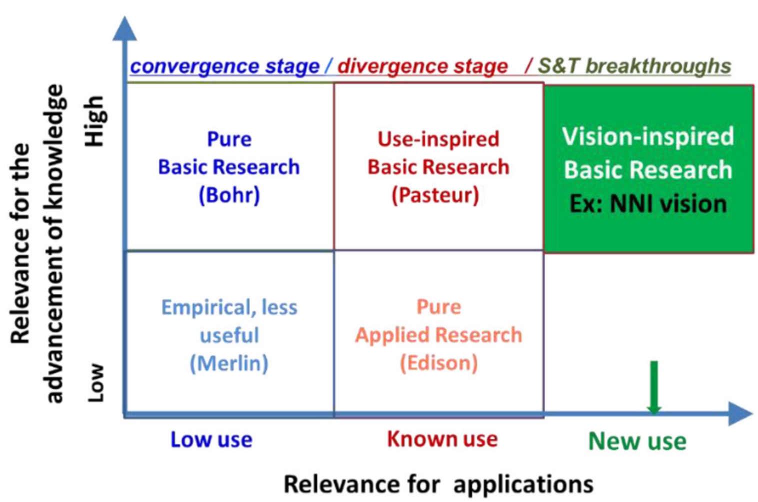


Fig. 6 Vision-inspired basic research and inventions are essential to address system challenges: The fifth domain "Vision-inspired Basic Research" was added to the initial quadrangle Stokes diagram (modified after Roco and Bainbridge 2013)

–2000, and the NNI announcement by President Clinton was made in January 2000. The NNI has continued for 20 years leading to research programs with cumulative research funding of about \$29 billion by 2020. The global nanotechnology revenues of products where nanotechnology is the key competitive factor have been estimated to reach about \$3 trillion in 2020, of which about 1/4 in the USA (Roco 2018). New areas of research and engineering such as metamaterials and plasmonics have emerged, and "new uses" appear in emerging technologies such as molecular manufacturing and production platforms for smart phones.

In another example, the Grant Opportunities for Academic Liaison with Industry (GOALI) concept proposed at NSF and extended to other organizations in the USA and abroad has the vision of advancing various collaborative models of participation of industry in long-term basic research performed by academic organizations. The models based on mutual interest principle expand from students and faculty internships in industry to full industry participation in joint research (Roco and Senich 1999). The concept was proposed in 1991, followed by a study on major engineering platforms in 1992–1993, and the first GOALI program announcement in 1994. Its impact has continued for 25 years, with numerous projects in various programs such as GOALI research project partnerships, Innovation Corps, and Intern.

Evolution pattern (Fig. 7): the typical convergence–divergence evolution cycle of natural or human processes is dominated by the innovation cross-domains-time spiral

The path of this spiral passes through the various domains of the system during successive time intervals while advancing toward a goal. The spiral path takes a shape that is determined by the internal mechanisms and external environment drivers.

There are four phases of a typical convergence approach:

i. *Convergence–confluence phase*: Confluence and assembling of knowledge, tools, domains, and modes of thinking are driven by a set of unifying concepts for reaching a common goal. The confluence may be across the domains of activity (disciplines, topics, economy sectors), participants involved (team interaction, integrated education, levels of organization), length scales (across domains), and along time (for evolutionary processes).
ii. *Convergence–integration phase*: To form new frameworks, paradigms or systems that allow people to answer questions, resolve problems, and build things that isolated capabilities cannot. The process of deep integration leads to the new system behavior as compared with its components. The

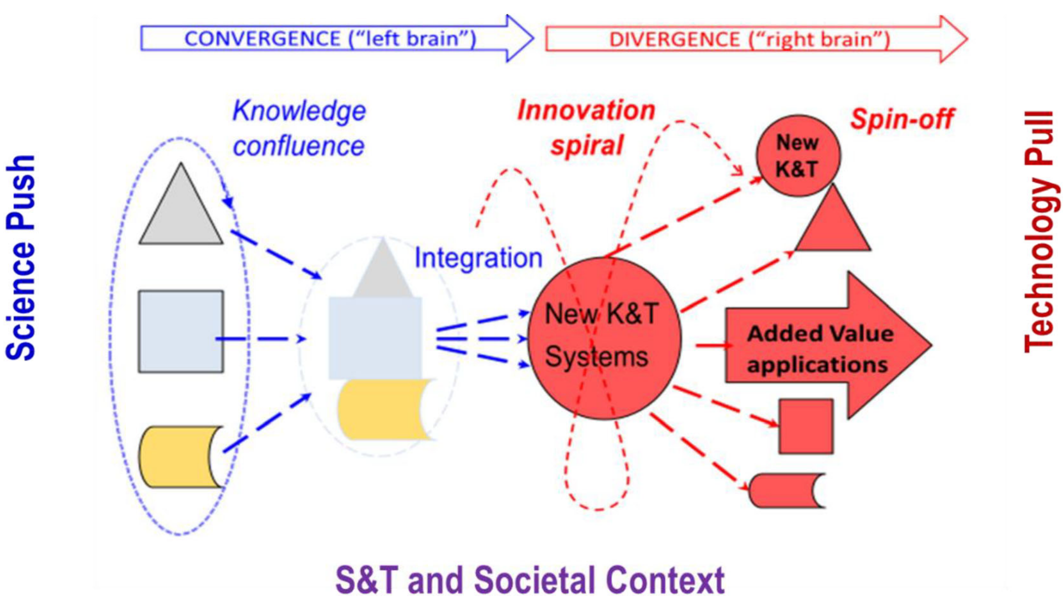


Fig. 7 The spiral process of convergence ("confluence of knowledge" and "integration") and divergence ("innovation" and "spin-off") in S&T: under the effects of science push, technology pull, and S&T and societal context

outcomes are creating or changing a system able to address the respective common goals, satisfying nature constrains, or respecting human values. For example, the use of three-dimensional printing and control of nanoscale interfaces leads to a new medical treatment system for tissue reconstruction.

iii. *Divergence–innovation phase*: From where novel pathways, opportunities and frontiers diverge (expand, branch-out) for new problem-solving and applications. This divergence stage may lead to expansion in knowledge, innovation, competencies, technologies, and applications. For example, after the basic logic unit CMOS for integrated electronic circuits were created, four qualitative R&D branches expanded around 2000: continuing Moore's law based on miniaturization; "More Than Moore" electronic elements to include in other existing technologies; "More Moore" to extend CMOS technologies using nanoscale phenomena and devices; and "Beyond CMOS" to create logic and memory elements beyond Moore's law as well as new architecture and multi-technical concept integrated systems.

iv. *Divergence–spin-off phase*: The initial outcomes of innovation create opportunities for spin-off development to new areas not planned in the initial phases and create seeds for new convergence-diverge cycles. For example, nanotechnology development has expanded into more than twenty spin-off S&T fields, from synthetic biology to quantum systems. Furthermore, foundational nanoscale knowledge, tools and products enable quantum information, AI systems, advanced wireless, advanced manufacturing, nano-biotechnology, nano-medicine, energy, water, food and environmental sustainability.

An illustration of the evolution pattern for S&T is shown in Fig. 7. The *push* of knowledge and technology that is dominant in the convergence phases of the process is combined with application and societal *pull* that is dominant in the divergence phases (Roco 2016), as well as *integrated* with other "lateral" and "time interval" domains. The convergence phases ("confluence" and "integration" in Fig. 7) lead to the creation of a new set of tools, framework, and/or ecosystem able to address the shared S&T goals. The divergence phases ("innovation spiral" and "spin-off" in Fig. 7) lead to emerging S&T solutions, qualifications, capabilities, and applications.

Methods associated with this convergence principle are supporting the respective four phases of the convergence–divergence process such as creativity, system integration, multiple outcomes from the innovation spiral path, and spin-off to unexpected outcomes. The challenge is to optimize the overall evolution pattern for the spiral path to reach the desired outcome most efficiently.

We have established the *innovation index in a convergence process*, which is determined by the evolution pattern and can be used for process optimization (Roco et al. 2013):

$$I \sim k(S,E)\ S2\ O/T3 \tag{1}$$

I is the potential increase of outcomes (innovation index describing augmentation of the effects of convergence or convergence intensity).

T is the timescale for the convergence–divergence cycle (proportional with the time needed for information exchange in the system).

S is the size of the convergence domain from where information is collected (the domain that is crossed by the innovation spiral; or the number of disciplines or application areas intersected by the discovery and innovation spiral).

O is the outcome ratio between the output and input; the ratio between outcome (O) and time (T) characterizes the divergence angle of the process (diffusion coefficient).

k is the coefficient of proportionality (a function of convergence domain S and external context E).

Several cases of (1) are:

a) The "Metcalf's law" (the value of a network scales is proportional to the square of the number of nodes ($I \sim S^2$) in network; Shapiro and Varian 1999)
b) The "Moore's law" in semiconductor industry (the proportionality with the ($I \sim O$ / TT) agrees with the exponential growth of technological developments)
c) The rate of technology diffusion ($I \sim 1 / T$)
d) Convergence accelerators for innovation ($I \sim 1 / T^3$) (NSF 2020)

Formula of the innovation index process (1) underlines the importance of reducing the time of convergence for improved outcomes. Several models for "convergence accelerators" have been established in industry

(Intel, SRC, others) and government programs (such as NSF and AFOSR in the USA).

Events from the upstream and downstream of an innovation process also affect a convergence–diverge innovation cycle. For example, connecting core research programs to upstream preparatory work (such as Germination program at NSF) and facilitating downstream connections to users (such as I-Corps program at NSF) can enhance the research and education projects and their impact.

An illustration of the convergence–divergence evolution cycle is its application to the development of nanotechnology in the USA coordinated by the National Nanotechnology Initiative (Roco and Bainbridge 2013).

System-centric actions (Fig. 8): making deductive system-logic decisions

This principle implies taking local decisions by considering the entire system and its evolution. This approach to problem-solving in complex hierarchical systems combines the top-down system vision with bottom-up research input, as well as with lateral and time evolution effects in decision-making.

An illustration of this principle is creating hierarchical decision-making systems for in R&D funding programs for nanotechnology regulatory aspects. Governance applies to four hierarchical levels of governance (Roco 2008): (a) adapting the existing regulation and organizations; (b) establishing new programs, regulations, and organizations; (c) building capacity for addressing those issues in national polices and institutions; and (d) advancing international agreements and partnerships.

Cross-domain languages (Fig. 9): creating and applying higher-level cross-domain languages (concepts, principles, and methods)

This principle facilitates the transfer of knowledge, synergism, and new solutions. It includes using universal languages such as mathematical abstraction, music, general-purpose databases, and general system architectures. It also includes identifying essential system characteristics through “simplicity” for efficient and timely solutions. Creating and sharing large multidomain databases and “trading zones” between areas of research and education in distinct areas facilitate developing multidisciplinary fields. Promoting technology integrators and benchmarking to facilitate introduction of emerging technologies in multiple areas are useful in developing multi-technology fields.

This principle has multifaceted dimensions. For example, Doyle and Csete (2011) have identified cross-domain unifying neural-like network diffusion patterns in many distinct systems and correlated the *robustness-speed* behavior relationship for those systems (Fig. 9). There is a similar *resilience-efficiency* relationship in the behavior of a system. A major lesson from Covid-19 pandemic in 2020 is that science and economics have overemphasized efficiency by short term optimization of componenets and left entire society to function with less resilience than needed in a longer term in a crisis or other low probability event. In another example, Jolliffe (2013) developed an algorithm designed to visualize complex databases to uncover information that can reveal the global structure of the data

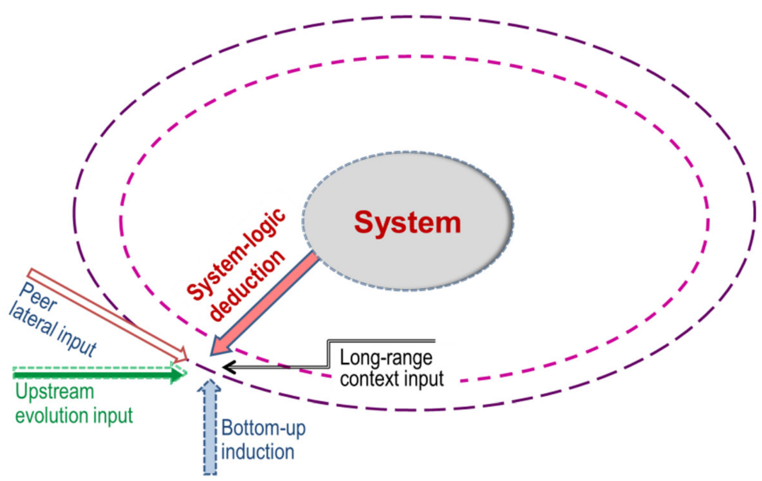


Fig. 8 System-logic deduction in learning, decision-making, and problem-solving. Results are better if the systems are larger, and information circulation across the systems is faster

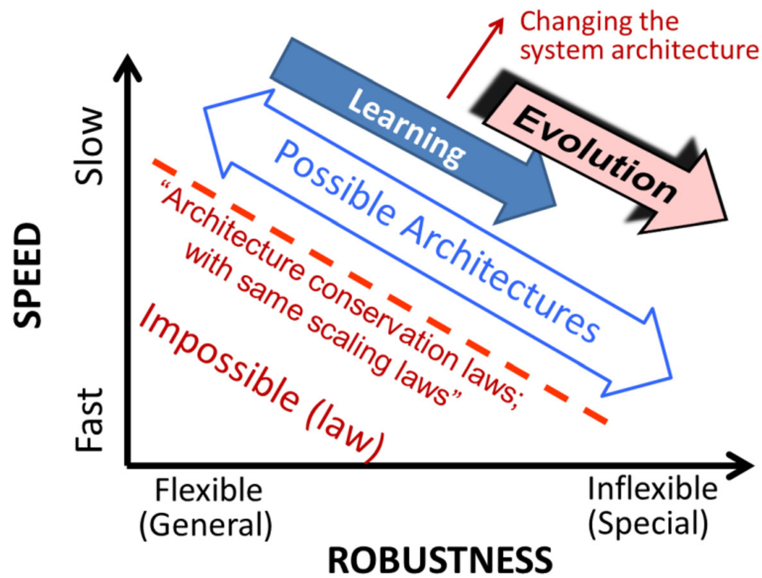


Fig. 9 Schematic for robustness-speed behavior of systems as a function of their architectures

under consideration while preserving local characteristics. The algorithm, Intensive Principal Component Analysis, has general applicability in fields such as astronomy, physics, and biology. In a separate project, Sia et al. (2019) proposed a community identification algorithm in complex networks based on interactions among entities. The approach also can discover hierarchical structures of the respective complex network. Universal laws for system architectures, including correlations and scaling laws have been proposed by West (2017). A universal theory for natural patterns has been advanced by Passotand and Newell (1994). Fortunato et al. (2018) have suggested that science may be an expanding and evolving network of ideas, communities, and publications. Searches can be made for universal and domain-specific laws underlying the structure and dynamics of science. Novelty is unconventional assembling of elements forming emerging ideas.

Multi-tasking (Fig. 10): to address concurrent cause-and-effect pathways in a large system

It leads to coevolution of paradigms for reaching a system goal, which may include multiple angles of

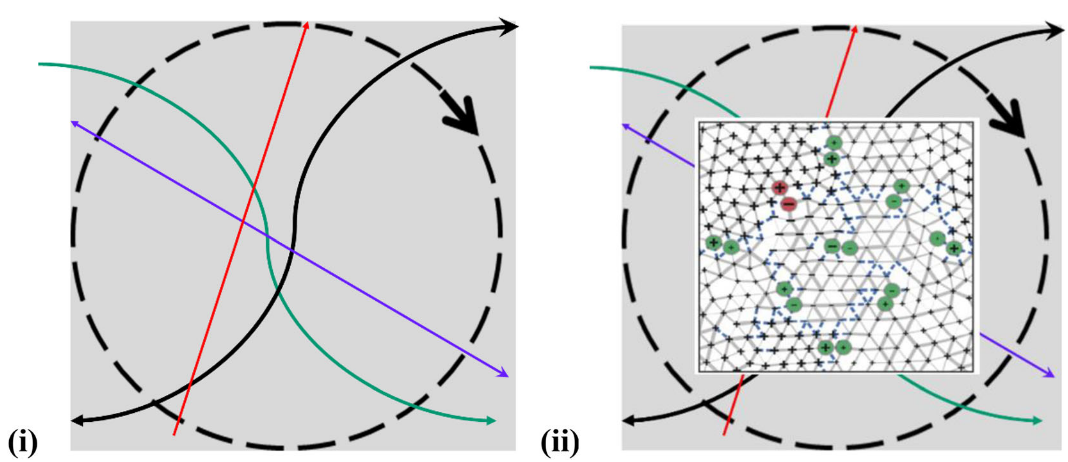


Fig. 10 Concurrent pathways with multi-tasking enable system multi-functions: (i) Multiple cause-effect pathways. It leads to co-current paradigms, which co-evolve and compete; (ii) e.g., water distribution network with multiple sources and sinks (concept Rocks et al. 2019)

observation, pathways, algorithms, lines of actions and modeling/simulation methods, and overall choices in multi-tasking (Prabhakaran et al. 2019; Rocks et al. 2019). Investigation of a large system requires competition of multiple-choice decision pathways and approaches (of logic steps, timescales, small parameters). Selection of investigative methods may lead to different conclusions. Knowledge mapping, network visualization, and fractal analysis are tools to identify the relevant cause-and-effect system patterns. A key concern is optimization and stability of the system functions. The challenge is to realize coherent management of various nonlinear and interdependent multi-algorithms for best system outcomes. Actions may include co-design, co-production, and co-management.

The limits of multi-tasking in physical, biological, and distribution networks, as well as in other complex systems, can be estimated (Rocks et al. 2019). This also appears to be true in a research and development endeavor. Smaller groups disrupt, and larger groups with increased multi-tasking develop (Wu et al. 2019). Physical examples of multi-tasking are the distribution networks of water (Fig. 10 ii), oil, or electricity that may involve multiple supply and consumer nodes. Biological networks have an even greater level of multi-tasking.

Added-value (Fig. 11): synergistic confluence of resources determines pronounced and accelerated system changes

In a typical situation, this yields the S-curve of increase of outcomes versus investments. Convergence is about changing the system (generating new system functions, changing the spatial, temporal and structure of the underlying neural-like network) and increasing the efficiency in the modified system. A specific innovation can produce a pattern of change that starts slowly as early adopters in the social system implement novelties, then accelerates as they influence others to follow their example, and then slows again as the innovation approaches full adoption. The challenge is proper concurrence of resource and staggering transformative actions.

Concurrence of scientific activities for a compelling goal is driven by both the internal scientific progress and external collaborations and requirements. Convergence of knowledge and technology realizes the benefits better if it is executed on an accelerating path (see (1) where the index of innovation $I \sim 1 / T^3$). This principle is at the origin of the Convergence Accelerators program (NSF 2019).

In another illustration, the NNI simultaneously has invested in a large spectrum of research programs,

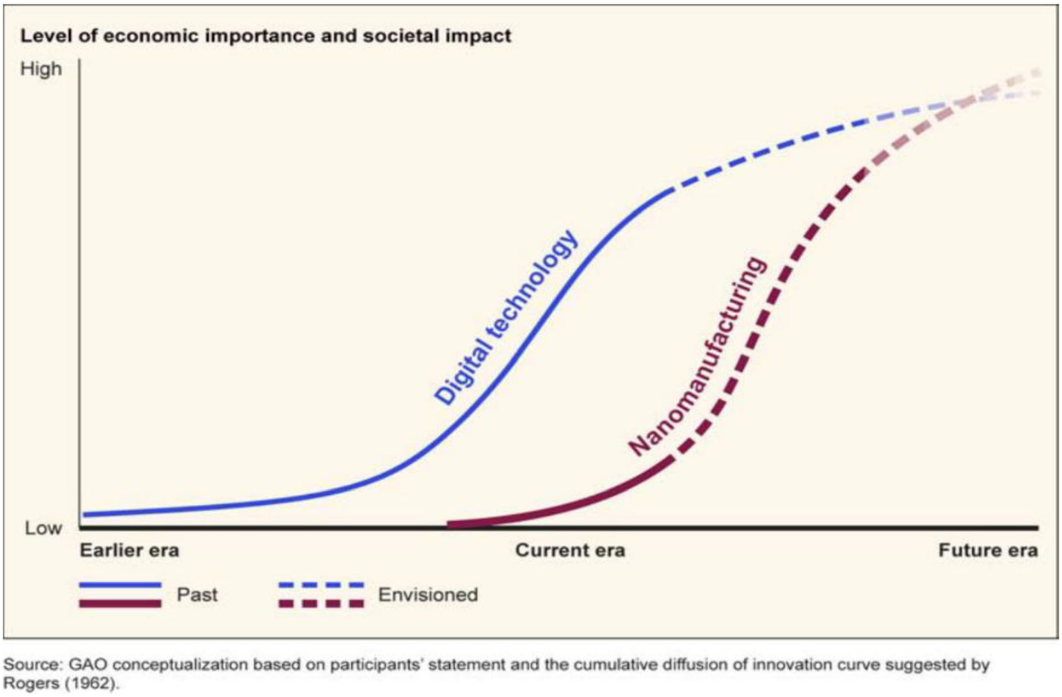


Fig. 11 Confluence of resources leading to system changes: illustration of the S-curve estimated for two emerging S&T fields (Ex: GAO 2014)

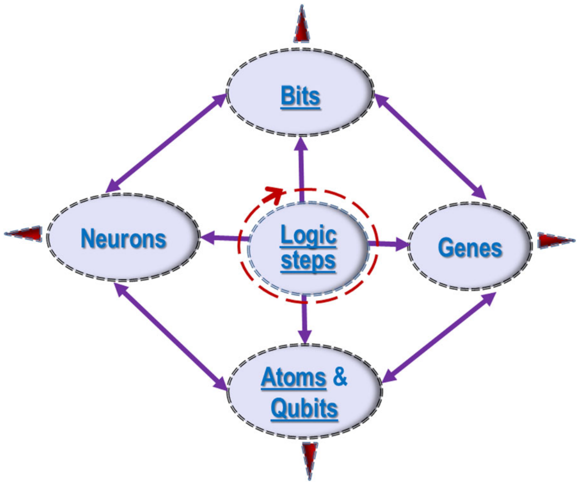


Fig. 12 Elemental building blocks of the convergence S&T system: atoms and qubits, genes, bits, neurons, and logic steps

infrastructure, education and training, environmental and health issues, ethical and legal issues, and international collaborations to reach its S&T targets.

The seven convergence principles have a dynamic collective action. They corroborate in reaching a common goal in a complex system. Each principle leads to various methods to facilitate convergence that has different relevance in various applications (Roco 2016).

Three hierarchical stages of science and technology convergence are underway

The emerging convergence S&T system at the beginning of the twenty-first century is based on five elemental building blocks: atoms and qubits, information bits, logic steps, genes, and neurons (Figs. 12 and 13). Three hierarchical S&T platforms have resulted from convergence of disciplines and technologies originating from these elemental building blocks (Fig. 14), and they have brought significant progress in economy and society:

- *General-purpose S&T fields*: (i) Nanotechnology integrating from atoms and qubits, (ii) IT (digital technology) integrating from bits of information, and (iii) AI integrating logic steps.
- *Convergence foundational S&T system (Nano-Bio-Info-Cogno-AI, in brief NBICA)* integrated from their elemental building blocks (atom and qubit-gene-bit-neuron-logic step, in brief a-q-g-b-n-l) (Fig. 13). A foundational S&T field is built up by hierarchical integration from a typical elemental building block, and the convergence foundational S&T system is built by hierarchical and cross-field integration of various building blocks.
- *Convergence of knowledge and technology solutions for global society*. The combined tools enabled in various human activity platforms (Fig. 5) are integrated to address converging solutions for societal benefit and human development, driven by societal values and needs.

General-purpose science and technology fields

General-purpose S&T fields are based on their respective elemental building blocks: *atoms and qubits* for the

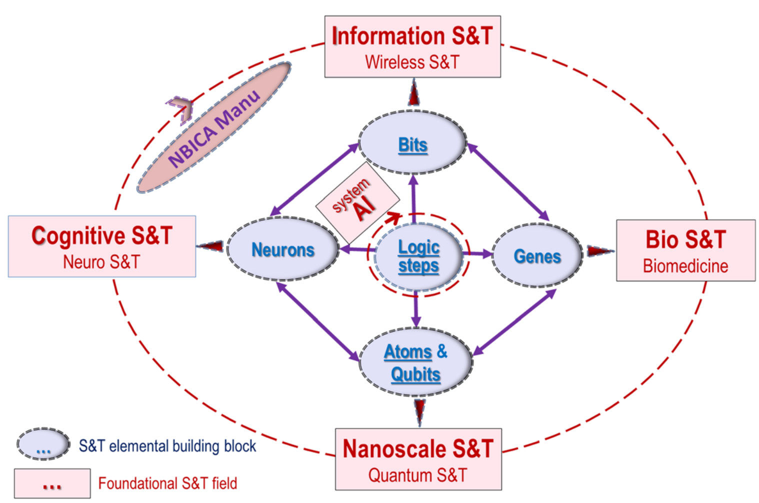


Fig. 13 *NBICA convergence S&T system*: foundational and emerging S&T fields (nanoscale, bio, information, cognitive, and AI) built from the five elemental building blocks

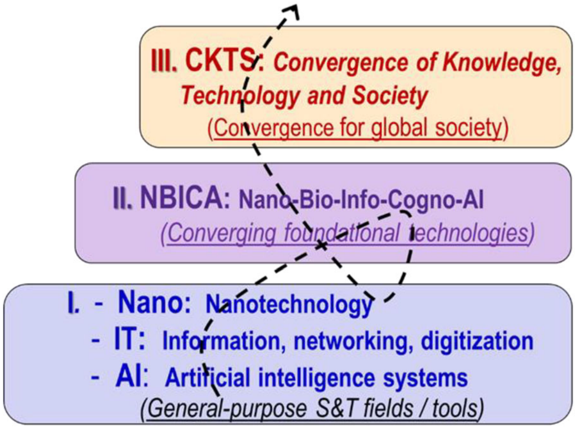


Fig. 14 Three hierarchical S&T platforms resulted from convergence: (I) General-purpose fields (Nano, IT, and AI), (II) convergence foundational system (NBICA), (III) convergence for global society (CKTS). The S&T evolves following a spiral path in time crossing these three platforms

material world, *bits of information* for the information and communication world, and *logic steps* for the decision-making and artificial intelligence world.

a. Nanotechnology—a term used for "nanoscale science, engineering, and technology"—integrates disciplines and knowledge of matter from the atomic and qubit level up to macroscale for all materials, devices, and systems. Similar nanostructures, nanoscale phenomena, and processes are investigated and applied in a variety of fields of relevance, from advanced materials and nanoelectronics to biotechnology and medicine. Nanotechnology currently continues its quasi-exponential growth by advancing its scientific depth, science-to-technology transition in areas such as nanoelectronics and nanomedicine, expansion to new areas such as in agriculture and constructions, and establishing new frontiers such as in nanophotonics and metamaterials. The National Nanotechnology Initiative (NNI) was proposed in the USA to take advantage of the new opportunities (Roco et al. 2000; Roco 2018). Nanoscale processes and phenomena also are important to understand nature.

Nanotechnology development has been guided by the convergence principles as summarized in Fig. 15.

b. Information technology (IT) integrates digital information, computer science, and data management, having as foundational element "a bit of information."

Digital society is an outgrowth of capabilities created by IT tools and has immediate relevance to the digital economy (Ansip 2016), digital manufacturing, cyber-physical-social systems, large databases, and Internet of Things. Digital relationships and networking are expected to change the ecosystems for production, learning, trading, and other areas. Digital convergence facilitates dissemination and replication of results, establishment of ubiquitous digital platforms, and multi-contribution patents and products. One facet of it is digital government (Fountain 2016), which refers to the use of information and communication technologies in governance. It encompasses citizen participation and engagement. Digital convergence within government has a focus on coordination and collaboration across boundaries to create "virtual agencies."

c. Artificial intelligence (AI) is evolving toward a general-purpose approach in science, technology, and society, to enable smart systems "to logically act like a human." It uses "logic steps" as the foundational elements. A more inclusive name of the field is "system AI" because both software and properly adapted hardware of a system need to be address.

The defining characteristics of AI are still evolving. AI was initially associated with pattern recognition and building models (symbolic, probabilistic, causal, hierarchical, artificial neural network) for the world. More recently, we are looking at building AI in a similar manner as a person grows from childhood. This includes earlier childhood contextual analysis, common sense knowledge and architecture, learning to learn,

Fig. 15 Nanotechnology development has been guided by convergence principles

Convergence in nanotechnology development

A. Holistic view – *Unity of matter at nanoscale; unifying phenomena; integrating disciplines*
B. Common goal – *Systematic nano-control for properties/functions/devices/systems/industries*
C. Evolution pattern – *Spiral convergence-divergence to new nanosystems & diverging applications*
D. Unifying actions – *Nanosystem-logic deduction in decisions & problem solving*
E. Cross-domain – Nanoscale concepts, methods and technologies
F. Multi-tasking – *Concurrent nanoscale phenomena and processes*
G. Added-value – Confluence of effects leading to novel nanosystems and applications

generalizing from an example, iterations in an artificial neural network thought engine, and going from vision to language.

System AI is the capability of machines to perform tasks and solve problems that require perception, reasoning, and logic, using information about the world and addressing competing objectives and constraints in the presence of uncertainty. AI systems may have the ability to learn, communicate, and act in the physical world; work collaboratively with humans; exhibit flexibility, resourcefulness, creativity, real-time responsiveness, and long-term adaptive capacity and resilience; use a variety of representation or reasoning approaches; and demonstrate competence in complex environments and social contexts.

The recent advances in AI and its emerging uses in various knowledge and technology fields have been enabled by improved logic algorithms, machine learning, increased computing power and availability of large data sets, improving model-free approaches, natural language processing, and understanding of self-organizing neural-like networks. Furthermore, significant progress in designing and creating new hardware suitable for AI, growth in automation and robotics, efficient handling of large complex systems, and new design and manufacturing methods in education are highlighting the role of engineering. The National Artificial Intelligence Research and Development Strategic Plan (NSTC 2019) provides a framework for the visioning activities and strategic objectives of investments in AI research in the USA.A convergence challenge is seamless integration of such logic steps and processes into key technologies and daily life. Another challenge is sharing and including in the AI process "foundational," moral/ethical, and "higher-level" values as they imply multiple and interdependent logic steps for which is more difficult to set rules. The goal is how to build AI to serve the human vision, instead of evaluating how technology would drive the society. Besides the general-purpose AI approach, one should consider the specifics of various areas such as using AI for "invention in the methods of invention." AI advances convergence of other S&T fields transferring concepts between fields such as from games to robotics.

An example of potential application is creation of Intelligent Cognitive Assistants. These are systems using AI for developing smart interfaces between people, people and machines, and people and environment (see more details later in the paper).

NBICA (nano-bio-info-cognitive-AI), the converging foundational S&T system

NBICA integrates five emerging and foundational S&T fields from their basic elements: atoms and qubits for nanotechnology, genes for modern biology, bits for information-networking-digitization, neurons/synapses for cognition-neurology, and logic steps for AI. The resulting technologies use similar system architectures, dynamic networking concepts, and scaling laws, driven by the convergence principles (Fig. 16) (Roco and Bainbridge 2003, 2013). Convergence yields new science and technology platforms that are different from just summing the components.

NBICA convergence shares abstractions from information technology and system theory, as well as solutions that are hierarchically integrated across technology domains and length/timescales. NBICA already has made inroads in areas such as nanoelectronics; synthetic biology; biomedical research at confluence of biology, medicine, physical sciences, and engineering; and in bio-nano-informatics.

In response to international interest, OECD has created a Working Party on Biotechnology, Nanotechnology, and Converging Technologies (BNCT) to address progress and organizations serving

Fig. 16 Convergence principles applied to the NBICA foundational S&T system

Convergence of foundational S&T system (NBICA)

A. Holistic view – *Similar neural network systems, use unifying concepts for integration*

B. Common goal – *Synergistic modeling & design for heterogeneous system architecture*

C. Evolution pattern – *Spiral multi-technology convergence for divergence in applications*

D. Unifying actions – *NBICA system-logic deduction in decisions & problem solving*

E. Cross-domain – *Languages and methods*

F. Multi-tasking – *Concurrent NBICA phenomena and processes*

G. Added-value – *Confluence of NBICA solutions leading to new processes and S&T platforms* converging technologies. Other international policy efforts building bridges between emerging converging technologies are the Global Science Forum (GSF) of OECD, the Group of Senior Officials (GSO) of G7 Science Ministers, and Global Research Council (GRC) formed by heads of national research organizations.

A schematic showing the NBICA system and its expansion is shown in Fig. 17. The research and education grants related to NBICA are about 6% in all NSF in 2019–2020 and about 50% in NNI projects (~ 14%). Nano-bio-science and engineering awards have the largest contribution, and AI-nano-info-related ones are the fastest growing in the 2019–2020 interval.

The industries of the future advanced by the US National Science and Technology Council in 2020 are included in Fig. 18, including Systems AI, Quantum Information Science, 5G Advanced Wireless, Advanced Manufacturing, Brain research, and Bioeconomy. IT and nanotechnology are general-purpose technologies providing innovative solutions and enabling the industries of the future.

Converging knowledge and technology solutions for global society

The seven convergence principles have been applied to the key platforms of societal activity—NBICA tools, human-scale, Earth-scale, societal-scale, and system behavior (Fig. 5) whose actions are motivated by the need to societal values and needs (Fig. 19). The first meeting on Converging Technologies for "Improving Human Performance: Nano-Bio-Information-Cognitive Technologies" was held at NSF in 2001 (Roco and Bainbridge 2003). An overview of the main topics and their benchmarking in over thirty countries has been presented in the report "Convergence of Knowledge, Technology and Society" (Roco et al. 2013). AI has become more relevant to NBICA after 2015 as "systems AI." NBICA is driven by unifying concepts for common core goals such as learning, productivity, and aging. An integrated vision for human development and the future society to be aimed by NBICA system have been proposed in the United Nations Millennium Development Goals reports.

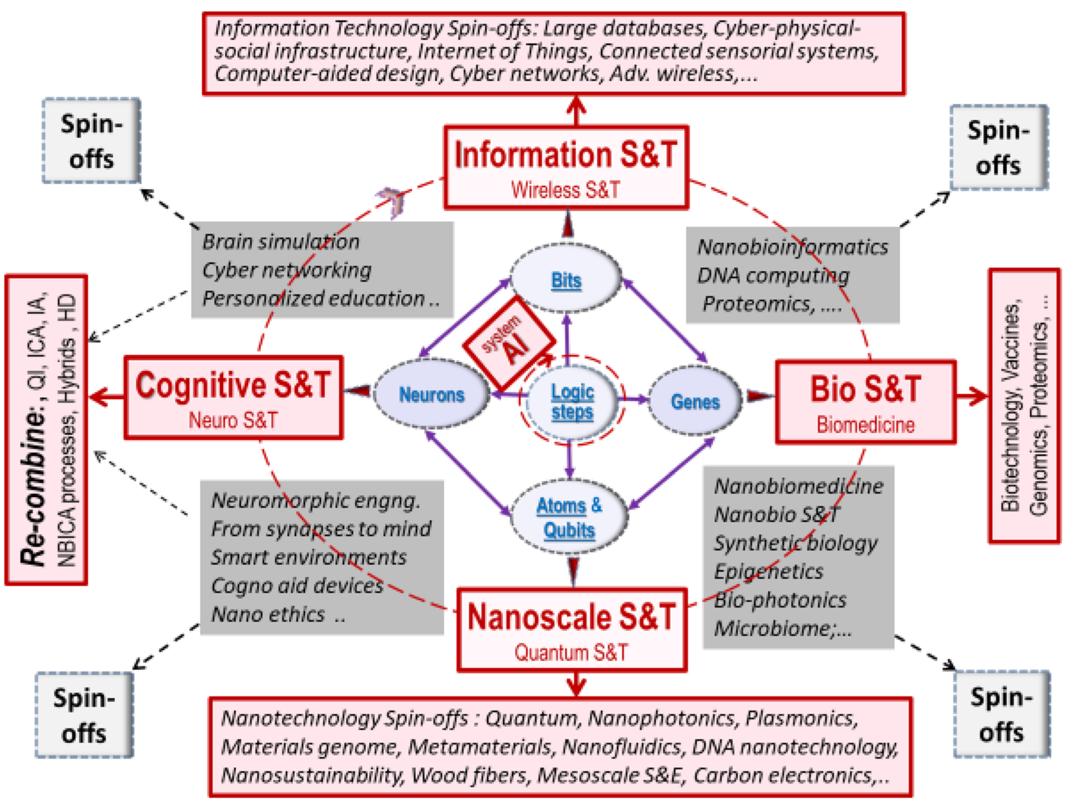


Fig. 17 Emergence and divergence of the foundational NBICA system

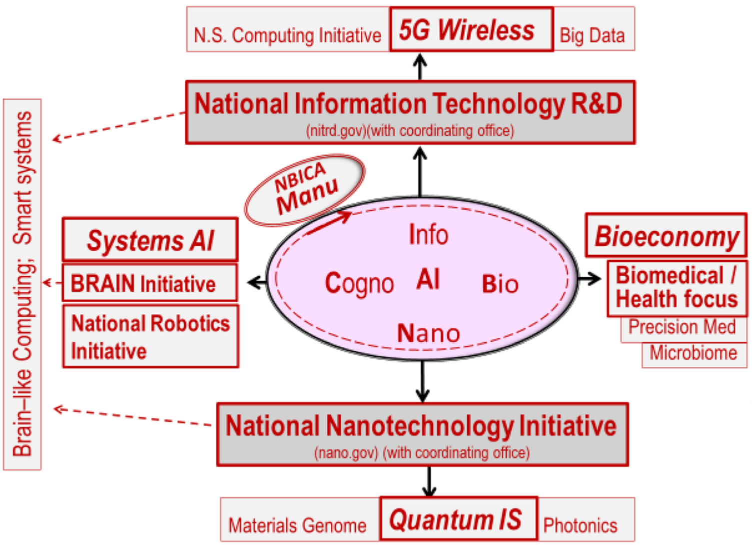


Fig. 18 Converging foundational NBICA system is at the origin of emerging S&T initiatives in the USA

Topical applications of convergence

Convergence is increasingly accepted as a method for future innovation and facilitating societal development in all fields, from topical to holistic (see convergence culture discussed by NASEM 2019, Murray and Calabrese 2019).

Convergence principles in nature

Everything is connected in nature. Astronomy, geology, life ecosystems, and interactions with people describe facets of it. Patterns resulting from interactions and evolutions have turbulent-like behavior with randomness at

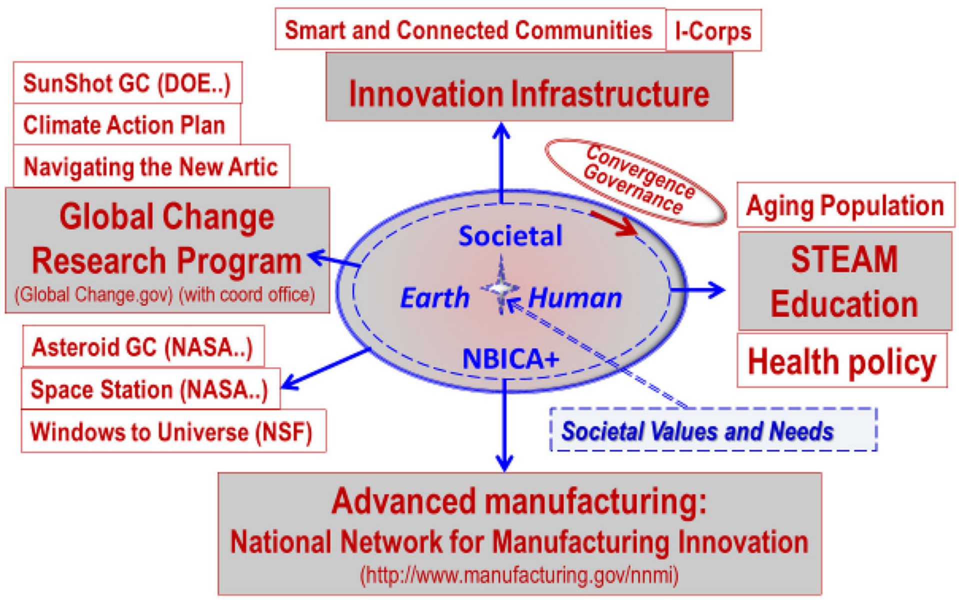


Fig. 19 US global society-oriented initiatives are addressing the main human activity platforms (NBICA, human-scale, Earth-scale, societal-scale, and convergence governance)

Fig. 20 Convergence principles applied to understanding nature

Convergence in nature

A. Holistic view – *Unity of nature; coherent, longitudinal evolution of ecosystems*

B. Common goals/trends – *Formation of chemical elements, higher-level material structures and biosystems; effects of population growth on global trends*

C. Evolution pattern – *Convergence–divergence cycles; space–time spiral structures*

D. Unifying actions – *Global context, fractals*

E. Cross-domain – *Physical and biological laws*

F. Multi-tasking – *Multiple cause-and-effect pathways; bifurcations in complex natural ecosystems because of small perturbations*

G. Added-value – Simultaneous events lead to ecosystem changes, such as in disasters

small scales and coherence at large scales. They typically have convergent–divergent evolution cycles, with spiral domain-time patterns. Figure 20 shows how convergence principles facilitate comprehension of nature.

Let us illustrate how convergence principles function in nature:

a. *Holistic*: Longitudinal (evolutionary) connections have been essential in nature, as it has been in the bacterial "tree of life."
b. *Common goals/trends*: Formation of chemical elements and high-level organization material structures and biosystems has been a general trend. Population growth affects global trends such as global warming and decrease biodiversity.
c. *Evolution patterns*: Natural convergent–divergent cycle (e.g., cell growth–division cycle) and the space–time spiral structures (e.g., tornado pattern, constellation pattern) are typical in nature.
d. *Unifying actions*: Smaller scale Earth events are affected by the global natural context, leading to similar patterns, such as fractals exemplified by a "fingerprint" in nature that holds across scales and fields (e.g., river drainage network, a network on a leaf, and lung and blood networks).
e. *Cross-domain:* Physical and biological laws are crossing water, air, soil environments, with same diffusion, convection, and radiation laws for temperature, mass, and contaminants.
f. *Multiple tasking*: Multiple cause-and-effect pathways coexist in nature. Complex natural ecosystems are the result of the confluence of various sources and sink events, pathways, and bifurcations caused by small perturbations. Multi-tasking is needed to address various dimensions of a natural ecosystem.
g. *Added-value*: Concurrence of natural and human-made events leads to significant ecosystem changes. For example, simultaneous, multiple disasters such as earthquakes, tsunami, and storms cause geographical/geological and infrastructure modifications.

Production processes

Convergence has the potential to bring major advances in production processes including manufacturing and services. Science and technology are increasingly integrated with emerging high-tech production. Convergence leads to introduction of NBICA manufacturing cells and modular fabrication. Exchanges of models between various production domains create "trading zones" in manufacturing. Digitization and cloud manufacturing are growing with the Internet of Things. Converging "supply chains," from concept to internet, production, and use, leads to "cyber-physical-social" manufacturing with cloud "mass customization" distributed model.

Convergence changes the processes in each manufacturing unit and in the network as illustrated by IT equipment convergence and sensors-computer-medical devices convergence. Interdependence in production, crowd funding, and overall convergence change the system itself. Convergence in manufacturing may lead to a bottom-up strategy to enable a self-propagating, profit-driven evolution of the software and hardware infrastructure needed to realize the "factories of the future." Individuals and communities will be empowered by distributed technologies. Integration required in production provides a good feedback for adopting convergence.

Sustainability in manufacturing, the life-cycle approach, and circular economy are fast growing paradigms. Convergence will change nano-EHS (environmental, health, and safety) and ethical-legal-societal-governance needs and capabilities by the introduction of concurrent processes, use of common language, and especially by emphasizing the societal context.

Biomedicine

Convergence catalyzes new research directions and guides research priorities in biomedicine. Convergence of life sciences, physical sciences, and engineering have been emphasized in the last decade in order to improve understanding, introduce new biomedical solutions using the DNA and cellular levels, advance personalized medicine, and overall create the environment for more breakthroughs in biomedicine (NRC 2009; MIT 2016; Sharp and Langer 2011). According to NASEM (2014), 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. Nanotechnology alone has opened significant innovations in areas such as diagnostics (imaging diagnostics, blood analysis, saliva analysis); therapeutics (targeting drug delivery, targeted cancer detection and therapy nanostructured implantable materials: bones, scaffolds); and regenerative medicine (tissue engineering, gene therapy for healthcare, stem cells, single cell conditioning).

Implementing R&D

Convergence offers a new universe of discovery and innovation in research through specific principles and methods. Vision-inspired and system view planning and implementation of research use forecasting and various processes for setting grand challenges (Bainbridge and Roco 2006a, b; Roco et al. 2013). Convergence includes cross-disciplinary, cross-sector, cross-cultural, and international sharing of organizations and projects. It may require combining multi-topic databases and changing the researchers and faculty recognition system.

Convergence has been embraced at NSF after 2017: "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." Examples of ideas and programs are "Future of Work at the Human-Technology Frontier," "Big Idea: Growing Convergent Research," and "Convergence Accelerators." An example of education and research center is the "National Convergence Technology Center" (www.connectedtech.org) that 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. Convergence opportunities in education and research were surveyed by Herr et al. (2019).

Forming efficient science and engineering research ecosystems may require changing interactions between students, faculty, and administration (e.g., student-driven research in collaborations with faculty), using system and team science or employing bottom-up incentives for convergence in degree accreditation, to name a few. Changing the culture is an ultimate goal that may include recognition and respect of other disciplines, leaving the comfort zone, facilitating and enabling meeting places, and networking at institutional and national levels.

Convergence already has contributed to developing the NBICA unifying S&T system, methods for identifying new fields on the map of emerging fields (extending, interpolating, and re-combining of fields shown in Fig. 17), and improved governance of S&T.

Personal behavior

One may argue that effective personal behavior also may be guided by general convergence principles. Figure 21 shows the correspondence between the convergence principles and the "habits of highly-effective people" behavior as described by Covey (2003) and explained in Eyre et al. (2017).

Personalized learning

Creating an improved ecosystem for personalized learning includes several convergence-driven trends. One is establishing a universal (multidomain, general-purpose) language and database library that makes connections between concepts and methods among various fields. Use of intelligent cognitive assistants, virtual reality, and other convergence-based methods to teach individually is another trend.

Fig. 21 Convergence principles applied to individual behavior

Convergence for improving individual behavior

A. **Holistic view** – *'Deep integration' of languages, values, beliefs and views and actions for addressing a goal; Proactive in different fields*

B. **Common goal** – *Begin with the common vision, and think backwards from the end*

C. **Evolution pattern** – *Focus on methods and tools first, then on broad use of new capabilities*

D. **Unifying actions** – *System-logic deduction in decisions for win-win outcomes*

E. **Cross-domain** – *Synergize information, and use cross-domain languages*

F. **Multi-tasking** – *Understand, then be understood – choice; Search for alternative win-win pathways*

G. **Added-value** – *Use all resources leading to priority life changes ("daily self-renewal")*

One needs to integrate cognitive psychology for learning, motivation, and emotional intelligence of individual and group in personalized learning process.

Improve team science outcome

The convergence approach facilitates team science by enhancing group interactions, decisions and their efficiency as applied to knowledge, technology, or society systems (Cooke and Hilton 2015; NASEM 2015). The implementation of convergence principles to team science is illustrated in Fig. 22.

Local, national, and global governance

Governance refers to the collective capacity for achieving socially desired community benefits under complex and changing conditions. This capacity is most robust to the extent that it is distributed across multiple stakeholder groups, emphasizes both innovation and responsibility, and consists of multiple instruments, both voluntary (organic) and enforced (hierarchical) (Roco et al. 2013). The convergence governance process is different from top-down governing as it is dominated by horizontal links and self-organization principles. Convergence in governance typically aims at changing the system to improve or expand its performance. "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 governance may contribute to major changes in science, technology, and society. For example, the US nanotechnology governance approach has aimed to be "transformational, responsible, and inclusive, and to allow visionary development" (Roco 2008). Innovative individuals in public groups (e.g., entrepreneur/inventor Elon Musk and his company SpaceX) and of public–private partnerships will increasingly push the development of new converging technologies separate from the roles of governments. New tools will emerge for participatory governance, such as games, collaborative design, and social media. Coevolution between science, technology, and societal norms and values will become increasingly evident to a larger number of actors.

Two regulatory approaches are developing in parallel for converging technologies: one is probing the extendibility of regulatory schemes ("developing the science" approach), and another is developing exploratory (soft) regulatory and governance models that work reasonably well even with insufficient knowledge for full risk assessment. Proactive convergence governance is essential for obtaining the benefits of the new technologies, limiting their negative implications, and fostering global collaboration.

A "Convergence knowledge and technology office" has been proposed (Roco et al. 2013) for R&D program and investment decisions to be taken by considering all the factors in a coherent and systematic way. Besides facilitating connections, that office would include tools for stimulating creativity, invention, and innovation paths, promoting longer-range connections and examining potential for the future. The Convergence Research Policy Center was established in Korea Institute of Science and Technology, South Korea, for national coordination of government decisions using convergence principles. Examples of successful governance of ecosystems are the convergence platforms for the earlier spaceflights, Silicon Valley (The Rainforest), and Semiconductor Research Corporation (SRC) and its community (Roco et al. 2013), to name a few. Measuring convergence in government research institutes is discussed by Bae et al. (2013) and Coh et al. (2019).

Fig. 22 Convergence principles applied to improving team science (collective behavior)

Convergence for team science

A. Holistic – *Connecting ideas; enables team input from diverse communities and fields*

B. Common goal – *Vision-inspired thinking to set the group end goals for the team benefit*

C. Dynamic pattern – *Spiral convergence and divergence: crossing capabilities faster*

D. Unifying – *System-logic deduction in group decisions for essential features & synergy*

E. Cross-domain – *Adopt higher-level common languages; Look out of team system*

F. Multiple choice dynamics – *Integrate various pathways for win-win outcomes*

G. Added-value – *Use confluence of resources to realize priorities and goals*

Convergence for sustainable society

A sustainable, progressing global society has many interconnected dimensions that require a convergence approach to address them holistically and effectively. These dimensions include environmental sustainability in planetary boundaries (such as keeping it clean, biodiverse, renewable) and resilience aspects (related to infrastructure, cities, and emergency response for life cycle). Sustainability also is determined by economic aspects (e.g., do "more with less," managing resources as materials, water, energy, land, food, climate, green chemistry), social aspects (population growth and human needs, governance, enduring democracy), and the efforts for maintaining quality of life and expectations for current and future generations (Diallo and Brinker 2010; Diallo et al. 2013). To address its multiple facets, sustainable nanotechnology may make use of cross-domain databases and neural network models enabled by artificial intelligence and managed under a unified digital network. A framework for reaching sustainable society is Deep Reasoning Networks (Chen et al. 2019) that combines deep learning with logical and constraint reasoning for solving complex tasks using stochastic-gradient-based neural network optimization. The Computational Sustainability Network (https://www.compsust.net/) has successfully implemented this approach. Figure 23 illustrates how convergence principles would apply for reaching a sustainable society.

Several trends

Improving human capabilities

The 2003 report Converging Technologies for Improving Human Performance (Roco and Bainbridge 2003) describes convergent approaches in a broad set of themes, including expanding human cognition and communication, improving human health and physical capabilities, enhancing group and societal outcomes, national security, and unifying science and education. The coevolution of human potential and converging new technologies is a trend with major implications for individuals, organizations, and society in the decades to come (Roco and Montemagno 2004).

Improving human capabilities has been a dream for centuries. At the beginning of the twenty-first century, we stand at the threshold of a New Renaissance in

Fig. 23 The convergence principles applied for reaching a sustainable society

Convergence for sustainable society

A. Holistic view – Identify essential interactions, use unifying drivers, and apply collective actions in sustainable systems

B. Common goal – Set up long-term compelling visions for common purpose (ex: UN, UNESCO, funding programs)

C. Evolution pattern – Converge to suitable methods and tools, and then expand divergent/emerging use of the new capabilities

D. Unifying actions – Create cross-ecosystems languages, use more general solutions

E. Cross-domain – Use higher-level languages true for multiple domains

F. Multi-tasking – Manage multi-actions and algorithms

G. Added-value – Advance concurrence and staggering of resources for synergism science and technology, based on a comprehensive understanding of the structure and behavior of matter from the nanoscale up to the most complex system yet discovered, the human brain. Rapid advances in convergent technologies have the potential to enhance both human performance and the nation's productivity. Examples of payoffs will include improving work efficiency and learning, enhancing individual sensory and cognitive capabilities, revolutionary changes in healthcare, improving both individual and group efficiency, highly effective communication techniques including brain to brain interaction, perfecting human–machine interfaces, and ameliorating the physical and cognitive decline that is common to the aging mind. Convergence may help to break those limits in the next decades.

Intelligent cognitive assistants (ICAs)

ICAs are harnessing new machine intelligence and problem-solving capabilities to work collaboratively and enhance human cognitive and physical abilities—by assisting in working, learning, and interacting with new cyber-physical systems, transport, healthcare, and other activities (Bainbridge and Roco 2016a, b; SRC/NSF 2016, 2018). ICAs are conceived to be smart interfaces between an individual or group with other people, with the surrounding environment, and with tools and machineries (Fig. 24). ICAs are an outgrow of NBICA convergence, with two main roots: (a) the report on advancing the human–technology frontier in Roco and Bainbridge (2003) where one of the visionary projects for 20–30 years ahead has been "personal assistant and broker" and (b) the brain-like computing grand challenge to "Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain" (OSTP/NNI Grand Challenge, http://www.nano.gov/futurecomputing, 2015).

ICAs are at the forefront of multiple fields of research including human-centered intelligent engineered systems with cognitive capabilities, artificial intelligence, and deep learning. Their development is based on semiconductors going beyond the Moore's law, complex cyber-physical-social modular systems, smart engineering materials, devices and systems, and large nano sensor systems. ICAs have areas of confluence with smart and autonomous machines, modular system architectures and devices wireless technologies, cognitive psychology, cognitive prosthetics, large data for decision-making and problem-solving methods, autonomous chemistry, neural-like systems, and neurotechnology. This makes ICAs a good case for convergence in the process of human–technology coevolution. The increase of human capabilities and opening of new fields of activity will be indicators of success.

Typical ICA functions are improving daily activities through human-machine collaborative work, learning machines, exploring things not possible before, and overall enhancing human abilities. Goals for ICAs include learning insights from data, solving unfamiliar problems, creating decision and action capabilities, and providing informed advice. They are at the confluence of IT-computer science, brain science, cognitive technologies, and nanotechnology.

Citizen science and innovation

Citizen science is an outgrowth of increase of general level of education, open communication, crowd sourcing, and the convergence of knowledge and technology in society that allows ordinary citizens to be partners in the progress of science, engineering, and innovation.

The term *citizen science* describes people who are not paid for their work and do not possess higher academic degrees but contribute to scientific progress. Examples are in the discoveries of previously unknown birds, fossils, and even galaxies. While less frequent, advances

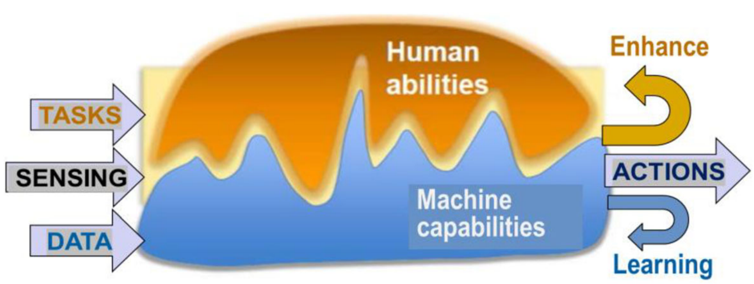


Fig. 24 Schematic for Intelligent Cognitive Assistants

in emerging technologies are possible through projects such as Nanocrafter, “a citizen science platform for the discovery of novel nanoscale devices built out of self-assembling strands of DNA” (Barone et al. 2005).

The technological equivalent of citizen science would logically be called *citizen innovation*. A related development is open source technology (Crowston 2016). The Maker Movement initiated with the introduction of additive manufacturing and three-dimensional printing has received considerable government support in the US. The Maker Movement has important implications for education.

Collaboration and conflict resolution in society

Peace is one of the most complex and important systems (Donofrio 2020) where convergence may play a role. Through convergence, people interact and understand better, and converging technologies offer means of reaching common goals by collaboration, rather than by confrontation. By changing the balance from advantages sought by confrontation and conflict to the shared benefits that can be realized by collaboration with the convergence tools, one may advance common goals via conflict resolution or, in other words, peace building. A critical phylosophy in convergence education is succeding in reducing the disturbances created by the “ human instinct of aggression” (Peters 2020).

This challenge for the complex dynamic human system may be met as a result of the several trends, including:

– Convergence to intellectual global thinking and training, with a focus on common values, approaches, and opportunities. The wholistic approach has the potential to diminish possible conflicts between the short-term or small group efficiency actions and the longer-term optimization endeavor for the entire community. A metric for success is the progress in “cross-domain languages.”
– Open deliberative observatories, interactions bridges, and networks between society groups and organizations are increasing. A metric for success is “beneficial to all people.”
– People become more interactive and promote collaborative behavior and win-win approaches between individuals, groups, and organizations.

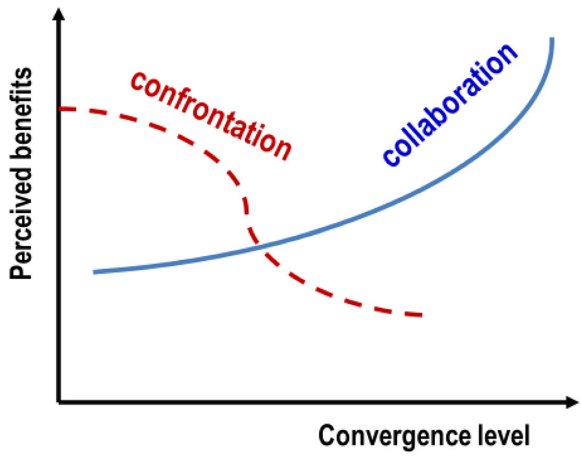


Fig. 25 Perceived change of balance of benefits from confrontation to collaboration through convergence

– Transparent changes in the disadvantage-benefit balance from more disadvantages to more benefits by conflict resolution. The schematic in Fig. 25 suggests how the benefits derived from collaboration would grow in time with convergence in society, as compared with possible advantages derived from confrontations that are decreasing in time.
– Improve decision-support tools by leveraging both human and machine intelligence to augment decision-making in individuals and organizations, aiming to create algorithms to manage potentially conflicting preferences using computational social choice, crowdsourced democracy, and crowdsourced forecasting (Joseph et al. 2019).

Closing remarks

Convergence approach offers a general opportunity of progress in knowledge society. It opens a new universe of discovery, innovation, and applications in research, education, production, and other societal activities. It already has changed the landscape of S&T fields. This paper has presented relevant theories, principles, and methods of the emerging convergence science. The case studies outlined on this basis show the generality of the convergence approach in reaching goals in science and technology, human development, society, or understanding nature. Education and organizational and cultural changes are needed to better solve emerging problems that transcend traditional boundaries.

Convergence in manufacturing, biomedicine, and cognitive technologies appears to bring earlier societal benefits as compared with other areas. Cross-domain programs in universities and funding agencies also show earlier results. International collaboration is essential for the development of convergence science and of convergent technology platforms.

Application of the principles of convergence in nature and society has successfully advanced from facilitating general-purpose S&T fields such as nanotechnology, digital technology, and AI to enabling broad knowledge, technology innovation and cultural interactions for global societal progress. Convergence offers efficient possibilities for improving human activity outcomes beginning with personal learning and production processes to improving economic performance of an organization and addressing societal conflicts. It brings science, technology and applications closer and accelerates their integration. Convergence offers the foremost opportunity for the comprehension of nature and societal progress in the increasingly "connected world" of the so-called fourth industrial revolution.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflict of interest.

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