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PERSPECTIVES

Science and technology convergence: with emphasis for nanotechnology-inspired convergence

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Abstract Convergence offers a new universe of discovery, innovation, and application opportunities through specific theories, principles, and methods to be implemented in research, education, production, and other societal activities. Using a holistic approach with shared goals, convergence seeks to transcend existing human limitations to achieve improved conditions for work, learning, aging, physical, and cognitive wellness. This paper outlines ten key theories that offer complementary perspectives on this complex dynamic. Principles and methods are proposed to facilitate and enhance science and technology convergence. Several convergence success stories in the first part of the 21st century—including nanotechnology and other emerging technologies—are discussed in parallel with case studies focused on the future. The formulation of relevant theories, principles, and methods aims at establishing the convergence science.

Keywords Nanoscale science and engineering · Convergence science · Convergence–divergence cycle · Supporting theories · Principles and methods for convergence · General purpose technology · Intelligent cognitive assistant

Introduction

Convergence is a transformation model in the evolution of science and technology (S&T) that unites S&T fields with society. It provides a framework and approach for advancing not only science and engineering but also business and policies. Convergence is a deep integration of knowledge, tools, and all relevant areas of human activity to allow society to answer new questions, to create new competencies and technologies, and overall to change the respective physical or social ecosystems. Such changes in the ecosystems open new trends, pathways, and opportunities in the following divergent phase of this evolutive process (Roco 2002; Roco and Bainbridge 2002).

This paper outlines core theories governing dynamic converge processes, as well as overarching principles and methods that facilitate convergence. Convergence may be illustrated through case studies of transformations in general purpose technologies well underway and on the horizon. Three case studies that have originated about 15 years ago are nanotechnology-inspired convergence, emerging technologies

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This article expands on "Handbook of Science and Technology Convergence," (W. S. Bainbridge and M. C. Roco,), Springer Reference, 2016, Berlin.

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NBIC (nano-, bio-, information, and cognitive) inspired convergence, and digital society. In the future, opportunities for convergence include a new platform for human–technology coevolution using intelligent cognitive assistants, and the expansion of citizen science and technology.

Nanotechnology came into being through convergence of chemistry, physics, engineering, and many other disciplines, notably biology and materials in which proteins and crystals are nanoscale structures, computer science in which the smallest components of electronic circuits approach the nanoscale, and mathematics which is essential for all kinds of research and design. Engineering, through its major components of mechanical, chemical, biomedical and electrical engineering, played a central role, not only applying nanoscience developments to technologies, but also energizing and coordinating the collaborative efforts across disciplines. By searching the online public abstracts describing grants the National Science Foundation made in the two decades 1996–2015, we have counted fully 4233 awarded grants that contained the word "nanotechnology." Of these, 51.6 % were managed from the Directorate for Engineering, and another 29.8 % were managed in the Directorate for Mathematical and Physical Sciences, which has divisions for Chemistry and Materials Research. Yet other fields participated as well such as computer science (5.5 %), biology (2.8 %), social and behavioral sciences (2.0 %), and geosciences (0.6 %). An additional 4.9 % of the grants related to education and thus were managed by the NSF Directorate for Education and Human Resources, while the remaining 2.8 % were made through miscellaneous, cross-directorate programs such as Science and Technology Centers. The first NSF grant with "nanotechnology" in its abstract was made by the Directorate for Engineering way back in 1989. Statistics using "nanoscience" or multiple keyword searches to describe the nanoscale science and engineering field have similar broad distributions by NSF research and education directorates (Chen and Roco 2009). Now that nanotechnology has advanced toward applications, while retaining its youthful discovery and innovation vigor, scientists and engineers in this field will have good reasons to collaborate with colleagues in many other fields, and a science of convergence is needed even more than before. But the present time may be an especially crucial era for science and technology more generally.

If nanotechnology were a human being, after a quarter century it would now be a young adult, old enough to vote and capable of playing a mature role in collaboration with all the older sciences and fields of engineering. Metaphors aside, there is every reason to believe that nanoscience and nanotechnology will continue to advance rapidly, but among the best ways to ensure progress during maturity is to collaborate closely with peers who also are mature but differ significantly in terms of their specialized expertise, access to resources, and current challenges. While the numbers of papers and patents have increased in average by about 16 and 30 %, respectively, between 2000 and 2015, the reported revenues from products incorporating nano as the competitive component have increased by about 25 % per year between 2000 and 2010 (Roco 2011), and by 35–40 % per year in 2011–2015 in the US and worldwide (Lux Research 2015). The goals and means for such cooperation around nanotechnology are outlined in a recently published reference book, *Handbook of Science and Technology Convergence* (Bainbridge and Roco 2016) which serves as the capstone to an arch of international conferences and proceedings books, that spanned the previous 15 years (Roco and Bainbridge 2001, 2003, 2006a, b; Roco and Montemagno 2004; Bainbridge and Roco 2006a, b; Roco et al. 2013). The scope was not limited to narrow areas where technical challenges required multidisciplinary collaboration, but extended to changing the ecosystem, the societal implications of nanotechnology, and the general convergence of science, technology, and society. The 2000–2020 convergence–divergence cycle for global nanotechnology development is marked by four generations of nanotechnology products and their spin-off industries (Roco and Bainbridge 2013, see Figure 8).

Recently, much discussion has been focused on human health. One workshop offered this vision: "Convergence is an approach to problem solving that cuts across disciplinary boundaries. It integrates knowledge, tools, and ways of thinking 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 that exist at the interfaces of multiple fields" (National Research Council 2014, p. 1). Another workshop report "shows that an accelerated Convergence research strategy can lead to truly major advances in fighting cancer, dementia and diseases of aging, infectious diseases, and a host of other pressing health challenges" (Sharp et al. 2016, p. 8). Opportunities for progress in many areas should be explored, including several identified here.

Key theories of the era of dynamic convergence

The present time may be an especially crucial era for science and technology because of convergence. Participating in converging technologies conferences and editing the substantial reports that resulted from them have called to our attention ten compatible theories (listed in Fig. 1) that suggest that the current moment in history is a watershed for essentially all technical fields. Each theory must be evaluated in its own terms, but together they make a strong case: (1) unity of nature, (2) human interaction ecosystem, (3) complexity, (4) economic growth, (5) specialization network, (6) reverse salient, (7) fundamental principles in convergence, (8) progress asymptote, (9) exogenous revolution, and (10) response to social problems. Convergence processes offer an integrative perspective on these theories and a dynamic approach of how to engineer the technological and social ecosystems for added value.

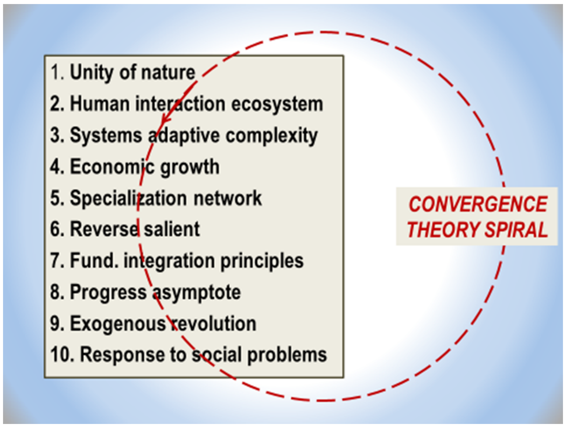

Fig. 1 Convergence is realized in conjunction with ten theories

1. The *Unity of Nature Theory* supports realistic hopes that convergence can realize unity in societal systems. From ancient times, people have debated the extent to which the world is based on a unified set of principles, perhaps conceptualized as a coherent set of laws established by a single God of Nature, or represents competing, irreconcilable realities. Exploring science and medicine in a holistic way was a defining characteristic of the Renaissance. A number of social scientists have argued that monotheistic religion was among the factors encouraging the rise of science in Europe, and in nineteenth century America, much scientific research was conceptualized as a pious quest to learn the will of God (Merton 1970; Evans and Evans 2008). In the twentieth century, mathematics provided a secular framework for conceptualizing the unity of nature, as illustrated by the example of Zipf's law which asserts that many kinds of data across many different sciences follow the same frequency distribution. George Zipf (1942), a linguist who may have been inspired by earlier work in physics, originally derived the distribution to chart the frequency of specific words; he later argued that the ubiquity of the Zipf distribution reflected the unity of nature. Evolutionary biologist Edward O. Wilson (1999) has argued that specialization in the sciences has obscured their natural unity, and he was one of the leaders in promoting the application of evolutionary theory from biology to the social sciences. In recent years, much work like that by Zipf and Wilson has accumulated, thus strengthening support for convergence at the present time. Convergence aims at realizing unity in knowledge, technology, and societal systems. Convergence *in nanotechnology*, for example, is based on using unifying structures (such as atomic clusters or biomolecules), phenomena (such as quantum and nanoscale confinement), processes (such as molecular self-assembling and templating), and control methods at the nanoscale (such as using external wave fields and mechanical/chemical/biological stimuli) to create diverse families of materials, devices, and systems for industrial applications, medicine, agriculture, energy, and environment.
2. The *Human Interaction Ecosystem Theory* is conceptually related to the unity of nature and complexity theories, yet raises distinctive debates within the scientific community. In this theory, all biological and social systems have a natural tendency to interact, assemble, and act collectively, not merely achieving homeostasis but occasionally preparing the way for evolutionary leaps forward. One variant is the Gaia Hypothesis proposed by the

chemist James Lovelock and the microbiologist Lynn Margulis, which argues that nature is a self-regulating complex system that is entirely compatible with and automatically supports ethical human civilization (Lovelock and Margulis 1974). A related perspective that gives meaning to the adjective "ethical" when applied to civilization is *appropriate technology*, as influentially presented in Ernst Schumacher's (1973) book, *Small is Beautiful*. Schumacher argued that the appropriate technologies for developing nations might not be the most technologically advanced alternatives, but those that best harmonized with environmental and economic conditions, but this perspective was soon applied to advanced nations as well, with the implication that at this point in history, we may need to abandon some advanced technologies in favor of simpler ones that harmonize better with nature. This was not an argument against technological progress but for proper guidance of it, as illustrated by the fact that Lovelock favored efforts to terraform the planet Mars to make it suitable for human colonization (Allaby and Lovelock 1984). If we consider the *material nano-particulate systems*, the behavior at the nanoscale is determined by particle-to-particle interactions and their overall dynamics with the surrounding media. The material interactions evolve qualitatively with the hierarchical system level, in a manner similar to biological and social systems.

3. *The Complexity Theory* observes that most natural and manmade systems are large and heterogeneous, possess nonlinear interaction networks and hierarchical architectures that evolve under external constrains at various spatial and temporal scales, and often reach emergent order. Of course, if an unstable system fails to adapt, it is likely to disintegrate, so complex adaptive systems may survive through a natural selection process akin to biological evolution (Levin 2005). Some purely natural factors may stabilize complex systems through, for example, a form of entropy. Yet today, so much of human life is dependent upon dynamic complex systems that our future is quite uncertain, potentially much better or much worse than today. Understanding such systems is difficult, but today several alternative scientific methodologies exist, for example, computational means for analyzing the form that feedback takes in the system (Holland 2006). Full understanding requires convergence of sciences from the nanoscale of complex molecules up to and perhaps beyond the atmosphere that covers the entire planet. Given understanding of the complex systems in which they live, human beings may undertake actions that add value and improve adaptation, based on awareness of the long-term consequences. The spatial–temporal interactions of a large number of *atoms at the nanoscale* typically lead to emergence of new properties in the respective complex systems as a function of the number of compounds, atoms, or molecules. Self-organized size criticality in nanostructured matter has been identified as an essential concept in many natural and human-made systems. It often manifests itself in the form of dynamic metastable patterns leading to new properties and functions that are not attributable to any constituent element of the system (Gimzewski et al. 2016). The modular "nano-grain" structure of materials has similarities to modular structures in large organizations or in brain functions.
4. The *Economic Growth Theory* observes that modern society is prosperous enough to afford research or development projects that would have been prohibitively complex and costly in earlier periods. Faster economic growth is made possible by concurrence of knowledge areas and investment efforts to introduce new technologies and products. One person gazing through a simple telescope was revolutionary in Galileo's day, and in the nineteenth century and early twentieth century, many of the world's increasingly large telescopes were funded by individual wealthy donors, and used by individual astronomers and small teams. A century ago, when Slipher (1917) reported measurements showing that galaxies were receding, the first "redshift" evidence for the expansion of the universe, he was the sole author of the publication, and he worked at an observatory funded by Percival Lowell, a businessman with a passion for astronomy. But when the first evidence of gravitational waves was discovered in 2015, there were 1011 authors of the report (Abbott 2016), and the Laser Interferometer Gravitational-Wave Observatory (LIGO) that detected it had been funded by the National Science Foundation at a cost estimated well above

half a billion dollars. While LIGO interferometers are based on coated mirrors with precisions in the nanometer range, each of the two detectors is 4 km on a side, and the two are 3000 km apart. The huge team was necessary in great measure because of the wide diversity of expertise required and organized to converge on a very specific goal. Another illustration is how the *National Nanotechnology Initiative (NNI)*, begun in 2000, established a large, flexible infrastructure and research and education programs across the United States, and how this effort is reflected in sustained R&D investments worldwide that reached over $15 billion annually by 2010. The NNI alone, cumulatively totaling about $22 billion for R&D in 2016 since its inception in 2001, is the second-largest coordinated multiyear program in the world after the Apollo program.

5. The *Specialization Network Theory* observes that the dynamics of teams or communities change as their numbers of 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. The formula estimating the number of relationships in a system is simple but effectively exponential. If N is the number of individuals or subdisciplines, and C is the number of connections between them: $C = N\,(N - 1)/2$. Social network research has shown that most social groups in modern society have incomplete networks, missing many of the potential connections, and that the implications of incompleteness are a mixture of good and bad. High density of social connections within a subdiscipline can energize collective efforts and converge on consensus, but more diffuse networks can reach far beyond their subdiscipline and serve to promote divergent innovation by sharing information more widely and rapidly (Burt 2004; Granovetter 2005). Thus, the socioeconomic dynamism of the present time, which is perceived by many people as chaos, can cause pulsations in the geometry of social networks in science and engineering, combining the advantages of both convergence and divergence into a dynamic feedback system. The structure or relations between individuals in a community (such an evaluation committee) relates to the size of a group, because groups tend to develop internal structure if they function over time, rather than briefly as in a laboratory experiment. Galesik et al. (2016) conclude that if members of an evaluation committee are selected randomly from a larger crowd, they can achieve higher average accuracy across all tasks than either larger groups or individuals. There is a striking similarity to fundamental behavior of *nanostructures* that have specific properties because of collective effects of the atoms and molecules that are different from individual atom or molecule or from larger assembly structures.
6. The *Reverse Salient Theory* applies a concept from military strategy to science and technology and potentially any other field, as was most influentially applied to understand the early history of the electric power and appliance industries (Hughes 1983). In conventional warfare, armies face each other along a wide front. If one army advances at a particular point, that incursion into enemy territory is called a *salient*. If one army advances all along the front, except in one particular sector where it has stalled, that is a *reverse salient*. If sciences and fields of engineering are advancing without much convergence between them, some areas that are between disciplines will fail to advance and are akin to reverse salients. Thus, convergence presents great opportunities for progress only if the relevant disciplines improve cooperation with each other. In *nanomaterials research*, it is essential to investigate nanoscale phenomena and process in ensemble—in a convergent way—including their nonlinear dependences, because the nanoscale phenomena are simultaneous and cannot be separated as they can at larger scales.
7. The *Fundamental Principles Theory* can be derived from the fact that science and engineering depend very heavily upon mathematics, and some of the same mathematical principles apply to a wide range of phenomena. This theory has relevance to higher level multidomain languages needed in convergence. Also, science is a human endeavor, and we use the same brain to perform astronomical research as we do to create nanotechnology, so some of our fundamental human modes of thought provide a framework for understanding in all fields. As some fields advance, they may therefore develop systems of

concepts that can be applied to other fields, not merely as rough metaphors, but rigorously with appropriate adjustments based on careful analysis of data (Bainbridge 2004, 2006). For example, *in nanoscience*, one has to formulate new fundamental concepts and methods for the specific ecosystem of nanoscale phenomena to allow for relevant and efficient solutions of problems that are essentially different from the micro- and macro-scales.

8. The *Progress Asymptote 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. It is difficult to measure the rate of progress, because the natures of discoveries, inventions, and innovations change, but at least some competent observers have said that physics and some other sciences might be reaching their limits (Horgan 1996). A recent massive study by highly respected economist, Gordon (2016), documents that technological development and economic growth were unusually powerful in the United States during the century 1870–1970, but both have been much weaker since then. If indeed we are approaching the natural limits of science and technology, then the last few advances may require unusually great investment not only of money but also of diversity of technical expertise, as in the LIGO discovery mentioned above. In another illustration, using the Landauer (1961) fundamental limit of energy dissipation *at the nanoscale* under the laws of thermodynamics, the Science and Engineering Center at Berkeley (Hong et al. 2016) has proven that magnetic computing is possible promising multiple orders of magnitude of energy consumption reduction in computing.
9. The *Exogenous Revolution Theory* notes that science and engineering are societal institutions, whose histories are significantly affected by all other human institutions, such that a radical transformation elsewhere can trigger transformations in technical fields. Convergence processes among initially distinct domains become important. The most familiar evidence for this theory concerns its opposite, namely the failure of the classical civilization of Greece and Rome to achieve the industrial or scientific revolutions that were delayed more than a thousand years, despite the progress in mathematics and the natural sciences prior to consolidation of the Roman Empire (Gibbon 1776–1788; cf. White 1959). Based on the history of the Copernican revolution in astronomy, which the ancient Greeks had nearly achieved, Thomas Kuhn (1957, 1962) developed a theory of scientific revolutions that postulated that every mature science would pose a stable paradigm, resistant to change. Yet 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. In an example, the *nanotechnology and NBIC convergences* have reached recognition and societal support in the past 15 years with significant progress in areas such as science, medicine, electronics, environment, energy, and space.
10. The *Response to Social Problems Theory* observes that 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. It is easy to think of convergent examples from the Second World War that contributed to subsequent peaceful technologies, such as civilian nuclear power from nuclear weapons, and such things as rockets to launch satellites and aviation radars. Yet it is hard to assess the overall costs versus benefits of military research efforts, given that resources are taken from the civilian sector and that secrecy deters intellectual convergence (Poole and Bernard 1992). To monitor environmental problems, nanotechnology is working in partnership with other disciplines to develop sensors (Porter et al. 2009). Bone fracture is a common medical problem with diverse causes, notably accident, aging and warfare, and nanoscale methods may prove more effective than traditional methods in repairing the damage (Venugopal et al. 2010). A social problem contemplated by the most recent converging technologies conferences is the possibility that advances in information technology are reducing jobs available for human beings (Brynjolfsson and McAfee 2011; Frey and Osborne

2013; Kristal 2013), yet it is difficult to be sure if that is happening, let alone find an adequate solution for the problem (Elsby et al. 2013). A good illustration for science, technology, and innovation (STI) response to societal problems is the *use of nanotechnology* and other emerging and converging technologies in the first part of this century for global healthcare, international competitiveness, and national defense programs.

These ten theories make heavy use of the social, economic, and physical sciences, although cognitive science and fields of scholarship like history are also major components. These theories increasingly connected and working together explain why convergence now is such an opportunity. The concurrence of developments enabled by internet, social networking, unifying science and technology, and other factors create a watershed moment in increasing connection of these theories toward a transformative socioeconomic ecosystem.

If indeed information technology is costing jobs, can nanotechnology in convergence with computer science and other disciplines produce sufficient new industries of whatever kind to cause a net increase in employment and better paying jobs? We cannot begin to answer such difficult and important questions without a comprehensive intellectual preparation using convergence concepts, principles, and methods that would enable changes.

Overarching principles and methods to facilitate convergence

Convergence of science and technology means more than simply the creation of multidisciplinary teams with effective communication. It also requires changing the respective ecosystems by *advancing specific concepts and methodologies* for research, design, production, and collaboration that bridge across fields and generate new competencies in time. This section will summarize principles and methods to improve and expedite convergence, with the aim of enabling people to more readily use convergence-enabled competencies and adding value in the convergence process. The methods are based on applying six principles of convergence, listed in Fig. 2:

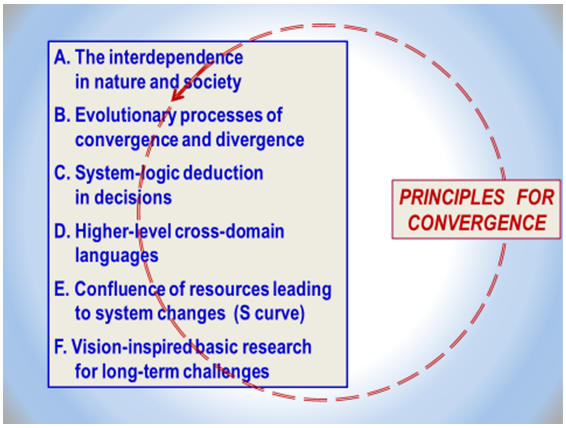

Fig. 2 Convergence of knowledge, technology, and society is guided by six general principles (**a**–**f**)

A. *Exploiting interdependence among domains in nature and society*: Convergence methods associated with this principle include integrating originally distinct domains and databases of science and technology. A main goal is forming efficient science and production networks and ecosystems with synergistic effects. Specific approaches are changing local interactions and guiding self-organization within socio-technical–economic systems to enable and reward desired outcomes and governance improvements. This may be encouraged through supporting system science, team science, and interpersonal and intrapersonal education (Cooke and Hilton 2015; Olson 2016; Kolodner 2016; Fisher 2016). Interdependence determines system changes by changing the links, nodes, and overall networked system in time (Roco 2016a). For illustration, we envision changing the *nanomanufacturing enterprise* from vertical production and large to more distributed and specialized because of the connectivity. Because of interdependence, we have new types of research and education organizations, such as the Network for Computational Nanotechnology (with 1.4 million visitors for lectures and tutorials, 13,000 users running interactive computer simulations, and over 3000 authored archival publications in 2015, all served by a cyber portal nanoHUB.org at Purdue University) (Klimeck et al. 2008; Madhavan et al. 2013). Another example is the Nanoelectronics Research Initiative (NRI) network (Welser et al. 2008). The NRI has 30 collaborating universities, six major companies, and three federal agencies and has been driven by a nanocomponent-based next generation computing vision-inspired program beginning with 2005 (see Fig. 3).

Earlier works on a holistic approach (Wilson 1999) and development of a technology-driven society (Kurzweil 1999) have been used as references. Wilson extended the meaning of *consilience* to convergence between different areas of knowledge. His aim was the unification of the realms of learning through a web of cause-and-effect explanation. With the increase of computational power, big data (OSTP 2012), and proliferation of new strategies enabled by evolutionary algorithms and network research, innovative problem solving in one domain can quickly affect others (Segerstrale 2016).

Interdependences among larger systems can lead to systemic risk, i.e., to the emergence of unforeseen behavior that could have not been predicted from the understanding of the single systems (D'Agostino and Scala 2016). Topologies of *systemic interdependencies* such as pooled (star topology), hierarchical (tree topology), distributed (graph topology), and network of networks is a main factor in system over all behavior and risk.

Biocognitive evolution (Peck 2016) implies a major shift from competitive achievement of individuals in disciplines to collaborative success in networks of interdisciplinary interactive teams. Such shifts occur by transcending while including previous cultures. The mainstream of scientific culture shifts to embrace the complex over the simple, new theory that encompasses worldviews from East and West, attention to personality as a facet of team success, and tools that reshape human interaction. There will be an increased need for advanced convergence tools and a wider public participation in science and technology.

B. *Improving the convergence–divergence evolutionary cycle*: Knowledge and technology pushes from the convergence stage are combined with societal pulls from the divergence stage and scaling up knowledge and technology diffusion in the divergence stage. Methods associated with this principle include integrated support for the four phases of the convergence–divergence process: creative, integration, innovation, and spin-off, via a cross-domain creativity and innovation spiral path. Convergence of disciplines to systematic control of matter at the nanoscale followed by divergence of applications in all

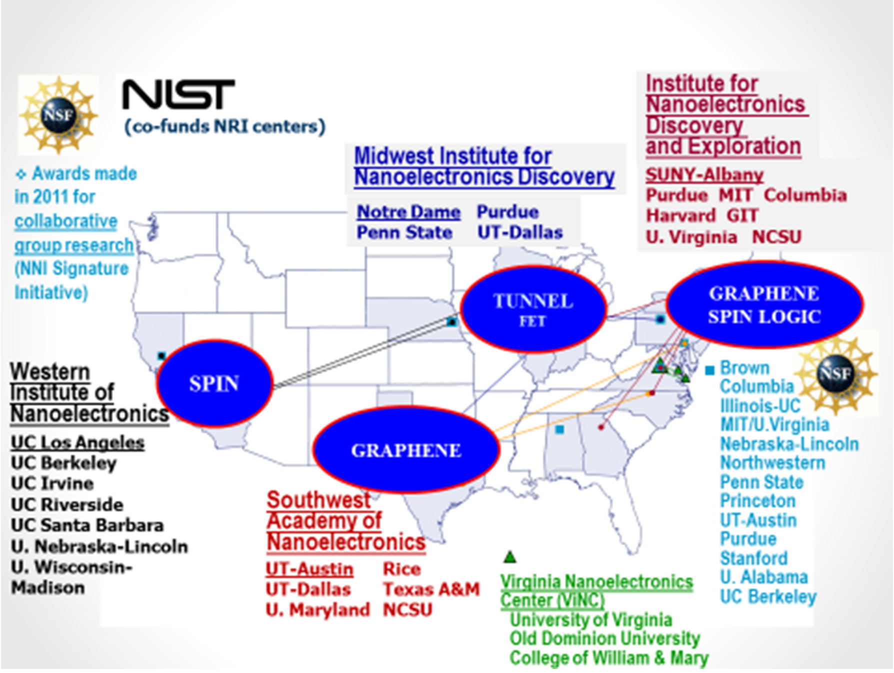

Fig. 3 Nanoelectronics Research Initiative (NRI)-funded universities by Semiconductor Research Corporation (SRC), Semiconductor Industry Association (SIA), National Science Foundation (NSF), and National Institute of Science and Technology (NIST) in 2014: Partnerships with 30 collaborating universities in 20 states (modified after NRI chart)

domains of the material world is an example of this process. Another illustration of the convergence–divergence process enabled by progress in *miniaturization and nanotechnology* is the cell phone platform. It began with the creative assembling of a wide range of technologies and cognitive and human–computer interface sciences, all of which converged to create the "smart phone" about 2005. With over 10 billion estimated subscriptions in 2016, cell phone enables now imagers, gyroscopes, microelectromechanical devices, speakers, and microphones and the immensely complex set of technologies, to name a few. Smart phones rely on convergence of high-frequency communication technologies and packet switching protocols; materials science and nanoelectronics for logic units, data storage, touch screens, antennas, etc., and cognitive science and human–computer interface technologies. This technology has at its turn unanticipated spin-off technology developments that are beginning to appear. Examples include new services such as Uber, wearable round-the-clock networked personal health monitoring devices, and mechanisms to connect automobiles to smart transportation grids in various ways.

Convergence–divergence process (Roco 2016b) is a typical cycle in science and technology (S&T) development. It consists of four phases: (i) creative assembling of contributions from multiple fields leading to new concepts or ideas, (ii) system integration leading to a new assembly or invention for known uses, (iii) technological innovation outputs leading to new products and applications, and (iv) spin-off outcomes that lead to solutions not possible before and that produce new competencies, tools, and applications. The convergence–divergence cycle is a reference in good governance of science and technology.

Self-organization and emergence of dynamic systems (Gimzewski et al. 2016) are results of the evolutionary convergence–divergence process. Self-organized criticality and emergence seem to spontaneously appear with a plethora of spatial–temporal fluctuations on all scales. Understanding of these phenomena requires a convergent effort of the sciences, arts, and humanities both in research and education.

C. *System-logic deductive decision making and problem solving*: Convergence methods associated with this principle include a holistic approach to problem solving in complex hierarchical systems, combining deduction with lateral and time evolution approaches in decision making, and balancing bottom-up research with top-down vision. Use knowledge mapping, network visualization, and fractal analysis help to identify the relevant cause-and-effect system patterns. An illustration of this principle is creating hierarchical logic systems for decision making in R&D funding programs for *nanotechnology regulatory aspects*. Governance functions apply to four levels of governance: (a) adapting existing regulation and organizations; (b) establishing new programs, regulations, and organizations; (c) building capacity for addressing these issues in national polices and institutions; and (d) advancing international agreements and partnerships (Roco 2008).

Decision making in a convergent society (Linkov et al. 2016) is a tool for progress in an increasingly interdependent environment with multiple options. Multicriteria decision analysis is suggested as an approach for system-logic deductive decisions to facilitate convergence. It provides research organizations with the ability to trade-off between criteria to provide practical and decision-relevant guidelines for individual scientific organizations to follow.

D. *Creating and applying high-level cross-domain languages to facilitate transfer of knowledge and new solutions*: convergence methods associated with this principle include using universal languages such as mathematical abstraction, music, and general system architectures. A second group of methods focus on: essential aspects through "simplicity" for efficient and timely solutions, promoting technology integrators and benchmarking to facilitate introduction of emerging technologies in multiple areas, and creating and sharing large multidomain databases and trading zones between areas of research and education in distinct areas. For illustration, the NNI is creating a network of centers for *nanoinformatics* sharing large multidomain databases toward a general nanomaterials and nanosystems database, which further supports multidomain benchmarking of nanoscale devices and systems.

Mathematical “*modeling and simulation*” (Oden 2016) provide an effective approach for connecting various R&D fields and creating an infrastructure for transdisciplinary research in knowledge society. Computational science and engineering is seen as a central focus in building suitable research, education, and production programs.

The convergence of curation (Lesk 2016) deals with integration of digital resources developed through a sequence of technical, economic, legal, and social steps. The computer problems have been solved first; now one can digitize and store images, sounds, and even 3-D objects. The economic problems are still serious but less so as the processes of digitization and delivery become less expensive. Legal issues are currently at the forefront, but even for objects old enough to pose few copyright problems, social obstacles are most important to the convergence of cultural institutions. Libraries, museums, and archives all have their own traditions of collecting, cataloging, preservation, user relationships, fund raising, and now Web presentations.

Big data and data analytics provide integration and the ability to get insights in multiple domains at various spatial and temporal scales. In 2012, the US Office of Science and Technology Policy announced the Big Data Research and Development Initiative to advance technologies needed to collect, store, preserve, manage, analyze, and share huge quantities of data. Subsequent Big Data research grants and workshops have aggressively explored how to accelerate the pace of discovery in science and engineering, transform teaching and learning and expand the economy and workforce, all for human benefits (Markus and Topi 2015).

E. *Confluence of resources for system changes (yielding the S-curve of development outcomes vs investments)*: Convergence is not simply multidisciplinary interactions or making connections; it is about changing the system (new things) and creating added value in current systems (increased efficiency). A major specific innovation, or a phase change in a system, can produce a pattern of change that starts slow as early adopters in the social system implement novelties, then accelerates as they influence others to follow their example, then slows again as the innovation approaches full adoption. Traditional innovation research noted that graphing adoption over time (or comparable variables) typically approximates a logistic curve, also called sigmoid or S-shaped, but the exact mathematical function is not crucial (Bain 1963; Meade and Islam 1998). The key observation is that transformative innovations tend to occur in surges, and interaction of several of them can appear chaotic or result in a very significant unified surge. Concurrence of efforts driven by the same opportunities and influencing each other is a characteristic of convergence in the fast ascend section of the S-curve of development. For example, the Government Accountability Office in its GAO-14-181SP report to the US Congress estimated that the fast ascendant section of the level of economic importance and societal impact curve for *nanotechnology* in the US began about 2010 (GAO 2014).

All four areas of *Nano-Bio-Information-Cognitive technologies* (Roco 2016c) have simultaneous growth because of synergism of concepts, transformative approaches, and areas of application. Each of these four foundational S&T fields (a) has a basic building block, that is, an atom, gene, information bit, or neuronal synapse; (b) interacts with other fields within the NBIC system at all length and time scales and levels of complexity; (c) has a similar computational architecture building from its respective elements up to macroscopic systems; and (d) leads to conceptually new opportunities for knowledge, technology, and socioeconomic advancement. Unifying concepts of NBIC that were first introduced in 2001 by Roco and Bainbridge (2002) lead to better understanding of nature, concurrent investments in convergence driven S&T platforms, creating new products and services, and improving human potential in activities such as working, learning, and aging

Convergence of nanotechnology and biotechnology (Choi and Montemagno 2016) is the strongest scientific convergence of two foundational fields in the last two decades. The union of nanotechnology and biotechnology has culminated in a new discipline, nanobiotechnology, through the synergistic leveraging of fundamental control of chemical, physical, and biological processes. Nanobiotechnology has, in turn, enabled both biologists to explore biochemical networks to develop a better understanding of life processes and engineers to propose an alternative approach to conventional fabrication technology. Because nanobiotechnology employs knowledge from both engineering and life science, methodology in both disciplines must be adapted to take full advantage of the opportunity to develop and demonstrate new ideas.

Space exploration (Launius 2016) and *astrosociology* (Pass and Harrison 2016) show that development was possible by innovation concurrence in many fields, including economic, technical, and political. Two twentieth century superpowers believed that space exploration was an important investment and made systematic investments in various areas of science and technology, commerce, and national security to serve the respective space programs to launch vehicles, spacecraft, and spacecraft payloads. An increased attention currently is given to robotic solar system exploration, nanobio solutions, and self-sustained crewed missions to space addressing overall challenges that are technical, political, social, and economic in nature.

Science and technology globalization (Bainbridge 2016b): Convergence of science and technology with society entails globalization, but will not necessarily lead to uniformity across nations or institutions of society. In the past, technologies differed from one place to another not only because societies differed in terms of their level of development but also because of contrasting natural conditions, historical accidents, and cultural values. Discoveries and inventions do tend to spread from their points of origin to other locations, and extensive research and theorizing have identified a large number and variety of factors that shape this diffusion. Innovation has tended to be localized, for example, in the familiar "Silicon Valley" phenomenon, in which a relatively small number of scientists and engineers communicated intensively with each other, as they collectively progressed. Thus, we cannot be assured that all parts of the globe will be equally creative in innovating, even as they all are affected by it. More effort should be invested on understanding diffusion of *innovating* (versus innovation), in which the ability to discover and invent spreads beyond its currently limited geographic homes. Over time, cycles of convergence and divergence can ensure dynamism on the global scale.

Institutional transformations in various societal areas need to be correlated and synergistic to reach converge development and welfare goals (Mason 2016). Crucial for progress in all other institutions is the educational system. Constantly improving norms and standards in education are needed for correlated, synergistic investments before the fast ascendant section of the S-development curve (Murday 2016). Science and engineering technical education is only part of the equation. At the same time, education must develop skills such as problem solving, critical thinking, design, communication, collaboration, and self-management, e.g., skills that can be transferred or applied in new situations.

F. *Using "vision-inspired" basic research to address long-term challenges*: Convergence methods associated with this principle include forecasting and scenario development, promoting a culture of convergence based on common goals, anticipatory measures for preparing people, tools, organizations, and infrastructure for the future technologies and relationships; and reverse mapping and planning. A recommended approach is to work backward from the vision to investigate intermediate research steps and approaches. This approach was used in researching and writing the NNI *nanotechnology research directions* reports beginning with the "Nanotechnology Research Direction: Vision for the Next Decade" (Roco et al. 2000).

In order to understand discovery and innovation, social scientists and historians have developed several systems for mapping kinds of thought and action, especially to learn where the convergence of multiple factors may achieve unusual progress (Bainbridge 2016a). The admonition that scientists and engineers should "think outside the box" has become a cliché, yet given adequate preparation, it can be a good advice. Convergence urges us to think outside any one disciplinary box, but there also exist more general conceptual boxes that we may also need to escape. There are at least three *dimensions of research* innovation. First, vision-inspired discovery transcends the traditional distinction between pure and applied research, but does not explain how to escape old habits of thought. Second, there may be some truth to the popular stereotype that a scientific genius has an unusual personality, which raises a whole array of research questions for cognitive science and social psychology. Third, socio-technical divergence allows creative division of labor in which different scientists and engineers can work within alternative frameworks, while finding common ground for cooperation (Powell and Snellman 2004).

Science and technology forecasting through futurism has historically been characterized by a lack of both focus and accuracy (Rejeski et al. 2016). Reflexive governance may be capable of addressing the limitations that often cause forecasting failures. Now it may be the critical time for implementation of a policy that effectively and adequately addresses cutting-edge scientific issues in a complex world. Yet is also true that improved rigor must be balanced by increased imagination, which can be inspired by v*isionary scenario development of emerging fields*. Science fiction in conjunction with general science and engineering background offers a means to explore possibilities and test ideas (Street et al. 2016). It can be used to drive scientific and technological imaginative discoveries; foment an interdisciplinary landscape to identify and address the global, complex challenges ahead; and facilitate the dialog between scientists and the general public to reduce barriers to acceptance of science concepts and technologies, including nano-bio-info cognitive technology convergence.

S&T convergence has the potential to transform the education, research, and production ecosystems. A challenge in proactively guiding the convergence process is to deliberately *encourage public and private efforts* that currently contribute to the unguided convergence of knowledge and technology to use a systematic approach to convergence that may amplify the most beneficial endeavors in the knowledge society. Illustrations of applying the methods for convergence to research, development, and education governance are discussed below.

Case studies: three general purpose technologies under way

Convergence has a strong impact on general purpose technologies when there are large intersections of production methods, of communities, a core common foundation, and a common vision. After establishing of new ecosystems of general purpose technologies, the following divergence phase leads to multiple application areas, increase in productivity, and overlapping with other complementary technology and business platforms (Evans and Gawer 2016). Convergence concepts and methods provide an enhanced cross-domain understanding, vision-inspired research, and added value productive actions. Three general purpose technologies have made significant progress on this basis:

- *Nanotechnology* has provided the integration of disciplines and technology sectors at the nanoscale of the material world building on new knowledge of the nanoscale (Roco et al. 2000, 2011; Roco and Bainbridge 2006a, b). The same 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 nanoelectonics and nanomedicine, expansion to new areas such as in agriculture and constructions, and establishing new frontiers such as in nanophotonics and metamaterials. The main drivers for progress are scientific discoveries and convergence with other fields.
- *Convergence of nanotechnology, biotechnology, information, and cognitive (NBIC) technologies* (Roco and Bainbridge 2003) connects emerging technologies based on their shared elemental components such as atoms, DNA, bits, and synapses, all with shared abstractions from information technology and system theory, hierarchically integrated across technology domains, and scales. NBIC already has made inroads with emergent results in areas such as synthetic biology, in nanoelectronics; in biomedical research at confluence of biology, medicine, physical sciences and engineering; and in bio-nano-informatics. In response to the international interest, OECD (2015) has created a Working Party on Bio-, Nano- and Converging Technologies (BNCT) to address convergence of biotechnology, nanotechnology, and other technologies.
- *Digital society* has immediate relevance to the digital economy (Ansip 2016), digital manufacturing, cyber-physical-social systems, large databases, and Internet of Things (SIA 2015). Digital relationships and networking are expected to change the respective ecosystems for production, learning, trading, and other areas. Digital

convergence facilitates dissemination and replication of results, establishment of ubiquitous digital platforms, and multicontribution 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." In spite of seemingly intractable challenges to privacy, security, and inequality, digital government appears to continue to hold enormous potential to advance well-being for individuals and governments.

Case study: intelligent cognitive assistant

This endeavor to create intelligent cognitive assistants is at the confluence of three national priorities in the US: brain-like computing (a Grand Challenge in the National Nanotechnology Initiative, NNI), National Strategic Computing Initiative (NSCI), and BRAIN research. Even more importantly, this topic is responding to the accelerating and increasingly important process of human–technology coevolution. A general goal is creating human-centered engineered cognitive systems. At a recent SRC-NSF workshop at IBM Almaden, participants identified intellectual cognitive assistants as a key feature of this framework. Current computers would be replaced by another general purpose technology to create modular intelligent cognitive assistants for various tasks. We envision creation of "machine intelligence" with versatile cognitive capabilities (such as solving new problems using higher level languages) acting as an interface between humans and their environments. They would provide perception, data, and information insights, calculations, and guidance for problems that cannot be handled by the unaided mind or by computers alone. A key research challenge is to create the system architecture with respective devices, and optimize this collaborative interaction between humans and these "intelligent" machines, where respective cognitive assistants have creative capabilities and evolve in time as they are learning. The research purpose is to create the foundation for future intelligent systems that can most effectively and efficiently assist individuals, businesses, and society at large, communicating via natural languages. No solution currently is known. Convergence is an approach to bring the known concepts and methods together to create a fundamentally new system. The increase in human productivity and opening of new fields of activity will be indicators of success.

One main component of intelligent cognitive assistants is brain-like computing: "a new type of computer that can interpret and learn from data, solve unfamiliar problems using what it has learned, and identify and solve problems without being asked, while operating with the energy efficiency of the human brain" (Whitman et al. 2015). In order to serve as an effective advisor to a human user, however, such a neuromimetic computer would need to perceive the environment and communicate with other sources of information in real time, in a way compatible with human perception and social interaction, but augmenting them. Such assistants therefore may be locally instantiated collective intelligence systems, which provide an alternative to relational databases, e-mail networks, conventional websites, and social media. Collective intelligence has been defined as an emergent property from synergies among data–information–knowledge, software–hardware, and experts and others with insight that continually learns from feedback to produce just-in-time knowledge for better decisions than any of these elements acting alone (Glenn 2016). Artificial intelligence personal assistants may serve as mediators between the person and all human knowledge, an advanced form of cognitive technology that connects the user to a new form of human cognitive society (Olds 2016; Oliva and Teng 2016).

Now is the opportunity for convergence research to address this challenge in 10–20 years at the confluence of several factors, such as reaching the limits of Moore's law in computation, difficulties in handling big data, opportunities in neuromorphic engineering and neural networking, the promise of quantum communication and quantum computing, as well as more interacting and demanding communities. Extensive and multidisciplinary research will be needed from these disparate scientific and research communities, which should hopefully serve as a useful guide for academia, industry and government in working together toward such "intelligent cognitive assistants." A first goal is to explore the functions to be accomplished by such assistants, and then developing novel algorithms, architectures, and supportive technologies for implementation. This will require collaboration of experts from nanoelectronics, photonics, neuroscience, computer architecture, biomimetics, brain visualization, neural networks, neuromorphic engineering, artificial intelligence, psychology, human–machine interface, systems theory, nanosensors, and sensorial systems, to name the most relevant. This topic has the promise to capture the imagination of public, industry, and governments because of its revolutionary objectives and general implications for human productivity and quality of life.

Case study: citizen science and technology

The societal implications of scientific discovery and technological innovation have often been conceptualized in such a way that society passively responds to change, following a *technological determinist* theory that at best gives society a period in which to adjust, traditionally called *cultural lag* (Ogburn 1922). Yes, it is important to perform *technology assessment*, in which social scientists study the human effects of engineering innovations, including possible unintended negative consequences. But today, convergence offers a very different and potentially much more optimistic perspective, which allows ordinary citizens to be partners in the achievement of progress (Kleinman et al. 2009; Cobb 2011). The examples given here only mark the beginning of a period of societal-technical partnership, and a much greater diversity of examples may be available for discussion in a few years.

Recently, the term *citizen science* has become popular, redolent with meaning and suggesting that amateurs may play very significant roles in scientific discovery. Of course, prior to the proliferation of science departments in universities during the twentieth century, many scientists were amateurs, in the sense that they were not paid for their work and did not possess higher academic degrees. The diversity of people who contributed to scientific progress in the past may have been rather greater than we commonly imagine, such as discoveries of previously unknown fossils by amateur paleontologists (Lipscomb 1995; McCoy et al. 2016).

Probably the best-known examples of contemporary citizen science are eBird and Galaxy Zoo. Drawing upon the existing community of bird watcher hobbyists, eBird has developed into a system for collecting vast data about the current geographic distribution of bird species, valuable not only for understanding their behavioral diversity and complex relations with the changing environment, but also providing very direct measures of the changing climate (Wood et al. 2011). Galaxy Zoo's initial project was enlisting volunteers, usually amateur astronomers, to classify images of 900,000 galaxies, through methods that achieved increasing reliability and built strong collaborations between professionals and amateurs (Lintott et al. 2011). Galaxy Zoo evolved into Zooniverse, not only adding many other kinds of astronomical data, but venturing into other fields, such as transcribing ancient Greek papyrus manuscripts, developing an historical understanding of the experience of soldiers in the First World War from documents such as diaries, analyzing the communications between whales, modeling the Serengeti lion population, and—most relevant to nanotechnology—classifying images of cancer cells, as part of a project involving genetics and protein expression (dos Reis et al. 2015).

Unlike birds and even galaxies and cancer cells, phenomena at the nanoscale are far from the direct experience of ordinary human beings, so developing significant citizen nanoscience would seem more challenging. However, a few other examples do already exist, and we might want to invent some high-quality citizen science projects precisely to educate and involve in decisions the general public about nanoscience and nanotechnology. Perhaps, the most famous citizen nanoscience project is Foldit, a remarkably successful convergence between biochemistry and computer game science, in which online players of a game actually achieved advances in the scientific understanding of protein folding (Khatib et al. 2011). A subsequent project by an expanded version of the Foldit team created Nanocrafter, "a citizen science platform for the discovery of novel nanoscale devices built out of self-assembling strands of DNA" (Barone et al. 2015).

The technological equivalent of citizen science would logically be called *citizen engineering*, but a term like this has not yet become popular. Yet, the related *Maker Movement* has received considerable government support. The Maker Movement already has clear implications for education. The period beginning in England two and a half centuries ago has long been referred to as the Industrial Revolution, a time marked by inventions such as the steam engine and by the transfer of manufacturing from small craft workshops to large factories, although there is much room to debate how sudden or complete this transition really was (Nef 1943). Already Jevons (1931) referred to a Second Industrial Revolution, in which the union of science and technology markedly strengthened (cf. Atkeson and Kehoe 2007). One can define the Second Industrial Revolution by the introduction of electrical power, or a century later by the introduction of Internet and other computer-based technologies, yet we tend to use the term *revolution* for a radical change in direction, rather than moderate acceleration in the same direction.

An Industrial Counter-Revolution may be occurring today, most visibly as Internet allows much greater variety in how people can do work, and who can contribute. For many years, new computer technologies, in hardware as well as software, have often come from small groups of enthusiasts, who were amateurs until their start-ups became major corporations, as in the cases of Microsoft, Apple, and Facebook. The open-source software movement has become a model for innovative forms of work that dissolve the distinction between professional and amateur (Crowston 2016), as networks of people with varying degrees of professionality took on specific subtasks in creating new software systems, of which the Linux computer operating system was an early influential example. When computer systems manage the actual production of physical products, we have what NSF calls *cyber manufacturing*, and this can include a wide variety of productivity designed to fit local or specialized markets, whether commercial or amateur as in the Maker Movement (Ciao et al. 2013; Lindtner 2014; Buehler et al. 2015).

We cannot confidently predict which direction distributed manufacturing will take, but perhaps three different structures will combine to define its trajectory. (1) Large manufacturing corporations may adopt the franchise system, currently used by fast-food businesses and auto repair shops, in which locally owned workshops affiliate with a corporation that provides the technology for production of a specific range of products adapted to local markets. (2) Promoters of creative ideas and emerging technologies will introduce nanotechnology, modern biology, automated machines, new information, and cognitive developments, to name a few, in various bottom-up and distributed projects using the increasingly available information about research breakthroughs, tools, and general databases. (3) Hobbyists in the Maker Movement, learning the needed skills at workshops set up at public libraries or colleges, will cooperate locally and with local investors, perhaps guided by volunteer nonprofit organizations but not affiliated with any large-scale corporation. Perhaps, each model will be common, either in different areas of manufacturing, or directly competing for the same customers. The citizen science approach is likely to be utilized in the Maker Movement and in training skilled workers in the franchises.

Conclusions

Convergence of knowledge and technology for the benefit of society (CKTS) is the *core opportunity for progress* in the twenty-first century (Roco et al. 2013; Bainbridge and Roco 2016). Convergence is as essential to our future knowledge society as engines were to the industrial revolution, using several foundational theories, principles, and methods as they were outlined in this paper. Based on these principles, one may suggest solutions for key societal challenges in the next decade, including accelerating progress in foundational emerging technologies and creating new industries and jobs at their frontiers and interfaces in the economic, human scale, Earth scale, and societal scale. It is about a strategy to increase productivity and outcomes in research, education, and at the working place.

The most comprehensive analysis of the convergence of science, technology, and society was conducted at a series of regional conferences in five nations: Brazil, Belgium, China, the Republic of Korea, and the United States—with representatives from many more (Roco et al. 2013). Convergence in nanotechnology development was used as a key illustration. One specific example of activity is the establishment of a convergence office to monitor government research and development decisions in the Republic of Korea (Bae et al. 2013). When the National Science Foundation surveyed the major research frontiers, from shaping the human-technology frontier to predicting phenotypes from genotypes to the next quantum revolution, it recognized that all required more convergent research (Córdova 2016; cf. Mervis 2016).

Convergence is *not merely multidisciplinary* science and engineering or better connectivity in business and society. First, it is about changing the respective research, production, or societal ecosystems using new interaction and integration tools. To converge, two or more fields need to adapt, integrate, and innovate in time. Each must to some extent adopt the perspective of the other, and together they must seek new methods of conceptualization and action that transcend their original limitations. Secondly, the newly established ecosystems can set the stage for other dynamic processes, most directly divergence based on the innovations achieved by the convergence. They can branch out into new pathways, competencies, and opportunities.

The nascent potential of converging technologies has been documented for nanotechnology, NBIC, and digital society, as well as for other domains. Larger implications have been obtained for general purpose technologies. *New opportunities of S&T convergence* may be achieved in numerous areas using either vision-inspired R&D to provide new ecosystem solutions to emerging technologies and other grand challenges; connecting and integrating foundational technologies including through well-organized initiatives or developing new technical or organizational capabilities to facilitate convergence science and convergence. Through cooperating with each other, and learning to share their diverse perspectives, scientists and engineers can become role-model examples for the people from other areas, demonstrating the opportunities of convergence in a global society.

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References

Abbott BP (2016) Observation of gravitational waves from a binary black hole merger. Phys Rev Lett 116(6):061102

Barone J et al (2015) Nanocrafter: design and evaluation of a DNA nanotechnology game. In: Proceedings of the 10th international conference on the foundations of digital games, Pacific Grove, CA

Buehler E et al (2015) Sharing is caring: assistive technology designs on Thingiverse. In: Proceedings of CHI 2015. ACM, New York, pp 525–534

Allaby M, Lovelock J (1984) The greening of Mars. St. Martin's, New York

Ansip A (2016) A bright digital future for all: global cooperation to make the best of the digital economy (OECD's Ministerial Meeting on the Digital Economy). European Community, https://ec.europa.eu/commission/2014-2019/ansip/blog/bright-digital-future-all-global-cooperation-make-best-digital-economy-oecds-ministerial-meeting_en

Atkeson A, Kehoe PJ (2007) Modeling the transition to a new economy: lessons from two technological revolutions. Am Econ Rev 97(10):64–88

Bae SH, Lim JS, Shin KM, Kim CW, Kang SK, Shin M (2013) The innovation policy of nanotechnology development and convergence for the new Korean government. J. Nanoparticle Res 15:2072

Bain AD (1963) The growth of demand for new commodities. J R Stat Soc 126(2):285–299

Bainbridge WS (2004) The evolution of semantic systems. In: Montemagno CD, Roco MC, Carlo D (eds) The coevolution of human potential and converging technologies. New York Academy of Sciences, New York, pp 150–177

Bainbridge WS (2006) Transformative concepts in scientific convergence. In: Bainbridge WS, Roco MC (eds) Progress in convergence: technologies for human wellbeing. New York Academy of Sciences, New York, pp 24–45

Bainbridge WS (2016a) Dimensions of research. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 125–138

Bainbridge WS (2016b) Science and technology globalization. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 621–634

Bainbridge WS, Roco MC (eds) (2006a) Managing Nano-Bio-Info-Cogno innovations: converging technologies in society. Springer, Berlin

Bainbridge WS, Roco MC (eds) (2006b) Progress in convergence: technologies for human wellbeing. New York Academy of Sciences, New York

Bainbridge WS, Roco MC (eds) (2016) Handbook of science and technology convergence. Springer, Berlin

Brynjolfsson E, McAfee A (2011) Race against the machine. Digital Frontier Press, Lexington

Burt RS (2004) Structural holes and good ideas. Am J Sociol 110:349–399

Chen HS, Roco MC (2009) Mapping nanotechnology innovations and knowledge: global and longitudinal patent and literature analysis. Springer, Berlin

Choi H-J, Montemagno C (2016) Convergence of nanotechnology and biotechnology. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 253–278

Ciao J et al (2013) Implications: societal collective outcomes, including manufacturing. In: Roco MC, Bainbridge WS, Tonn B, Whitesides G (eds) Convergence of knowledge, technology and society. Springer, New York, pp 255–285

Cobb MD (2011) Creating informed public opinion: citizen deliberation about nanotechnologies for human enhancements. J Nanopart Res 13:1533–1548

Cooke NJ, Hilton ML (eds) (2015) Enhancing the effectiveness of team science. National Academies Press, Washington, DC

Córdova FA (2016) 10 big ideas for future NSF investments. National Science Foundation, Arlington, VA, www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf

Crowston K (2016) Open source technology development. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 475–486

D'Agostino G, Scala A (2016) Systemic interdependencies. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 181–194

dos Reis C et al (2015) Crowdsourcing the general public for large scale molecular pathology studies in cancer. EBioMedicine 2:681–689

Elsby MWL, Hobijn B, Şahin A (2013) The decline of the U.S. labor share. Brook Pap Econ Act 2:1–52

Evans JH, Evans MS (2008) Religion and science: beyond the epistemological conflict narrative. Ann Rev Sociol 34:87–105

Evans DS, Gawer A (2016) The rise of the platform enterprise: a global survey. The Center for Global Enterprise, New York, NY, http://thecge.net/archived-papers/the-rise-of-the-platform-enterprise-a-global-survey/. Accessed date on Jan 2016

Fisher D (2016) Online courses. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 1105–1118

Fountain JE (2016) Digital government. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 781–794

Frey CB, Osborne MA (2013) The future of employment: how susceptible are jobs to computerization?. Oxford Martin, Programme on the Impacts of Future Technology, Oxford

Galesik M, Barkoczi D, Katsikopoulos K (2016) Smaller crowds outperform larger crowds and individuals in realistic task conditions. Decis Am Psychol Asso. doi:10.1037/dec0000059

Gibbon E (1776–1788) The history of the decline and fall of the Roman Empire. Seven volumes. Methuin [1896], London

Gimzewski JK, Stieg AZ, Vesna V (2016) Self-organization and emergence of dynamic systems. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 163–180

Glenn JC (2016) Collective intelligence systems. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 53–64

Gordon RJ (2016) The rise and fall of American growth: the U.S. standard of living since the Civil War. Princeton University Press, Princeton

Government Accountability Office (2014) GAO-14-181SP report on nanotechnology to U.S. Congress. Government Accountability Office, Washington, D.C

Granovetter MS (2005) The impact of social structure on economic outcomes. J Econ Perspect 19:33–50

Holland JH (2006) Studying complex adaptive systems. J Syst Sci Complexity 19(1):1–8

Hong J, Lambson B, Dhuey S, Bokor J (2016) Experimental test of Landauer's principle in single-bit operations on nanomagnetic memory bits. Sci Adv. doi:10.1126/sciadv.1501492

Horgan J (1996) The end of science. Addison-Wesley, Reading

Hughes TP (1983) Networks of power: electrification in Western society, 1880–1930. Johns Hopkins University Press, Baltimore

Jevons HS (1931) The second industrial revolution. Econ J 41(161):1–18

Khatib F et al (2011) Crystal structure of a monomeric retroviral protease solved by protein folding game players. Nat Struct Mol Biol 18:1175–1177

Kleinman DL, Delborne JA, Anderson AA (2009) Engaging citizens: the high cost of citizen participation in high technology. Public Underst Sci 1:1–20

Klimeck G, McLennan M, Brophy S, Adams III G, Lundstrom M (2008) nanoHUB.org: advancing education and research in nanotechnology. IEEE Comput Eng Sci (CISE). doi:10.1109/MCSE.2008.120

Kolodner J (2016) Cyberlearning. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 1007–1022

Kristal T (2013) The Capitalist machine: computerization, workers' power, and the decline in labor's share within U.S. industries. Am Sociol Rev 78(3):361–389

Kuhn TS (1957) The Copernican revolution. Harvard University Press, Cambridge

Kuhn TS (1962) The structure of scientific revolutions. University of Chicago Press, Chicago

Kurzweil R (1999) The age of spiritual machines: when computers exceed human intelligence. Viking/Penguin Group, New York

Landauer R (1961) Irreversibility and heat generation in the computing process. IBM J V(x):183–191

Launius RD (2016) Space exploration. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 635–650

Lesk M (2016) The convergence of curation. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 95–112

Levin SA (2005) Self-organization and the emergence of complexity in ecological systems. Bioscience 55(12):1075–1079

Lindtner S (2014) Hackerspaces and the internet of things in China: how makers are reinventing industrial production, innovation, and the self. China Inf 28(2):145–167

Linkov I, Gisladottir V, Wood MD (2016) Decision making in a convergent society. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 113–124

Lintott C et al (2011) Galaxy Zoo 1: data release of morphological classifications for nearly 900 000 galaxies. Mon Not R Astron Soc 410(1):166–178

Lipscomb D (1995) Women in systematics. Annu Rev Ecol Syst 26:323–341

Lovelock JE, Margulis L (1974) Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. Tellus 26(1–2):2–10

Lux Research (2015) Update to 2014 research effort concerning nanotechnology R&D spending, revenues and related information. New York, October 2015

Madhavan K, Zentner M, Klimeck G (2013) Learning and research in the cloud. Nat Nanotechnol 8:786–789. doi:10.1038/nnano.2013.231

Markus ML, Topi H (2015) Big data, big decisions for science, society, and business. ACM Digital Library, New York

Mason RM (2016) Institutional transformation. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 847–860

Massey DS (2002) A brief history of human society: the origin and role of emotion in social life: 2001 presidential address. Am Sociol Rev 67(1):1–29

McCoy VE et al (2016) The “Tully monster” is a vertebrate. Nature 532:496–499

Meade N, Islam T (1998) Technological forecasting—model selection, model stability, and combining models. Manag Sci 44(8):1115–1130

Merton RK (1970) Science, technology and society in seventeenth-century England. Harper and Row, New York

Mervis J (2016) NSF director unveils big ideas. Science 352(6287):755–756

Murday J (2016) Norms and standards of learning. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 1089–1104

National Research Council (2014) Convergence: facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond. National Academies Press, Washington DC

Nef JU (1943) The industrial revolution reconsidered. J Econ Hist 3(1):1–31

Oden TJ (2016) Modeling and simulation. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 139–148

OECD (2015) Biotechnology, nanotechnology and other converging technologies working group, Paris, France. www.innovationpolicyplatform.org/oecd-working-party-bio-nano-and-converging-tech-bnct-0

Ogburn WF (1922) Social change with respect to culture and original nature. Huebsch, New York

Olds J (2016) Cognitive technology. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 227–238

Oliva A, Teng S (2016) Cognitive society. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 743–754

Olson GM (2016) Collaboratories. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 391–400

OSTP (March 29 2012) Big data research and development initiative. Washington, www.whitehouse.gov/sites/default/files/microsites/ostp/big_data_press_release_final_2.pdf

Pass J, Harrison AA (2016) Astrosociology. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 545–558

Peck JC (2016) Bio-cognitive evolution. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 43–52

Poole E, Bernard J-T (1992) Defense innovation stock and total factor productivity. Can J Econ 25(2):438–452

Porter JH et al (2009) New eyes on the world: advanced sensors for ecology. Bioscience 59(5):385–397

Powell WW, Snellman K (2004) The knowledge economy. Ann Rev Sociol 30:199–220

Rejeski D, Pauwels E, Koo J (2016) Science and technology forecasting. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 149–162

Roco MC (2002) Coherence and divergence of megatrends in science and engineering. J Nanopart Res 4:9–19

Roco MC (2008) Possibilities for global governance of converging technologies. J Nanopart Res 10:11–29

Roco MC (2011) The long view of nanotechnology development: the National Nanotechnology initiative at 10 years. J Nanopar Res 13:427–445

Roco MC (2016a) Principles and methods that facilitate convergence. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 17–42

Roco MC (2016b) Convergence-divergence process. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 79–94

Roco MC (2016c) NBIC. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 209–226

Roco MC, Bainbridge WS (eds) (2001) Societal implications of nanoscience and nanotechnology. In: Kluwer, Dordrecht (Mihail C. Roco and WSB)

Roco MC, Bainbridge WS (eds) (2002) Converging technologies for improving human performance: integrating from the nanoscale, J Nanoparticle Res 4:281–295

Roco MC, Bainbridge WS (eds) (2003) Converging technologies for improving human performance. Kluwer, Dordrecht

Roco MC, Bainbridge WS (eds) (2006a) Nanotechnology: societal implications–maximizing benefit for humanity. Springer, Berlin, (Mihail C. Roco and WSB)

Roco MC, Bainbridge WS (eds) (2006b) Nanotechnology: societal implications–individual perspectives. Springer, Berlin, (Mihail C. Roco and WSB)

Roco MC, Bainbridge WS (2013) The new world of discovery, invention, and innovation: convergence of knowledge, technology, and society. J Nanopart Res 15(1946):17

Roco MC, Montemagno CD (eds) (2004) The coevolution of human potential and converging technologies. New York Academy of Sciences, New York

Roco MC, Williams RS, Alivisatos P (eds) (2000) Nanotechnology research directions: vision for the next decade. National Science and Technology Council, Washington, DC, http://www.wtec.org/loyola/nano/IWGN.Research.Directions/). Kluwer Academic Publ. (now Springer), Dordrecht

Roco MC, Mirkin CA, Hersam MC (eds) (2011) Nanotechnology research directions for societal needs in 2020. Springer, Dordrecht

Roco MC, Bainbridge WS, Tonn B, Whitesides G (eds) (2013) Convergence of knowledge, technology and society. Springer, New York

Schumacher EF (1973) Small is beautiful. Blond and Briggs, London

Segerstrale U (2016) Consilience. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 65–78

Sharp P, Jacks T, Hockfield S (eds) (2016) Convergence: the future of health. MIT, Cambridge

SIA, SRC (2015) Rebooting the information technology revolution. Report sponsored by NSF, www.nsf.gov/crssprgm/nano/reports/2015-0901_RITR%20WEB%20version%20FINAL_39p.pdf

Slipher VM (1917) Nebulae. Proc Am Philos Soc 56(5):403–409

Street A, Savage N, Page A (2016) Visionary scenario development of emerging fields. In: Bainbridge WS, Roco MC (eds) Handbook of science and technology convergence. Springer, Berlin, pp 195–206

Venugopal J et al (2010) Biomimetic hydroxyapatite-containing composite nanofibrous substrates for bone tissue engineering. Philos Trans 368(1917):2065–2081

Welser JJ, Bourianoff GI, Zhirnov VV, Cavin RK III (2008) The quest for the next information processing technology. J Nanopart Res 10:1. doi:10.1007/s11051-007-9305-8

White L (1959) The evolution of culture. McGraw-Hill, New York

Whitman L, Bryant R, Kalil T (2015) A nanotechnology-inspired grand challenge for future computing. White House Office of Science and Technology Policy, Washington, DC

Wilson EO (1999) Consilience: the unity of knowledge. Random House, New York

Wood C, Sullivan B, Iliff M et al (2011) eBird: engaging birders in science and conservation. Public Library of Science Biology 9(12):e1001220

Zipf GK (1942) The unity of nature, least-action, and natural social science. Sociometry 5(1):48–62