J Nanopart Res (2013) 15:1946
DOI 10.1007/s11051-013-1946-1

PERSPECTIVES

The new world of discovery, invention, and innovation: convergence of knowledge, technology, and society

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Received: 13 August 2013 / Accepted: 14 August 2013

Abstract Convergence of knowledge and technology for the benefit of society (CKTS) is the core opportunity for progress in the twenty-first century. CKTS is defined as the escalating and transformative interactions among seemingly different disciplines, technologies, communities, and domains of human activity to achieve mutual compatibility, synergism, and integration, and through this process to create added value and branch out to meet shared goals. Convergence has been progressing by stages over the past several decades, beginning with nanotechnology for the material world, followed by convergence of nanotechnology, biotechnology, information, and cognitive science (NBIC) for emerging technologies. CKTS is the third level of convergence. It suggests a general process to advance creativity, innovation, and societal progress based on five general purpose principles: (1) the interdependence of all components of nature and society, (2) decision analysis for research, development, and applications based on dynamic system-logic deduction, (3) enhancement of creativity and innovation through evolutionary processes of convergence that combines existing principles and divergence that generates new ones, (4) the utility of higher-level cross-domain languages to generate new solutions and support transfer of new knowledge, and (5) the value of vision-inspired basic research embodied in grand challenges. CKTS is a general purpose approach in knowledge society. It allows society to answer questions and resolve problems that isolated capabilities cannot, as well as to create new competencies, knowledge, and technologies on this basis. Possible solutions are outlined for key societal challenges in the next decade, including support for foundational emerging technologies NBIC to penetrate essential platforms of human activity and create new industries and jobs, improve lifelong wellness and human potential, achieve personalized and integrated healthcare and education, and secure a sustainable quality of life for all. This paper provides a 10-year "NBIC2" vision within a longer-term framework for converging technology and human progress outlined in a previous study of unifying principles across "NBIC" fields that began with nanotechnology, biotechnology, information technology, and technologies based on and enabling cognitive science (Roco and Bainbridge, Converging technologies for improving human performance: nanotechnology, biotechnology, information technology and cognitive sciences, 2003).

This article contains excerpts from "Converging Knowledge, Technology and Society: Beyond Convergence of Nano-Bio-Info-Cognitive Technologies", edited by M.C. Roco, W.S. Bainbridge, B. Tonn and G. Whitesides, National Science Foundation/World Technology Evaluation Center report, Springer 2013, Boston (available on http://www.wtec.org/NBIC2-report) (Accessed on 27 Aug 2013).

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Published online: 31 August 2013

Keywords Nanotechnology · Biotechnology · Information technology · Cognitive science · Research and development system · Innovation · Vision-inspired research · Governance · Societal implications

Introduction

Nanoscale science and technology can play decisive roles in a coming transformation of science, technology, and society marked by convergence across technical fields and domains of human activity. Research and engineering at the nanoscale already draw upon and link together physics, chemistry, biology, and engineering and computer science. This article presents a perspective on the wider environment in which nanotechnology and its co-development with modern biology, information technology, and cognitive sciences will take place, while implementation details are presented in the full report (Roco et al. 2013). CKTS is the natural extension of precursor unifying principles in science and technology (S&T) (AAAS 1989; Wilson 1999; Roco and Bainbridge 2003; Sharp and Langer 2011). The study was sponsored by the National Science Foundation, the National Institutes of Health, the National Aeronautics and Space Administration, the Environmental Protection Agency, the Department of Defense, the U.S. Department of Agriculture, and international partners from Asia, Europe, and Australia. The prime insight is that convergence of knowledge and technology for the benefit of society CKTS is the core opportunity for progress in the twenty-first century. The dynamic integration of knowledge, technologies, and society is a fundamental opportunity for human progress as expansion in harnessing Earth's resources and availability of larger investments have reached limitations. It is reflected in bridging the divide between research, education, innovation, and production needs in national and global activities.

Intellectual unification of the diverse branches of science and engineering should progress hand-in-hand with expanding the cultural unification and economic effectiveness of the world as an interdependent system. However, interdependence and convergence of approaches should increase rather than diminish the importance of the individual human being. Since the invention of the wheel and the lever, effective technologies have increased human potential, but now capability augmentation of entirely new kinds is becoming possible. The challenge will be to increase the capabilities of both individuals and societies in a manner conducive to collective and individual human well-being and freedom, and based on respect for commonly held ethical principles.

The five CKTS principles and their implications are discussed in the following sections.

The convergence vision

Interdependencies between the human mind and the surrounding natural system determine a coherent convergence–divergence evolutionary process in the interconnected knowledge, technology, and societal development that leads to creation of added value and progress. Convergence includes bringing together all relevant areas of human, machine, and natural resource capability that enable society to answer questions and resolve problems that isolated capabilities cannot; divergence creates and disseminates new competencies, technologies, and products. The convergence–divergence process aims at what is essential in a system: synergism, new pathways, innovation, efficiency, and simplicity. CKTS provides a systematic approach to connect and enable emerging technologies and then implement them in essential domains of human activity: Technology-scale, Human-scale, Earth-scale, and Societal-scale. Convergence processes already have begun between several specific domains of science and technology (Kurzweil 1999; Gregorian 2004; Hey et al. 2009; Dunbar 2003; NRC 2010; Sharp and Langer 2011; Hood and Flores 2012; Roco and Bainbridge 2012).

Nature is a single coherent system, and diverse methods of scientific and engineering investigations should reflect this interlinked and dynamic unity. Accordingly, general concepts and ideas should be developed systematically in interdependence, with cause-and-effect pathways, for improved outcomes in knowledge, technology, and applications. At the same time, industrial and social applications rely on integration of disciplines and unification of knowledge. Thus, convergence is both a fundamental principle of nature and a timely opportunity for human progress.

"It was the best of times, it was the worst of times." So Dickens described the revolutionary changes of a past century. But the words aptly describe the collection of scientific and social revolutions currently raging today, some admirable—such as increased human connectivity enabled by new digital technologies, and the eradication of starvation and epidemic diseases in nation after nation facilitated by medical and social innovations—and some lamentable, such as global economic crises and bloodshed fueled by ethnic and ideological intolerance. The most powerful creations of the human mind—science, technology, and ethical society—must become the engines of progress to transport the world away from suffering and conflict to prosperity and harmony. Today, because science and society are already changing so rapidly and irreversibly, the *fundamental principle for progress must be convergence*, the creative union of sciences, technologies, and peoples, focused on mutual benefit.

The discrepancy in most of the world's economies between the accelerated quasi-exponential growth of knowledge (discoveries and innovations) since 2000 and the relatively slow quasi-linear economic growth underlines the unmet potential of governance to improve technology deployment for economic benefit, and the need for a better approach. Convergence approaches offer added value solutions in many application areas to address this knowledge outcomes gap and eventually accelerate economic and societal development. Implementation of convergence approaches is timely, as recent statistics show a deceleration of GDP per capita growth rate in developing countries, including in the United States (Mouw and Kalleberg 2010).

Furthermore, in the last decades, there has been a gap between the rates of growth of R&D investments—which indicate future trends in knowledge growth—in several countries and the rate of GDP growth. For example, in the United States, the Federal spending for research and development grew at just 1.3 % annually from 1989 to 2009, while gross domestic product rose annually 2.4 % (National Science Board 1991–2012; Reif and Barrett 2013). Because of this investment slow-down, finding cost-effective means to address the knowledge outcomes gap discussed in the previous paragraph is an even more timely opportunity.

The United Nations 2011, 2012a, b, c studies on human development provide a well-considered blueprint of the global status of human society and desirable, immediate goals: inclusive economic development, inclusive social development, environmental sustainability, and peace and security. The concept of the convergence of knowledge, technology, and society is an approach to addressing human challenges through the synergism it generates in creativity, innovation, and decision-making. The 2011–2013 NBIC2 or CKTS study that informs this article received input from leading academic, industry, and government experts from four continents and a number of major economies, including the United States, Australia, China, the European Union, Japan, Korea, and Latin America, in the context of five workshops.

Convergence of knowledge and technology has been identified as an emerging field around the world, with specific actions recommended to accelerate progress and to benefit from it as promptly as possible. For example, the European Union draft program HORIZON 2020 has used convergence principles and was the subject of EU–U.S. workshop deliberations. In another example, the South Korea program "Convergence Research Policy Development Centre" was the subject of U.S.–South Korea–Japan workshop deliberations. Building an international network to collaboratively advance the methods and applications of convergence would be valuable to all nations. The primary conclusion of the U.S. panel's deliberations has been that a Federal CKTS initiative could best take advantage of this fundamental opportunity for progress in the United States.

Having a vision and projecting trends into the future, of course, are not sufficient to specify the scope and direction of such an initiative. Goals in science and engineering must be pursued rigorously, and with constant, critical debate among professionals and with representatives of the wider society. Indeed, much research will need to focus on convergence itself, to achieve better understanding of the processes that achieve it, to develop methods for improving it, and to ensure it benefits humanity through transformed governance (see the CKTS conductor analogy in Fig. 1). Notably, convergence incorporating knowledge and technology progress must serve three humanistic goals: (1) improved economic productivity, (2) increased human potential, and (3) securing a sustainable quality of life for all.

Three successive levels of convergence have been described by increasingly holistic U.S. Government-sponsored studies:

Fig. 1 CKTS Logo: the conductor suggests societal governance of converging human activity platforms for societal benefit (the *ribbons from left to right* suggest: Earth-scale platform, nano-bio-info-cogno technologies, Human-scale platform)

- First, in the late 1990s moving into the 2000s, *nanotechnology* provided integration of disciplines and technology sectors of the material world building on new knowledge of the nanoscale (Roco and Williams 1999; Roco and Bainbridge 2001, 2007), which is at the transition from fixed properties of atoms to a variety of materials, devices and inert or living systems encountered at macroscale.
- Second, in the 2000s, converging nanotechnology, biotechnology, information technology, and cognitive ("NBIC") technologies—starting from basic elements, atoms, DNA, bits, and synapses—led to foundational tools that integrated (both horizontally and vertically) various emerging technologies into multifunctional hierarchical systems (Roco and Bainbridge 2002, 2003; Roco and Montemagno 2004; Bainbridge and Roco 2006a, b).
- Third, moving into the 2010s and beyond, *CKTS* (also referred to as "beyond-NBIC" or "NBIC2") is integrating essential human activities in knowledge, technology, human behavior, and society, distinguished by a purposeful focus on supporting societal values and needs.

Each level of convergence changes in a specific way the network connections, the nodes, and the human activity system.

Around four hundred million years ago, the ancestors of all four-legged animals, including us, left the sea to walk on land. Fins evolved into legs, gills into lungs, and brains adapted to the radically changed environment. We are currently at a similar threshold, and as no intelligent fish could have imagined what its descendants could achieve, it is only with great difficulty that we can plan for the radical transformation that lays ahead of us. As in the case of the emergence of the amphibia, however, the future will be a combination of incremental changes and disjunctive adjustments in the functioning of a complex, adaptive system.

A dynamic systems approach

Each level of convergence is defined by an application domain and a specific process of integration. There are hierarchical levels of the convergence domains, the top level being the global and evolutionary human activity system driven by societal values and needs for progress in human development. Under this, the four essential convergence platforms (see Figs. 2, 3, 4, 5) are each defined by a core system with key players (individuals, organizations, and technologies), specific interactions and characteristics, tools, and outcomes.

In considering this complex system of systems, a good starting point is the original NBIC convergence conception that began with nanotechnology, recognized the significant connections that already existed with biotechnology and information technology, and then proposed that cognitive science and new technologies based on it were needed to complete a set of Foundational Tools/Technologies (Roco and Bainbridge 2002). Each of these starts from a basic element (atom, DNA, bit, or synapse), which serve as twenty-first century building blocks for progress, and is integrated into multiple systems, ultimately forming NBIC. Nanotechnology and Information Technology (framed in the schematic) are two general purpose enabling technologies providing methods and connections for the material/biomedical world and information/communication/computing, respectively. Biotechnology and Cognitive Sciences (on shaded background) are the

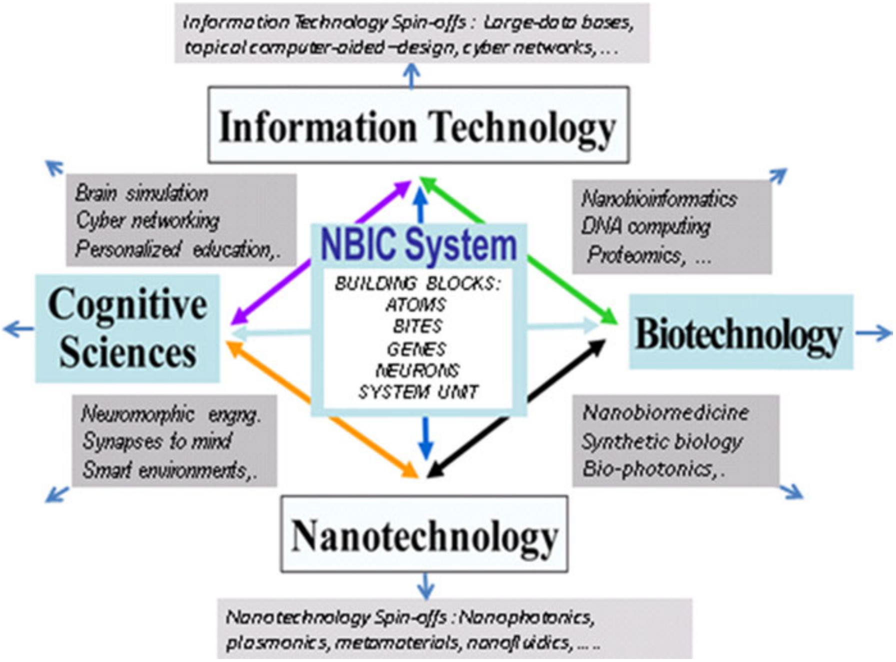

Fig. 2 The Foundational Tools/Technology (NBIC) platform and the spin-off research branched out from each N, B, I, and C and between them since 2000

main knowledge and technology drivers of the development to satisfy human needs in biomedical/environmental and cognitive areas, respectively. All four foundational emerging and converging technologies NBIC are connected using a general purpose system approach. Each foundational emerging technology has spin-offs in its own area or at the intersection with one or more of the NBIC domains, as shown in Fig. 2.

From the very beginning, the National Nanotechnology Initiative (NNI) has emphasized that the must serve the needs of human beings, in an ethical and sensitive manner, and as the convergence–divergence process progresses more and more of the applications serve individual users. The second major platform to consider is the Human-scale platform, characterized by the interactions between individuals by pairs and in groups, between humans and machines and computers, and between humans and the environment. The platform is enabled by two general fields (Human–technology–environment and Human-communication virtual integration, both framed in Fig. 3) and two key drivers Bio-physical needs and Cognitive needs.

The Human-scale interactions between individuals go beyond cognitive science, requiring involvement of social psychology and the social sciences more generally, which prepares for the third system component, the Societal-scale platform. It is characterized by the activities and systems that link individuals and groups on several larger scales; it consists of collective activities, organizations, and procedures, including governance. The platform is enabled by two general fields (Human–technology co-evolution and Governance, investment policies and regulations, both framed in Fig. 4) and two key drivers bio-physical (health, education, infrastructure) and cognitive (Moral, ethical) needs.

At some time in the perhaps distant future, human society will extend beyond our small planet to encompass the solar system, but at present the largest scale for concerted human activities is the Earth-scale platform. This is the environment for human activities,

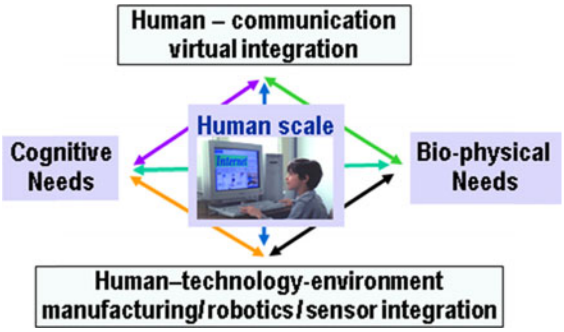

Fig. 3 The Human-scale platform

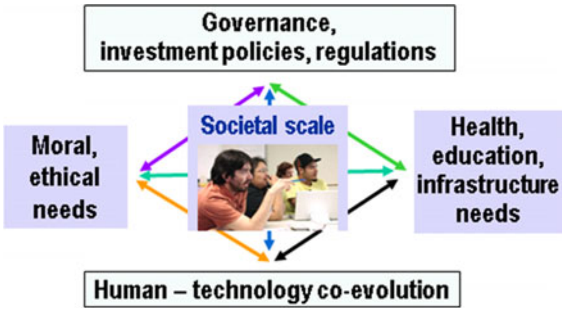

Fig. 4 The Societal-scale platform

including global natural systems, communication systems, and the global economy; there are limitations for human intervention. The platform is enabled by two general fields (Earth-technology integration and Earth systems, both framed in Fig. 5) and two key drivers Global bio-physical needs and Global cognitive needs. One can recognize a progression of the platform components and their systems from the foundational converging tools (Fig. 2) to the other three (Figs. 3, 4, 5).

In the total evolutionary human activity system, feedback interaction loops operate within each platform, and integrate them into a general spiral of creativity and innovation. Figure 6 outlines this conceptualization, incorporating placeholder boxes for each of the four platforms illustrated in finer detail above. Complete evolutionary human activity Global system interactions are driven by societal values and needs (see the core in Fig. 6) that causes actions and transformations in one or more of the four essential, general convergence platforms, and finally leading to progress in human development, having their effect primarily in one or more of the four general convergence platforms.

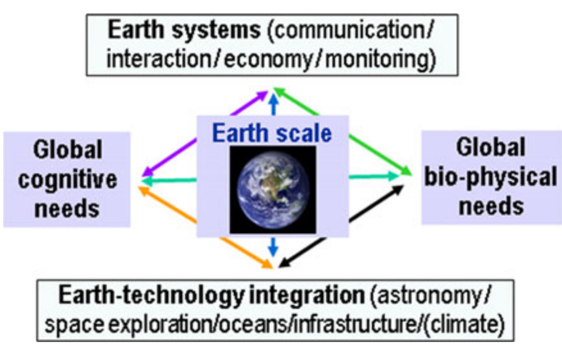

Fig. 5 The Earth-scale platform

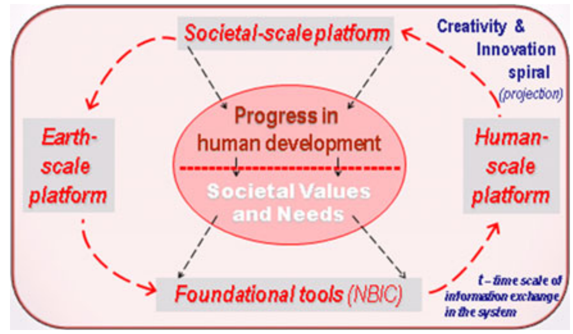

Fig. 6 The complete evolutionary human activity system. It includes four essential convergence platforms: Foundational Tools/Technologies, Human-scale, Earth-scale, and Societal-scale. In this figure, the projection of the creativity and innovation spiral covers all essential convergence platforms of the system

One focus of CKTS is penetration of high added value emerging NBIC technologies on the essential platforms of human activity. By establishing the essential platforms and their connections, it is possible to use logical deduction and induction between various hierarchical levels of the system for decision-making, establishing partnerships, and for other purposes.

The convergence–divergence evolution process

The first phase of NBIC convergence integrated foundational, emerging technologies that are defined from elementary components and interact at all scales and levels of complexity. CKTS builds on that foundation to achieve integrated knowledge and capability across all fields of science and engineering, based on common convergence platforms and concepts, to achieve societal benefits. The core ideas are that CKTS:

- Advances an integrative approach across human dimensions, encompassing value systems, operating at societal and global scales, while remaining valuable for each individual person.
- Is based on the material unity at the nanoscale, integrated systems, and information universes, connected via human behavior and other integrators.
- Is best facilitated by a holistic approach with shared methodologies, theories, and goals, which

is quite different from traditional forms of collaboration in which a division of labor separates disciplines from each other.

- Renews the focus on people's capabilities and human outcomes, rather than allowing decisions to be technology-driven, and seeks to transcend existing human conflicts to achieve vastly improved conditions for work, learning, aging, physical and cognitive wellness, and to achieve shared human goals.

The convergence process is defined as the escalating and transformative interactions among seemingly different disciplines, technologies, and communities to achieve mutual compatibility, synergism, and integration, and thus to create added value to meet shared goals. This societal convergence definition expands on convergence–divergence concepts in science and engineering megatrends (Roco 2002) and applies them to unprecedented interconnected advancements in knowledge, technology, and social systems. The result of societal convergence thus broadly conceived is expected to be numerous new applications of science and technology with significant added value to society. Convergence is not a simple, unidirectional process. The convergence–divergence processes follow in cycles of various intervals, in topical and temporal coherence with each other, and are applicable to the various human activity platforms noted earlier.

Figure 7 outlines the process in terms of four conceptually distinct phases, although in any significant field of endeavor they overlap and are constantly influencing each other. In the Creative Phase, previously separate multidisciplinary components achieve significant synergy but maintain a degree of independence. Then, in the Integration Phase they fuse into a new and unified system, which might be mistaken for the conclusion of the convergence. However, at this point multiple synergies launch the Innovation Phase, leading to new competencies and products, which not only diffuse across the boundaries of the original convergence and contribute to more distant fields, but also may bring into being entirely new scientific, engineering and societal activities. The Outcome Phase consists of new applications and new inputs that feed back into the Creative Phase of successive cycles of convergence and divergence.

Convergence as a process unites knowledge, technology, and applications, both across traditionally separate disciplines, and across multiple levels of abstraction and organization. *Divergence* as a process starts after the formation of the new system and leads to new competencies, products, and application areas for the knowledge achieved in the convergence process.

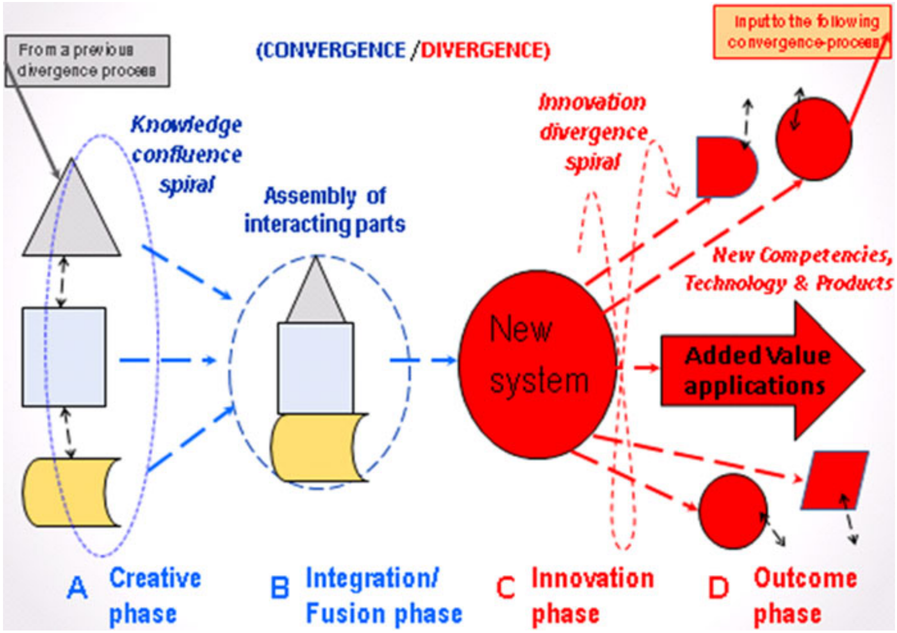

Fig. 7 The convergence (*A*, *B*)–divergence (*C*, *D*) cycle. It includes (*A*) a creative phase dominated by synergism between multidisciplinary components, (*B*) integration/fusion into a new system, (*C*) an innovative phase leading to new competencies and products, and (*D*) an outcome phase leading to new technologies, commercialization and societal outcomes. The knowledge confluence (creativity) spiral and innovation spiral are dominant in the creative phase and innovative phase, respectively

The rapid pace of change in science and the emergence of new technologies require new approaches that manage complexity, achieve sophisticated functionality, and yet are intelligible for ordinary human users of the applications. Convergence thus extends beyond science and technology, even beyond new applications, to include harmonious unification of activities across the entire societal spectrum.

One way to conceptualize this is in terms of the complementary functions of the human brain, recognizing that in fact brain lateralization is only modest in degree, and individuals differ in the specialization of their brain hemispheres. The convergence phase—characterized by analysis, creative connections, and integration—is perhaps best done by the left half of the brain. The divergence phase—characterized by synthesis or formation of the new system, innovation in applying to new areas, finding new things (outcomes in knowledge, technology, and society), and multidimensional outcomes—may best be done by the right half of the brain. Whatever model or metaphor one prefers, the convergence–divergence process reflects two complementary roles of brain functions. Decision-making follows a convergence–divergence process driven by the need for improvement and added value that is at the core of human thought and behavior, which also is reflected in group and organization actions.

Each convergence–divergence process is cause-and-effect connected to upstream and downstream related processes and is in coherence with other simultaneous CKTS processes at various domain and temporal scales. One way to consider and better use such longer-range coherence is by engaging the brain functions of contemplation and reflection that may be called "mindfulness" (Fichman 2004; Langer 1997) to focus on making the most beneficial decisions by considering the relevant events and by anticipating and avoiding unintended harmful aspects of the new powerful and connected technologies. Mindfulness is distinguished by expanded perspective, context-relevant interpretations, and receptiveness that can lead to more long-range, discriminating, and holistic innovation and solutions. Contemplation and reflection in research and education will also help provide a foundation for enhancing human capacity and unity of purpose in terms of addressing longer-term aspects of wellness, creativity, and innovation.

One specific example of convergence and of the convergence–divergence process described above is the development of the *cell phone platform*, where a wide range of technologies including high-frequency communications and packet switching protocols (for connections to global networks); materials science and nanotechnology (for CPUs, data storage, touch screens, antennas, etc.); and cognitive science and human–computer interface technologies (for the user interface) *converged* to create the "smart phone" about a decade ago. This is now *diverging* into thousands of applications scarcely imagined 10 years ago, from social networks to controlling swarms of very inexpensive miniaturized satellites, and many other examples, too many to list, affecting virtually every aspect of our society. These impacts in turn have profound implications for and secondary impacts on areas as diverse as national security, education, and cognitive science.

Another more general example of the convergence–divergence process is in *creating and implementing S&T programs* (such as the space program, or a program on sustainable urban systems) that seek to deliver solutions by linking the creative phase of scientific excellence available in society to generate converging knowledge and technologies that can then be used to address technology needs and societal grand challenges.

A good example is the convergence–divergence process for *nanotechnology development* between about 2000 and 2020, shown in Fig. 8. Knowledge confluence (of bottom-up and top-down disciplines, in various sectors from materials to medicine, adopting new tools and methods of investigation and synthesis) is leading to control of matter at the nanoscale. Increasing control at the nanoscale enables the creation/integration of four successive generations of nanotechnology products and productive methods (for passive nanostructures, active nanostructures, system of nanosystems, and molecular nanosystems) marked by inventions. In the divergent phase, the spiral of innovation leads to new products and applications that are estimated to $3 billion in 2020 (Roco 2011) and branching out to new activities including spin-off disciplines and productive sectors, business models, expertize, and decision-making approaches.

The size and time scales of the information exchange in the system (Fig. 6) and the characteristics of the convergence–divergence cycle (Fig. 7) are key factors for the creativity and innovation outcomes. To conceptualize the influence of convergence on creativity and innovation, we have defined an index of

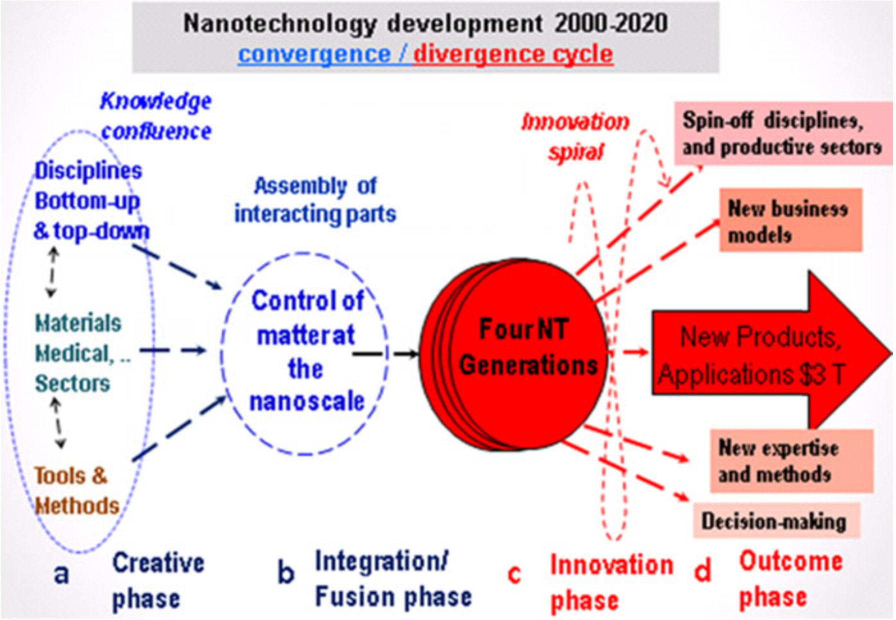

Fig. 8 2000–2020 convergence–divergence cycle for global nanotechnology development

innovation rate (I). This index is estimated to be in direct proportion to the size S of the convergence domain from where information is collected (the domain circumscribed by the innovation spiral, or the number of disciplines or application areas intersected by the circumferential creativity and innovation spiral, in Fig. 6); the speed of information exchange supporting innovation in that platform (*S/t*) where *t* is the time scale of information exchange; the speed of the convergence–divergence cycle (*1/T*) where *T* is the duration of the cycle (from phase A to phase D, in Figs. 7 and 8); and the divergence angle in realizing the outcomes ($\sim O/T$):

$$I \sim k\,(S)\,(S/t)\,(1/T)\,(O/T) \sim k\,S^2O/(T\,T\,t) \sim k'S^2O/T^3 \quad (1)$$

where $t \sim T$ (the time scale *t* for the circumferential projection is proportional with the time scale *T* for the convergence–divergence cycle, both being projections of the same three-dimensional spiral), *O* is the outcome size, and *k* and *k*' are coefficients of proportionality. This qualitative correlation underlines the importance of the size of the convergence domain (S^2) and time scale of the convergence–divergence cycle ($1/T^3$) on the innovation rate. The (S^2) term in the equation agrees nicely with the well-known "Metcalf's Law" (which states that the value of a network scales as the square of the number of nodes in the network; Shapiro & Varian, 1999). The (*O/TT*) term in the Eq. (1) is in agreement with the empirical exponential growth model for science and technology (illustrated by the well-known semiconductor industry Moore's Law and Kurzweil 1999). The remaining (*1/T*) term is proportional with the rate of technology diffusion.

To reduce this time, one can develop better communication and collaboration tools, including the wide-ranging networks called collaboratories. A profoundly important example is the Network for Computational Nanotechnology, nanoHUB.org, which supports a global ecosystem of connectivity and collaboration for the nanotechnology community, now serving about 300,000 users annually. Equally important are programs to link innovation to upstream discovery and innovation and downstream commercialization and societal acceptance, such as the multi-agency Small Business Innovation Research and Small Business Technology Transfer programs, and special National Science Foundation programs like Grant Opportunities for Academic Liaison with Industry (GOALI) and Innovation Corps (I-Corps).

High level convergence languages

The cultivation of higher-level (multidomain) languages is to support fruitful transfer and application of new knowledge in planning, management, and other areas.

By *convergence language* we understand the common concepts, network relationships, methods, and nomenclature used in a multidomain of science, technology, and society. Languages evolve over time. Each scientific discipline and technology area has a specific language. An effective convergence process across a CKTS platform will require a more comprehensive and faster exchange language for communication and synergism among its disciplines, areas of relevance, and stakeholders. This would allow for better integration of the components and faster spirals of creativity and innovation in order to support successful communication and synergism across disciplines and cultures. Establishing of multidomain convergent (or higher-level) languages is using knowledge, technology, and cultural integrators such as unifying theories. The approach finds what is common and essential in multiple domains, and bottom-up and horizontally establishes languages and rules that are suitable to all those involved.

An example of an existing *convergence language is using music* to help bridge cultural divides at the human and societal-scales. Throughout human history—probably before word-driven language—music has been used to create a common mood, bringing people together during important social events, from tribal meetings to funerals and modern military parades; it is a universal means of communication. Music education can contribute to development of the human personality, be used as therapy in difficult life situations, and be a means of communication and mutual understanding between different cultures in problem-solving processes.

Another example of a convergence language is one that will support understanding, reasoning, and decision analysis with respect to *unstructured data, patterns, and methods*. Such languages are in development and will allow generalizations across apparently unrelated fields, novel solutions, and new mathematical concepts.

Unifying physical, chemical, and biological concepts would lead to a convergent scientific language for those scientific domains.

Multidomain benchmarking is a form of higher-level language relevant to both knowledge and technology areas. It can be used in both creative and divergent phases of convergence. It may help to identify where to focus the efforts, steer the interest to broader goals, spotlight the key areas for creativity and innovation, and better communicate across fields.

An example of a process to establish a convergent language is *using shared databases* to connect computer simulations and evaluation methods for the respective convergence platforms such as NBIC or Earth-scale. This would facilitate interactions and broad principles of optimization.

An approach to establishing a convergence platform and its suitable convergence language is to identify the *knowledge and technology integrators* describing the essential features of the platform. A higher level of generality of a convergence platform and its language are reached when the respective integrators are applicable for larger domains and with faster information exchanges. Three successive levels of convergence have been reached, by advancing nanotechnology in 2000 (NNI convergence principles in societal system in 2000), foundational emerging technologies in 2002 (NBIC 2003), and convergence principles in societal system in CKTS (2013).

Vision-inspired basic research and grand challenges

The first step in "thinking outside the box" is to recognize that the box exists. Indeed, science and engineering are collections of boxes, and multidisciplinary work is one way to escape some of them. But there also exist more general conceptual boxes that may be more difficult to perceive and thus to escape.

One of the most influential conceptual frameworks for thinking about the goals of research was proposed by Stokes (1997), who advocated research in what he called Pasteur's quadrant. This is defined as research motivated in such a way that both of the following questions are answered in the affirmative: "Are considerations of the practical utility of the results crucial?" and "Is the research a quest for fundamental understanding?" Visionary research may also fit both of these criteria, but adds two others: "Is the research leading to emerging uses beyond known applications?" and "Is the work transformative in the sense that entirely new ideas are being explored and invented?"

The CKTS methods may be used to set up the connection between long-term science and technology visions and basic research activities. As shown in Fig. 9, this proposed “Vision-Inspired Basic Research” domain will expand the existing four domains of the Stokes diagram to a new quadrangle dedicated to basic research for new emerging applications inspired by a vision (“new use”) beyond the Pasteur quadrangle that has been defined for predetermined applications (“known use”). The work done in the Vision-inspired Basic Research quadrangle is complementary to that in the Pasteur quadrangle.

Different basic research approaches are needed as a function of the phase in the knowledge and technology convergence–divergence process (Fig. 7): the Bohr approach corresponds to the Creative Phase (A), the Pasteur approach mostly to the Integration/fusion Phase (B) when the application is known, and Vision-inspired Basic Research mostly to the Divergent Phase (C and D). Using forecasting, early signs of change, science and economy based scenario setting, and other approaches, it is possible to establish a credible vision for what is desired in the longer term for a knowledge and technology field. For example, NNI has been developed by formulating a twenty year vision (2000–2020) followed by a longer view fostering knowledge and technology convergence. The NNI vision has had specific scientific and engineering targets established for 2001–2010 (Roco and Williams 1999) and with a successive group of scientific and engineering targets for 2011–2020 (Roco et al. 2011). The 2020 targets include:

1. Theory, modeling, and simulation: 1,000 times faster in 2020 as compared to 2010, essential in nanoscale system and engineering design.
2. “Direct” measurements of nanoscale structures—6,000 times brighter, accelerate R&D & use.
3. A shift from “passive” to “active” nanostructures and nanosystems.
4. Semi-autonomous nanosystems: some self powered, self repairing, dynamic.
5. Penetration of nanotechnology in industry (toward mass use; catalysts, electronics; innovation) by means of platforms, consortia.
6. Nanotechnology environmental, health and safety management: more predictive, serviced by a multidomain database and informatics, integrated with nanobiology and environmental science.
7. Personalized nanomedicine, from monitoring to treatment.
8. Photonics, electronics, magnetics—new capabilities, integrated
9. Energy photosynthesis and efficient storage, rendering solar energy highly economic in competition with fossil fuels.
10. Enabling and integrating with new areas, notably biotechnology, information technology, and new cognitive technologies, as well as breakthrough technology in addressing sustainable society.

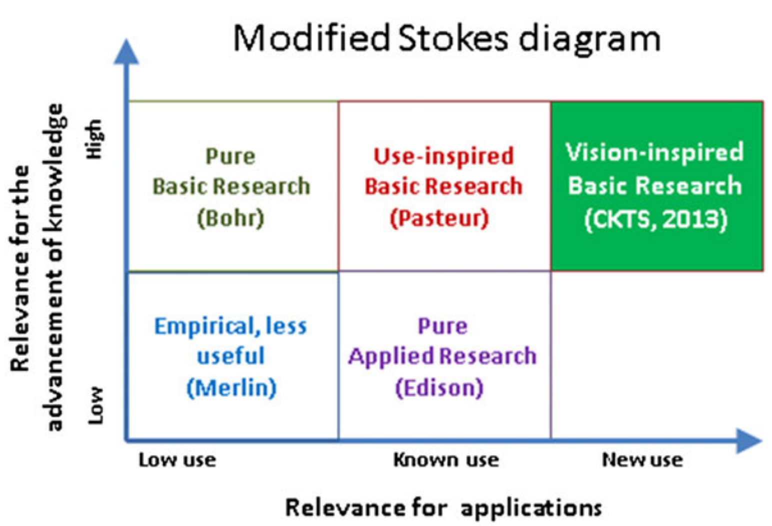

Fig. 9 Schematic for the proposed “Vision-inspired Basic Research” domain in the modified Stokes (1997) diagram. Three *basic research approaches* (Pure, Use-inspired, and Vision-inspired) are suggested to be implemented as a function of the respective phase in the knowledge and technology convergence–divergence process: creative phase, integration/fusion phase, and divergence phase, respectively (see Fig. 7)

11. Earlier educational preparation for nanotechnology workers—system integration.
12. Governance of nanotechnology for societal benefit via institutionalization.

The National Nanotechnology Initiative has been a high priority for the past three U.S. administrations, and it has developed to the point where its long-term view can continue driven by the nanoscale science and engineering community alone. On January 21, 2000, President Clinton gave a major speech at Caltech about the need to increase and refocus federal funding for scientific research and technology development, with nanotechnology for the first time taking a preeminent place (Sadava and Oh 2000). On December 3, 2003, President Bush signed the twenty-first Century Nanotechnology Research and Development Act, and the Obama administration has continued to support this crucial emerging field. NNI preparation took place in the period 1997–2000, with visioning and international benchmarking, and formal strategic plans were published in 2004, 2007, and 2011. Now, nanotechnology can play a leading role in convergence of knowledge and technology for the benefit of society.

Vision-inspired research is a way to advance long-term convergence through forecasting, scenario setting and other methods, optimize convergence–divergence processes in time, and create new solutions.

Timeline

Because convergence is a process operating on a vast scale and along many dimensions and time scales, as it is achieved, its own focus and characteristics will continue to evolve. We can identify three successive and overlapping phases in the convergence of science, technology, and society, as described in Table 1.

Building on previous NBIC studies, the CKTS report seeks to provide a vision for the future of societal convergence and to define transformational actions for key stakeholders. This includes understanding convergence mechanisms and methods to improve the outcomes in various human activity areas on this basis, defining the roles of national science and technology strategies, and open governance approaches. The study's key findings on future trends, methods for convergence, and overarching opportunities for transformative actions are presented in the following sections.

Table 1 Three phases of CKTS convergence

Time frame	Phase	Characteristics
2001–2010	Reactive convergence	Coincidental, based on ad hoc collaborations of partners or individual fields for a predetermined goal
2011–2020	Proactive convergence	More principled and inclusive, approaching convergence through more explicit decision analysis; the immediate future of CKTS
After 2020	Systemic convergence	Holistic, with higher-level (multidomain) purpose, with input from convergence/governance organizations

Emerging paradigms of human benefit

Convergence of knowledge, technology, and society can benefit humanity in many significant ways. In a sense, convergence can be viewed as the ultimate grand challenge, which if successfully achieved, can pave the way to achieve the numerous other grand challenges for society. This is because convergence, as defined in this study, provides approaches for added value and synergistic benefits for human endeavors to: (1) improve wellness and human development, (2) increase productivity and promote economic development, (3) achieve societal sustainability, (4) empower individuals and communities, (5) expand human knowledge and education, and (6) achieve an innovative and equitable society (details are discussed in the full CKTS study, www.wtec.org/NBIC2-report).

Improving human development is a main societal goal, not merely combatting disease but increasing physical well-being, enhancing intellectual capacity, and extending the healthy lifespan. All forms of scientific and technological progress will depend upon the ability of human beings to have the intelligence, wisdom, and health to invest energy into new projects and make carefully considered decisions about convergence and developments that fundamentally impact their lives. It is realistic to believe that physical and cognitive potential can indeed be increased at the individual and collective levels to a significant extent, and one key facilitator will be a holistic approach for healthcare, achieving a range of goals, such as:

- Improved methods will detect cancer and chronic diseases earlier and identify the appropriate treatment for the particular condition and patient, with reduced side effects.
- Improved collection, analysis, and delivery of data will monitor general health, as well as a myriad of specific conditions, toward wellness and prevention of disease.
- Given more effective ways to halt the progress of a disease, the emphasis will shift to repairing damage and restoring healthy functioning, including tissue regeneration and advanced prosthetics.
- Radically improved understanding of the complex human immune system, including swift and efficient analysis of biomarkers in individual patients, will harness the immune system as a constant monitor of health and disease, and enhance its curative powers.
- Reduction in the time needed to detect and treat the emergence of highly infectious diseases at the global level will occur, along with design and development of cost-effective medical responses to the threats, repurposing of drugs, the tailoring of drug and vaccine use to the individual, and seeking innovative cures for currently untreatable conditions.

Productivity and economic development require improved human capabilities, decision processes, and infrastructure, which at this point in history only convergence can provide. Without progress in these areas, it will be difficult to create new types of useful, meaningful, and well-paying jobs, and thus without convergence the economic condition of the population is likely to worsen. The convergence–divergence process generally implies an increase in diversity, not in uniformity, within a set of rational overarching principles. Thus, development of a global economy can be compatible with local autonomy; for example, the growth of largely self-sufficient urban communities can rely heavily upon renewable resources such as solar energy and conducting much manufacturing locally, even as information is shared worldwide. Transformation of organizations and businesses would guide convergence by higher-purpose criteria such as improvement of economic productivity, human potential, and life security, including sustainable development. Despite the popular perception that we have reached the state of post-industrial society, advancing manufacturing through converging NBIC technologies will be essential to the progress of the economy and quality of life initiatives. Three areas show promise:

- Distributed and connected manufacturing—enabled by process flexibility, modularity, in-process metrology, predictive sciences and technologies, and human–machine interaction—could greatly improve the ease and efficiency of making products available, customizing designs (from performance-specific wearable sensors to replacement body parts for surgery or individual art works), and scalability from small- to large-batch production.
- "Manufacturing process DNA" is a metaphor suggesting that the design of manufacturing processes could be structured in a manner like the genetic code, allowing the rapid switching in and out of production steps and system components, and allowing precise control over product parameters with very little effort.
- Integration of the social and physical sciences could optimize design and production methods, not merely relying upon the functioning of market mechanisms to determine what products are produced, but also incorporating sustainability and general human welfare into decision-making at all stages of manufacturing toward knowledge-, capital-, and skill-intensive innovation cycles.

Societal sustainability is an absolutely crucial goal for humanity, because current energy consumption, water usage patterns, agricultural practices, manufacturing practices, climate stability, clean environment, communities, and other components of modern life and economies are not currently sustainable within the Earth's boundaries. In the absence of sustainability in any of these areas, humanity faces not only a degraded natural environment but also severe threats to world peace, as economic crises bring undemocratic forces to power in nations suffering from one or more unsustainable conditions. Conflict would further degrade the world's ability to deal with these problems; thus, it is essential to bind the people of the world together, and knowledge and technology convergence will play a key role in that global unification:

- Given that the world is an integrated natural, human, and technological system, it will be impossible to achieve sustainability without a global data and information infrastructure, measuring in real time a wide range of sustainability indicators, from air and water quality to the migrations and health of key species.
- The convergence of intelligent software, ubiquitous sensors, and mobile devices can substantially increase the efficiency of megacities with respect to transportation, energy production and consumption, and manufacturing.
- The convergence of NBIC2 technologies can support fresh approaches to reducing fossil fuel use, sequestering carbon from the atmosphere, and the development of new sustainable technologies such as water-related systems ranging from small-scale purification to large-scale desalinization.
- Earth is a single ecosystem, upon which a unified economic system of production, distribution, and resource use is consolidating, so future activities need to be focused on the sustainability of global society by considering demographics, societal needs, and governance, and enabling CKTS solutions for mitigation and life security.

Empowered individuals and communities will result from systematic convergence, giving hundreds of millions of people the ability to explore new pathways to improving the quality of their lives. NBIC2 technologies can support the development of tools for lifelong-learning, participation in public policy decision-making, and peer production of information resources, software, and other goods and services. It is important, though, that these tools be designed with respect for human cognitive capabilities and limitations:

- A new form of large-scale organization may evolve, the Cognitive Society, bestowing intelligence on a unified world, based on a new cognitive model of the social mind and empirical research to understand our evolving mentality, cognitive computing, cognition and communication in team science, and a cognitive science of science.
- By analogy with the multidisciplinary convergence by which cognitive science came into being, a new field will emerge, Cultural Science, including the most rigorous parts of cultural anthropology, sociology, political science, and social psychology.
- Flexible anticipation of change through convergence will transform education into an engine of creativity and innovation, both person-centered and based in new forms of supportive infrastructure: physical, informational, and institutional (NRC 2012).
- Citizen science and citizen engineering will achieve serious involvement of non-specialists in research and development, enlisting the energies of large numbers of volunteers and creating a well-informed citizenry that can participate positively in the governance of science and engineering.

Human knowledge will not only grow but also consolidate, undergoing evolution and even possibly revolution, with enormous implications for education. We are already witnessing converging disciplines, design principles, and transformative tools. Transdisciplinary approaches are linking together disparate knowledge bases to produce new knowledge. Convergence can achieve even the consilience of the humanities with the natural and social sciences. Innovation occurs best in the modern world by integration into a single system of science, engineering, and society, through a process with two fundamental phases: (1) the novel, creative assembling of previous knowledge and technology components into a new system, and (2) diffusion of innovations from the original application to others that may be far removed in materials, goals, and design traditions. New communication and design platforms—hardware, software, cognitions, and cultures—can accelerate the spirals of creativity and innovation:

- Powerful scientific and engineering computer simulation and material processing tools have been developed over the past few decades in each of the four NBIC disciplines, and further progress needs a new class of tools to address problems at the interfaces of these disciplines and many others.
- Exciting new educational initiatives are bringing low-cost, high-quality educational resources to a global audience via open online courses, and a similarly ambitious initiative is needed to develop new approaches to education that are specifically

designed for the era of convergence, which will require new types of computer simulation tools, new conceptual frameworks, and new approaches to education.
- Scalable universal databases are needed for convergence, providing publications as well as the data on which they were based, which requires a major transformation of current scientific publishing practice that poses substantial economic, organizational, and technical challenges.

Achieving an innovative and equitable society faces challenges that include developing the multidisciplinary knowledge foundation, strengthening the innovation chain from priority-setting and discovery to societal use, addressing broader societal implications including risk management, and creating the tools, people, and organizations to responsibly develop and equitably distribute the benefits of the new technologies. The governance of knowledge and technology currently involves very complex economic, legal, and management systems, and it seems unlikely that the institutions developed decades ago are perfectly designed for today's rapidly changing circumstances. There are clear signs that problems are endemic in the current system, as illustrated by the public controversies about climate change, healthcare, and national defense investments—all of which have substantial science and engineering components—plus difficult debates about growing income inequality that brings into question the very concept of human progress:

- The transformative power of convergence must be used for human benefit, which means more than merely having good intentions, but also possessing the fact-based wisdom to avoid negative unintended consequences.
- The overarching challenge is to support rational governance of visionary ideas that benefit from their positive possibilities, without being deceived by fads or abandoning those practices of the past that still function well.
- Fundamental reconceptualization of the social sciences may be needed, if they are to play the crucial new roles assessing the functionality of existing societal institutions, and developing better alternatives.
- The emphasis on converging technologies, and on basic research in strategic application areas, should not detract from the importance of pure research to gain knowledge about the universe in which we dwell.

The future converging society

The envisioned benefits of convergence can be brought to life through a coordinated CKTS Initiative based on (1) the *convergence–divergence process* in science, technology, and applications; (2) a *holistic deductive approach* based on the bottom-up, top-down, and interdisciplinary horizontal interconnected knowledge, technology, and societal system; (3) establishment of *higher-level, multi-domain languages* in planning and management; (4) *vision-inspired basic research and grand challenges* enabled by convergence, and (5) *opportunities to channel public and private efforts* that are now contributing only chaotically, into a proactive, systematic approach.

Opportunities for the CKTS Initiative are in the following areas:

- *National Convergence Centers and Networks* would be established in research and education institutions to address the formation and dissemination of CKTS, in such fields as education, biomedical technologies, and new combinations of theory and methods.
- *Converging knowledge, technology, and society research platforms*, created in areas of national interest, could improve R&D focus on priority topics: manufactured products, environmental sensors, Cognitive Society, mapping brain activity (Alivisatos et al. 2012), cognitive computing, sustainable urban communities, and the sustainable water, energy, and materials nexus.
- *Societal convergence data, systemics, and informatics research* could develop new methodologies and paradigms to achieve integration across topics, scales, and time in parallel with revision of rules and regulations to advance individual and group creativity and innovation in convergent processes in the economy as a critical condition for competitiveness.
- *Transformation of organizations and businesses* is an essential precondition for convergence, with emphasis on monitoring increasing human potential, improving decision analysis, and supporting citizen science.

- *Increasing human potential* will require human capacity-centered convergence, including human–machine interaction, computer-supported collaboration, complementary robotics, brain-to-brain communication, biomedicine-centered convergence, cognitive computing, and brain activity mapping.
- *Application of converging revolutionary technologies to individualized services* could be invaluable, where individual services include providing and receiving personalized education, medicine, production, and general services (web-based or not), and creating personalized smart environmental and cultural surroundings.
- Fostering an ecosystem for increased creativity, invention, and innovation.
- *Government coordination and support* will be needed in the highest-priorities areas of physical and mental wellness, fostering discovery, invention and innovation processes, sustainable Earth systems, and the ethical, legal, and public participation aspects of societal convergence.
- A CKTS *Federal Convergence Office* would have the responsibility to identify, facilitate, and coordinate opportunities of convergence in the Federal Government, and between Federal and local governments, the private sector, and civic organizations, as well as taking the lead on visionary planning, promoting integration of the components, and revising rules and regulations to advance individual and group creativity.

Integration of the main CKTS Initiative components would benefit from the results of basic NBIC research emerging from the National Nanotechnology Initiative, the Networking and Information Technology Research and Development Program, the Global Climate Change Initiative, the Global Earth Observation System of Systems, and similar existing efforts. The CKTS Initiative would support them in return.

CKTS can manifest at all levels in knowledge, technology, and society, and typically is an outcome of bottom-up input and multidomain reasoning. Convergence is at the forefront of scientific discovery and technology development, promising to become a foundational and integrating knowledge and transforming field, as information technology and nanotechnology already have done. CKTS is a general purpose approach as pervasive in future knowledge society as electricity has been a general purpose technology in industrial society changing the connections, the nodes and the system itself. The CKTS Initiative has the potential to impact every sector of society, from improving education to enhancing wellness, from achieving environmental sustainability to promoting innovative economic development.

There is an urgent need to nationally and internationally take advantage of this opportunity and to take concrete steps to implement convergence in a timely way to deal most effectively with the serious problems facing humanity today. The prospect of new knowledge, ideas, materials, and technologies that will emerge from convergent activities is profoundly exciting. Their impact on everyday lives is expected to be extraordinarily beneficial in terms of the way we and our descendants learn, work, thrive, and age. Societal convergence has the potential to greatly and efficiently improve human capabilities, economic competitiveness, and life security.

Acknowledgments The National Science Foundation (NSF)/World Technology Evaluation Center (WTEC) international study was completed with panel members and expert contributions from U.S., and abroad (www.wtec.org/NBIC2-report). The opinions, findings, and conclusions expressed here are those of the authors and do not necessarily reflect the views of the National Science Foundation or National Science and Technology Council/Nanoscale Science, Engineering and Technology committee.

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