EXECUTIVE SUMMARY[1]

Convergence of Knowledge, Technology, and Society:
Beyond Convergence of Nano-Bio-Info-Cognitive Technologies

A general process to improve creativity, innovation, and outcomes

Convergence as a Fundamental Principle of Progress

Convergence of knowledge and technology for the benefit of society (CKTS) is the core opportunity for progress in the 21st century. It is defined in this study as the escalating and transformative interaction among seemingly distinct scientific 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 into emerging areas to meet shared goals. Convergence is as essential to our future knowledge society as engines were to the industrial revolution. CKTS allows society to answer questions and resolve problems that isolated capabilities cannot, as well as to create *new* competencies, technologies, and knowledge on this basis. This concept is centered on the principles presented in this report: of interdependence in nature and society with application to the essential platforms of human activity system; the enhancement of creativity and innovation within knowledge and technology through convergence–divergence (spin-off) evolutionary processes; a holistic system deduction approach being applied in decision analysis; the value of higher-level cross-domain languages to generate new solutions and support transfer of new knowledge; and the value of vision-inspired basic research endeavors.

Based on these principles, this report suggests solutions for key societal challenges in the next decade, including: (a) 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 platforms; (b) increasing creativity, innovation, and economic productivity through convergence, including developing a universal domain of information exchange and interaction; and (c) improving lifelong wellness and human potential, including advancing a cognitive society, achieving individualized and integrated healthcare and education, and securing a sustainable quality of life for all. The report also suggests developing a knowledge-based platform for decision-making to implement the most effective convergence methods to valuate and assemble individual theories and technologies and find integrated solutions for societal challenges.

This Study of Convergence

CKTS builds on previous stages of convergence, beginning with the integration of disciplines at the nanoscale, followed by convergence of nanotechnology, biotechnology, information, and cognitive (NBIC) technologies. This study addressed the third level of convergence, that between emerging NBIC technologies and the essential platforms of human activity (technology, human-scale, Earth-scale, and societal-scale platforms), and sought to identify the general convergence processes that characterize all three stages. Longer-term views of convergence, looking up to forty years ahead, that were outlined in previous NBIC studies provide reference points for this study. The main goals of this study were (1) to understand how convergence works and how it can be improved and implemented, (2) to chart trends for the next decade, and (3) to identify opportunities for key transformative actions to improve societal outcomes through convergence.

This study sought the input of leading experts in the United States and other nations, from academia, industry, government, and NGOs, in five brainstorming meetings held in the United

[1] *Note*: The Executive Summary represents the findings of the study group as a whole, whereas case studies in the report represent individual perspectives.

States, Latin America, Europe, and Asia between October 2011 and November 2012, with a final U.S. presentation in December 2013. The study was supported 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.[2]

Overview of Convergence and Principal Study Findings

Convergence has been increasing by stages over the past several decades. In the first stage, concerted efforts to research and develop nanotechnology called attention to the convergence of many formerly separate scientific and engineering disciplines (biology, chemistry, condensed matter physics, materials science, electrical engineering, medicine, and others) when applied to the material world, based on growing understanding of atomic and nanoscale structures. "NBIC" convergence was the second stage, connecting emerging technologies based on their shared elemental components such as atoms, DNA, bits, and synapses (all with shared abstractions from information science), integrated across scales. CKTS is the next stage in convergence; it expands emerging technologies at their interfaces and frontiers, and intimately introduces them into the human-scale, Earth-scale, and societal-scale platforms. It brings together the relevant areas of human, machine, societal, and natural resource capabilities to attempt to answer questions and resolve problems that isolated capabilities cannot, as well as to create and disseminate new competencies, technologies, industries, products, and solutions for human well-being. This report provides a status survey of CKTS, the hierarchical structure of the evolutionary human activity system, methods to improve and expedite knowledge and technology convergence within this structure, a vision for the next decade, and implementation opportunities.

The experts around the world who were consulted in this study recognize CKTS as a timely engine of change that has the potential to provide far-reaching solutions to achieve improved economic productivity, new industries (new jobs) and products (such as smart phones), increase human physical and cognitive potential, and secure a sustainable quality of life. The study identified barriers to progress; this report proposes a framework, methods, and possible actions to overcome them. The proposed convergence methods have wide applications, for example, to improve the "innovation chain", evaluate commercial network performance, support planning for emerging technologies, and study cognitive processes. To effectively take advantage of this potential requires immediate action, particularly because of the current environment of limited resources. Principal opportunities for immediate action are (1) creation of a global convergence network to build and connect the convergence efforts of various regions, (2) creation of a U.S. CKTS initiative coordinated by the Federal Government, (3) development of the EU multi-annual 2014–2020 framework program of research and innovation activities called "Horizon 2020," and (4) enactment of a South Korean program for a "Convergence Research Policy Development Center."

Organization of the Report

The four essential and interdependent platforms for convergence are defined in Chapters 1–4: (1) *"NBIC" foundational tools*, (2) *human-scale activities*, (3) *Earth-scale environmental systems*, and (4) convergence methods for *societal-scale activities*. Chapters 5–10 define and illustrate the main implications of and proposed responses to converging sciences and technologies in terms of (5) *human health and physical potential*, (6) *cognition and communication*, (7) *productivity and societal outcomes*, (8) *education and physical infrastructure*, (9) *societal sustainability*, and (10) *innovative and responsible governance*. The Overview and Recommendations section, which follows the Executive Summary, provides details both on the intellectual framework for convergence activities and on the kinds of Federally led actions that the panel believes will take best advantage of the inevitable progression of convergence in science and technology. As a whole,

[2] The full list of sponsors is given in Appendix A.

the report aims to show how concerted efforts that acknowledge and assist the CKTS processes as a fundamental principle of progress can achieve major goals that support broad societal benefits.

How Convergence Works

Convergence is actually part of a dynamic and cyclical *convergence–divergence process* that originates organically from brain functions and other domains of the global human activity system. This process can provide a structure and specific improvement methods for the creative-innovation-production chain. The convergence phase consists of analysis, making creative connections among disparate ideas, and integration. The divergence phase consists of taking these new convergences and applying them to conceptual formation of new systems; application of innovation to new areas; new discoveries based on these processes; and multidimensional new outcomes in competencies, technologies, and products. This convergence–divergence process is reflected in the coherent chain of ideas from the ancient to modern eras, in the evolution over time of knowledge and technology, and in the development of human organizations and industries. The model proposed in this report suggests that creativity and innovation rates are increasing with respect to the convergence domains of various activities and the speed of movement between the convergence and divergence cycles. To conceptualize the influence of convergence on creativity and innovation, this study (see Chapter 4) has defined an index of innovation rate (I) that is a function of the size (S) of the convergence domain ($I \sim S^2$) and time scale (T) of the convergence–divergence cycle ($I \sim 1/T^3$).

There are five general approaches that are at the core of the CKTS concept (Chapter 4):

(a) *Added-value decision-making and knowledge transformation* based on the convergence–divergence (spin-off) evolutionary processes in science, technology, and applications.

(b) *A holistic systematic deduction approach*, beginning from the global evolutionary system of human activity and considering hierarchical interconnections among knowledge, technologies, and societal systems.

(c) *Establishment of higher-level languages* (multidomain, convergent) using knowledge, technology, and cultural integrators—such as unifying theories, benchmarking, multidisciplinary nanotechnology, informatics, knowledge mapping, similar fractal patterns, and music—that can allow construction of shared terminology and concepts that are common and essential to multiple domains.

(d) *Focusing efforts on vision-inspired basic research and grand challenges* enabled by convergence. To efficiently and responsibly achieve the benefits of research in emerging areas, convergence processes will be used to identify the vision and then its corresponding basic research strategic areas, changing priorities periodically as interdependencies change. The proposed "Vision-Inspired Basic Research" quadrangle will extend the Stokes diagram beyond the Pasteur quadrangle.[3]

(e) *Proactively encouraging coherent public and private efforts* that currently contribute to the unguided convergence of knowledge and technology to use a systematic approach to convergence that amplifies the most beneficial endeavors for society to consider undertaking.

Examples of coincidental, rapidly evolving, and valuable convergences in knowledge, technology, and society can be seen in NBIC emerging technologies; universal databases; cognition and communication developments; cloud computing; human–robotics systems; mind-cyber-physical systems; platforms for unmanned vehicles; the space program; the research program on fundamental particles (Higgs et al.); the birth of entirely new disciplines such as synthetic biology, quantum communication, nanophotonics, and nanofluidics; and the integration of biomedicine with physics and engineering that is already effecting transformations in human healthcare systems. One

[3] Stokes, D.E. 1997. *Pasteur's quadrant: Basic science and technological innovation*. Washington, DC: Brookings Institution Press.

specific illustration of the convergence–divergence process is the cell phone platform, which 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 a decade ago. This is now diverging into thousands of applications scarcely imagined ten years ago that have profound "cascade" implications on areas as diverse as national security, education, and cognitive science.

The main barriers to overcome for such bold technologies are insufficient synergistic methodologies and interconnections between NBIC technologies and the human-scale, Earth-scale, and societal-scale activity platforms. The methods and domains of convergence discussed in the report provide a framework for solutions to overcome such barriers.

Emerging Paradigms of Convergence

This report identifies a number of convergence trends with goals that are poised for radical paradigm transformations in human endeavors:

- *Support the emerging and converging technologies* by bottom–up discovery-driven and top–down vision-driven programs. A grand challenge is to accelerate progress in the foundational NBIC technologies and *create new industries and jobs at their frontiers and interfaces* (Chapters 1, 7, and 10).
- *Expand human physical and cognitive potential* through convergence of NBIC technologies with the human-scale platform (see Chapters 1, 2, 4–6, and 8). A grand challenge is to achieve coordinated improvements *in lifelong wellness, cognitive technologies, and human development.*
- *Achieve higher societal productivity and economic efficiency* through convergence of human activity platforms focused on societal governance (see Chapters 1, 4, and 7–10). Improving economic productivity is envisioned through facilitating the circuit of creativity and innovation and a vision-driven expansion into new knowledge and technology fields. Challenges are in developing resource-efficient production systems; establishing information technology with capability far beyond silicon integrated circuits; creating a universal domain of information exchange, including a database for all disciplines and industry sectors; and developing a flexible and efficient transportation system, complementary human–robotics systems, brain–computer communication (e.g., for neuromorphic engineering and prosthetics), cognitive computing, and mapping of brain activity and brain–behavior interdependencies. A grand challenge is to use converging technologies in manufacturing methodologies.
- *Secure a sustainable quality of life for all* through convergence of the Earth-scale and human-scale platforms (see Chapters 2–6 and 9–10). This includes providing equitable access to knowledge, natural resources, food, healthcare, and safety in the face of increasing population, bounded Earth resources, higher carbon and nitrogen levels in the atmosphere, and climate change (Chapter 3). A grand challenge is to achieve societal sustainability, including efficient solutions to interconnected water, energy, and materials needs, and sustainable urban communities (Chapter 9).
- *Empower individuals and groups* through integrated education, use of the spiral circuit of creativity and innovation within larger domains—including multidomain design, expansion of human knowledge and cognitive capabilities—and added-value decision analysis, made possible by convergence (Chapters 4, 6–8). A grand challenge is to build a CKTS-based individualized lifelong education system.
- Advance societal progress through integration of convergence methodologies, ethical aspects, citizen participation, and management for responsible development into *a new governance model* (Chapter 10). A grand challenge is to change the framework and improve the efficiency of the methods of societal governance by applying CKTS principles.

Action Opportunities

The study panel sees an international opportunity to develop and apply CKTS in ways that will produce synergies leading to technological, economic, environmental, and societal benefits. An international network to collaboratively advance the methods and applications of convergence is proposed. The panel also proposes a proactive, integrative program in the United States to focus disparate R&D energies into a coherent activity that distills the best of our knowledge and abilities to the greater good of the national and global human communities. Concerted efforts would be required to develop a CKTS initiative that could take advantage of convergence as a fundamental opportunity for progress. This initiative could cooperate with and maintain U.S. competitiveness with parallel efforts already underway in other economies, including in the European Union, Korea, Japan, Brazil, and China.

The proposed U.S. CKTS initiative would incorporate convergence innovations in five modes of support:

- **Centers** for establishing new, creative, and innovative socioeconomic models based on convergence, including methods, education, research, standards, informatics, and biomedicine
- **Technology platforms** for addressing societal grand challenges, including distributed and connected NBIC manufacturing and global virtual factories, use of converging cognitive technologies in society, brain-mapping activities, and cognitive computing
- **Programs** for creating a shared universal convergence database and methods to evaluate convergence, risk governance, and integration of science into society
- **Organizations** to monitor and accelerate increases in human potential, societal sustainability, and improved decision analysis using the convergence–divergence cycle
- **Government coordination** (a "Federal Convergence Office") for supporting convergence in science, technology, investment planning and policies, decision-making, wellness and long-term human development activities, supporting our aging society, and sustaining Earth systems, as well as advancing ethical, legal, and public participation aspects of convergence

The primary initiative opportunities for government involvement are in the application of the five CKTS approaches (convergence–divergence, system deduction applied to decision-making, higher-level languages, vision-inspired basic research and grand challenges, and proactive channeling of public–private R&D efforts toward CKTS) in the emerging paradigms of convergence identified above. Promising high-impact areas for the next decade are in improving productivity using converging technologies in personalized, distributed, and connected manufacturing and services; promoting a cognitive society to increase human potential; improving quality of life through wellness initiatives, support for a sustainable society, and biology- and healthcare-centered convergence; developing integrated education devoted to promoting creativity and innovation; and advancing coordinated and responsible management of convergence through Federal convergence offices dedicated to critical areas of science, technology, and investment policy and planning. Detailed analysis in the areas of interest is needed for constructive and beneficial application of CKTS.

Several areas with immediate societal benefits are opportunities for pilot projects in the CKTS framework: "converging revolutionary technologies for individualized services (CORTIS)" (where individualized services include providing and receiving personalized education, medicine, cultural, productive, and general services); a distributed cyber nanobiomanufacturing network; R&D for emerging logic devices and new information carriers for nanoelectronics; creating a universal domain of information exchange between converging areas; cognitive computing; physical and mathematical modeling of the brain from the nanoscale (synapse-level); biomedicine-physical-engineering convergence; convergence–divergence decision-making in R&D planning; a CKTS summary document for policymakers on innovation policy; and a "Federal Convergence of

Knowledge and Technology (CONEKT) Office" to identify the best approaches and areas of implementation.

CKTS is a foundational transformational approach to connect, synergize, and valuate existing and emerging technologies in much the same way as Higgs-Boson has become an essential standard model particle that provides connections and interactions (mass, forces) with previously discovered fundamental physics particles. CKTS promises to become a key science and technology field of the same level of importance as the key technologies it promises to connect and synergize.

With the increasingly complex interactions in our knowledge society, and limited resources, a systematic CKTS approach would most efficiently bring about the kinds of beneficial societal transformations explored in this report in the same way as selective "small changes" have been shown to yield major changes in large complex systems.

Vision for Societal Convergence

The concept of "societal convergence" in this report encompasses the involvement of society at all stages of supporting the progressive convergence of scientific knowledge, its technological applications, and democratic principles of equal opportunities for progress. This concept provides a rich resource that can lead to revolutionary advances in sustainable global development, economic productivity, human potential, and national security. Over the next decade, proactive and systematic convergence can fundamentally improve the quality of our daily lives, transforming the ways we and our descendants learn, work, thrive, and age, and protecting the many integrated natural and social systems that support our human activities.