CHAPTER 4

METHODS TO IMPROVE AND EXPEDITE CONVERGENCE

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DEFINING CONVERGENCE

Convergence includes all relevant areas of human and machine capability that enable each other to allow society to answer questions and to resolve problems that isolated capabilities cannot, as well as to create new competencies, knowledge, technologies, and products on that basis. Convergence of knowledge, technology, and society (CKTS) also includes societal dimensions (such as socio-ethical, institutional, and governance aspects), and has been called in this study “beyond NBIC” (nanotechnology, biotechnology, information technology, and cognitive sciences) or “NBIC2.” General CKTS convergence platforms are the foundational and emerging (NBIC) tools, human-scale platform, Earth-scale platform, and societal-scale platform (Figure 4.1a).

The convergence process in this report is defined as the escalating and transformative interaction of seemingly different disciplines, technologies, and communities to (a) achieve mutual compatibility, synergism, and integration, and (b) create added value (generate new things, with faster outcomes), to meet shared goals. The convergence process is evolutionary and non-uniform. It requires a preliminary degree of development in each domain; it begins with achieving reciprocal compatibility such as in communication and knowledge exchange, and it leads to changes in the system in terms of its assembly, functions, and outcomes. The initial interaction between fields of study may be either coincidental or deliberate. The convergence process typically is followed by a process of divergence (branching and growing out) between newly created knowledge and its technological components. This convergence–divergence cycle is a typical, coherent process in science and technology (Roco 2002) that ultimately leads to novel systems with unanticipated applications and benefits (Figure 4.1b).

The human activity system evolves during the convergence process. In order to better understand and characterize the system, we have defined four essential general convergence platforms of human activity that are driven by societal values and needs and that ultimately lead to progress in human development (Figure 4.1a). Creativity and innovation are enhanced by the circuit of information and ideas between various platforms of the system. As exchanges happen faster and between larger domains within the platforms, the foundation for creativity and innovation broadens.

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1 For the institutional affiliations of chapter authors and contributors, please see Appendix B, List of Participants and Contributors.
a. The four general convergence platforms of the evolutionary human activity system: foundational tools, human-scale, Earth-scale, and societal-scale. It includes the major human activities involved in and impacted by creativity/innovation inputs into the system. This system evolves from A to D during the convergence–divergence process outlined in (b).

b. Schematic of the convergence (A, B)–divergence (C, D) process, initially formulated for megatrends in science and engineering (S&E) (based on Roco 2002). This concept is extended here to other knowledge, technology, and societal domains. It includes (A) a creative phase dominated by synergism between multidisciplinary components, (B) integration/fusion into a new system, (C) an innovation phase leading to new competencies and products, and (D) an outcome phase leading to new competencies, technologies, and products.

This study expands the concepts of convergence and divergence megatrends in science and engineering that were applied in 2001 to NBIC convergence (Roco and Bainbridge 2003; Figure 4.2) to include the more general concept of convergence defined above, which is broadly applied to unprecedented, interconnected advancements in knowledge, technology, and social systems. The result of CKTS thus broadly conceived is expected to include numerous new applications with significant added value to society.

Figure 4.1 Human activity system (a) and its typical convergence–divergence evolutionary process (b) (based on Roco 2002; both images courtesy of M. C. Roco).
Figure 4.2 As envisioned in 2001, convergence of foundational and emerging technologies would have the effect of changing the societal fabric towards a new structure that would improve human potential: “The integration and synergy of nanotechnology, biotechnology, information technology, and cognitive science originate from the nanoscale, where the building blocks of matter are established. This picture symbolizes the confluence of technologies that offers the promise of improving human lives in many ways, and the realignment of traditional disciplinary boundaries that will be needed to realize this potential. New and more direct pathways towards human goals are envisioned in working habits, in economic activity, and in the humanities.” (Roco and Bainbridge 2003; figure by R.E. Horn).

There are important and potentially transformative benefits in proactively advancing systemic convergence of knowledge and technology. Such convergence will allow us to better understand socio-economic processes, stimulate creativity in knowledge-generation activities, increase the speed of development and innovation in technology, and create valuable new tools and products in various science and technology domains (Sharp and Langer 2011; Roco 2012). Together these kinds of developments offer new prospects not only for improving economic productivity and human potential but also for understanding and solving the immensely complex problems that the world faces today. As a result, the participants in this study see an urgent need to thoughtfully but deliberately expedite the convergence process. This chapter discusses approaches for systematically promoting compatibility, synergism, and integration in the CKTS processes that have already begun.

4.1 VISION

4.1.1 Changes in the Vision over the Past Decade

Since the first NBIC conference in 2001, convergence has been reported mostly in just two or three domains of NBIC, in citation index papers, funded projects, and multiple-technology organizations motivated by the benefits of convergence. Reinforced by seed projects, use of all four domains has been reported, although somewhat sporadically. However, there has been a growing appreciation in scientific and academic communities worldwide that converging technologies in general, and synergies among “nano, bio, info, and cogno” areas of science, engineering, and technology specifically, are likely to create important advances toward societal gain (Bainbridge and Roco 2006; h+ 2010). Meanwhile, significant progress has been made in most regions of the world toward achieving the twenty major goals of NBIC convergence identified in 2003 (Roco and Bainbridge 2003); these goals are listed in Appendix D.

Several other noteworthy trends in NBIC convergence over the past decade are described below:

- Overall, the R&D focus for converging technologies publications has remained reactive (or “coincidental”) to various opportunities of collaboration, rather than being driven by a holistic, systematic, proactive approach towards promoting convergence. Reactive convergence is
observable over the last ten years mainly in terms of paired collaborative activities between nanotechnology and biotechnology and between information technology and cognitive sciences.

- The pervasive availability and growing sophistication of converging knowledge and technology has been revolutionizing the way science, engineering, commerce, and government are practiced. Colossal changes have taken place in computing, handling of “big data,” materials processing, digital sensing, biomedical advances, robotics, space communication, brain research, and other fields, building upon the NBIC foundational tools. In terms of the changes in commerce and government, for example, witness the growth in webinars and virtual meetings, and in global communications services companies such as Skype (http://beta.skype.com/en/) and Cisco WebEx (http://www.webex.com/). The nanoscale has enabled the devices that have enabled such trends and is also providing opportunities for measurement and control of biologically important processes, thereby opening up opportunities to marry information technologies with biology, medicine, and cognition (Murday et al. 2009).

- There is increasing recognition that investments in innovative technologies must engage society in terms of focus on social sciences, entrepreneurial education (e.g., Roco and Bainbridge 2006; Centers for Nanotechnology in Society 2006), and overall human development (e.g., the UN Millennium Project studies: http://www.millennium-project.org/). Such trends help to facilitate better-informed decisions on benefit/risk management, legislation, and regulation. In parallel, there is a growing belief that the NBIC science and engineering convergence will also enable the evolution of social sciences (which reflect the study of human behavior and cognition) from phenomenological observation toward a much stronger basis in the fundamental laws of chemistry and physics.

- R&D activities have become more participatory and group-oriented in the process of developing NBIC foundational tools. The last decade witnessed appearance on an ad hoc basis of integrated S&T platforms driven by users; these include smart phone platforms, formation of associated communities of interest or affiliation, collective creation of large databases, and “cloud”-based computing that provides distributed and shared access to information and tools. The decade also witnessed the integration of converging technologies into social science—a reflection of the multipolar research world. There is now a self-regulating convergence of communities facilitated by social networks. New data collection tools utilize multiple technologies, create big data, and indirectly create opportunities for integration. In addition, more social scrutiny of emerging technologies has been observed since 2000.

- Converging trends between academia and society have become increasingly geared to industrial and societal needs. In the last decade, with large deficits constraining governmental budgets, partnerships between industry and government have increasingly been touted as mechanisms to support university research (NRC 2012). Further, there has been growing attention paid to fostering mechanisms that will facilitate the transition of university-based science and engineering discovery into functional innovative technology to address societal concerns.

- Convergence concepts have become progressively more focused on sustainable development. For example, the increasing evidence for global climate change (NRC 2009b; NRC 2009c; see also http://globalissues.org) and security and economic concerns over petroleum resources (NRC 2009a) have focused global attention on renewable energy. It is recognized that secure petroleum resources and renewable energy resources require an integrated international effort to foster both a multidisciplinary science approach to create the necessary technological innovations and the necessary societal behavioral transformations.

### 4.1.2 The Vision for the Next Decade

In the next decade proactive, holistic systemic convergence will be cultivated in various domains of knowledge, technology, and society. A science of convergence is likely to emerge. Convergence
4. Methods to Improve and Expedite Convergence

Methods will become ubiquitous in decision analysis and planning processes. Different fields of S&T will increasingly feed into each other and provide new opportunities for synergy, creating a virtual “spiral of innovation” (or a “Lagrangian path of ideas”) within the broader converging knowledge and technology platforms, including synergies between theoretical and applied sciences and social and behavioral sciences. From the science of convergence is expected to emerge better methods of promoting and managing convergence, better insights about which methods are best for which convergence contexts (e.g., academic or manufacturing contexts), and how to collect and evaluate data that could indicate how well convergence methods work in various contexts.

Convergence in the investigation of natural phenomena (analogous to the convergence in the forces of matter) will accelerate, and will underpin the technological effectiveness of society.

Higher-level convergence languages based on new concepts, relationships, and methods are envisioned to be developed to allow integration of components from the language levels for particular topics; that will facilitate integration into and among essential platforms, and in turn that will facilitate innovation (confluence of streams), improved manufacturing (hybrid NBIC methods, mind-cyber-physical systems), and advances in all emerging technologies. For example, the unified theory of physicochemical forces provides a higher-level language than the language for investigating individual mechanical forces, and concepts of converging technologies have a higher degree of generality than concepts for a specific technology such as biotechnology. Using higher-level convergence languages will enhance comprehension of surrounding complex systems and understanding of how knowledge is generated over time and crosses multiple fields using logic models (patterns). Cultural anthropologists will help make this transition. A database and an expert system could be established to select the methods of convergence to accelerate unprecedented discovery and innovation.

Important drivers will be the emerging technologies informed by a holistic view of society. For example, converging knowledge and technology will support personalized medicine (rooted in the integration of medicine, electronics, robotics, bionics, and data handling), leading to an increase in average life expectancy. CKTS will support personalized online education—for formal and informal lifelong learning—that exploits advances in neuroscience, communication, psychology, and understanding of learning.

There will be an increased focus on communities defining their own needs for using CKTS to address major issues affecting them, on an as-needed/as-requested basis, relying on self-regulation (through professional societies, nongovernmental organizations [NGOs], etc.) in a manner that is less paternalistic than that of current systems.

Implementing convergence methods will create a continuing focus on discovery, innovation, and responsible development, as well as on economic benefit. Scientific convergence and technological change are inevitable, and the public is expected to demand more social convergence, such as fusion of foods, music, and fashion, providing new experiences. Convergence will drive innovation in R&D organizations around the world and will become a source of competitive economic advantage in the global economy.

Sustainable development on Earth over the long term will depend on using converging knowledge and technology to develop new observatories and new methods to simulate Earth’s dynamic systems using new sensing capabilities, large data, and so forth.

Changes in governance (structures, decision analysis, and measures to reach decisions and solve conflicts) will be needed to enable societal benefits rooted in CKTS developments such as those noted above. As a result, government organizations and regulations will need to be updated to allow the convergence processes to work better and provide increased benefits to society.
4.2 ADVANCES IN THE LAST DECADE AND CURRENT STATUS

The National Science Foundation (NSF) and U.S. Department of Commerce (DOC) organized the initial NBIC workshop in 2001 (Roco and Bainbridge 2003). Science and engineering professional literature addressing NBIC convergence first appeared after that workshop but has averaged only about five papers per year where all four domains were addressed, as determined by a simple keyword search of the ISI Thompson Web of Science database – nano*+bio*+info*+cognit*. In the same time frame, papers on nanoscale science and engineering continued to experience exponential growth. While the literature addressing convergence of all four NBIC areas has not grown appreciably, there has been significant growth in the number of papers addressing the convergence of two or three of the NBIC areas.

A number of U.S. universities, as well as institutions in other nations, have begun efforts to foster convergence (MIT 2011; Sharp and Langer 2011; also see Table 4.1 below and Figure 8.1 in Chapter 8 of this report).

Table 4.1 Examples of U.S. and Other Programs with Seed NBIC/CKTS Approaches

<table>
<thead>
<tr>
<th>Program Name and Website</th>
<th>Home Institution</th>
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<tbody>
<tr>
<td>Biodesign Institute: <a href="http://biodesign.asu.edu/research/research-centers">http://biodesign.asu.edu/research/research-centers</a></td>
<td>Arizona State University, Tempe, AZ (U.S.)</td>
</tr>
<tr>
<td>The Wisconsin Institute for Discovery: <a href="http://wid.wisc.edu/about/">http://wid.wisc.edu/about/</a></td>
<td>University of Wisconsin, Madison (U.S.)</td>
</tr>
<tr>
<td>Center for Nanotechnology in Society (CNS-ASU): <a href="http://cns.asu.edu">http://cns.asu.edu</a></td>
<td>Arizona State University, Tempe, AZ (U.S.)</td>
</tr>
<tr>
<td>Converged Technologies for Security, Safety, and Resilience (CTSSR): <a href="http://www.it.vt.edu/organization/ctssr/">http://www.it.vt.edu/organization/ctssr/</a></td>
<td>Virginia Polytechnic Institute and State University, Blacksburg, VA (U.S.)</td>
</tr>
<tr>
<td>Centre for Mobile and Converging Technologies: <a href="http://www.leedsmet.ac.uk/aet/computing/centre-for-mobile-and-converging-technologies.htm">http://www.leedsmet.ac.uk/aet/computing/centre-for-mobile-and-converging-technologies.htm</a></td>
<td>Leeds Metropolitan University, UK</td>
</tr>
<tr>
<td>Kurchatov Centre of Converging of Nano-, Bio-, Information and Cognitive Sciences and Technologies: <a href="http://www.kiae.ru/e/nbic.html">http://www.kiae.ru/e/nbic.html</a></td>
<td>Moscow, Russia</td>
</tr>
<tr>
<td>Tsukuba Innovation Arena: <a href="http://tia-nano.jp/en/about/index.html">http://tia-nano.jp/en/about/index.html</a></td>
<td>Japan</td>
</tr>
<tr>
<td>Inter-university MicroElectronics Center (nano-bio-IT-cogno): <a href="http://www2.imec.be/be_en/home.html">http://www2.imec.be/be_en/home.html</a></td>
<td>Belgium</td>
</tr>
<tr>
<td>MINATEC (nano-bio-info): <a href="http://www.minatec.org/en">http://www.minatec.org/en</a></td>
<td>Grenoble, France</td>
</tr>
<tr>
<td>“NBIC–New Opportunity for China,” China National Natural Science Foundation: <a href="http://nsfc.gov.cn/Portal0/InfoModule_584/37502.htm">http://nsfc.gov.cn/Portal0/InfoModule_584/37502.htm</a></td>
<td>China</td>
</tr>
<tr>
<td>CRPC(Convergence Research Policy-Development Centre) (2012-)</td>
<td>Korea</td>
</tr>
<tr>
<td>Knowledge NBIC Project, <a href="http://www.converging-technologies.org/">http://www.converging-technologies.org/</a></td>
<td>Zeppelin University, Germany</td>
</tr>
<tr>
<td>Centech, <a href="http://www.centech.de">http://www.centech.de</a></td>
<td>Munster, Germany</td>
</tr>
<tr>
<td>Interdisciplinary Center for Technology Analysis and Forecasting (ICTAF): <a href="http://ictaf.tau.ac.il/index.asp?lang=eng">http://ictaf.tau.ac.il/index.asp?lang=eng</a></td>
<td>Tel Aviv University, Israel</td>
</tr>
<tr>
<td>Centre for Converging Technologies: <a href="http://www.uniraj.ac.in/cct/">http://www.uniraj.ac.in/cct/</a></td>
<td>University of Rajasthan, Jaipur, India</td>
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As shown in Table 4.1, targeted NBIC efforts have been initiated by the European Union, Japan, Russia, and China, among others, and attention has been given to this issue by the independent International Risk Governance Council (Renn and Roco 2006; IRGC 2009). Several national and EU science and technology (S&T) multiyear plans use components of the convergence approach within their predetermined political context and requirements; Table 4.2 gives several examples.

**Table 4.2 National and EU S&T multiyear plans with approaches related to CKTS**

<table>
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<tr>
<th>Program Name and Website</th>
<th>Economy</th>
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<tr>
<td>Korea S&amp;T plans</td>
<td>Korea</td>
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<tr>
<td>China S&amp;T plans</td>
<td>China</td>
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</tbody>
</table>

Figure 4.3 shows ten-year trends in numbers of publications in NBIC areas. Work in all four NBIC domains began to be cited after 2001 when NSF and DOC organized the first NBIC workshop and the U.S. National Nanotechnology Initiative was begun. The rate of increase in publications with at least some convergence component has been roughly doubling each three years since 2001. Figure 4.4 shows the increase in the number of NBIC awards at NSF having at least two components in each award. The search was performed by using keywords in the abstracts published on the NSF website ([http://www.nsf.gov](http://www.nsf.gov)). NSF’s rate of increase of awards in NBIC domains is significantly higher than the overall budget increases for all research areas. Since 2010, the NBIC awards represent about 5% of the total NSF awards.

A mechanism for improving convergence is increasing the level and speed of interactions in the creative phase (A in Figure 4.1b). Support for interdisciplinary interactivity among scientists from different traditional disciplines appears to be increasing. Recent research describes creativity as being spurred by real physical environments where people and ideas converge and synergies arise (e.g., in the books *Imagine* by Jonah Lehrer [2012] and *InGenius: A Crash Course on Creativity* by Tina Seelig [2012]), In a number of large companies such as 3M and IBM, scientists are rotated from one department to the next, regardless of their training, to spur synergistic and creative thinking. In several universities such as Cornell University and MIT, PhD students are rotated through various laboratories during the course of their studies. Creation of multidisciplinary campus spaces for faculty and students is a reality in an increasing number of campuses such as University of California–Los Angeles and Seoul National University. Such practices need to be expanded and systematized. One could imagine routinely rotating professors from department to department. Leading engineering design centers may provide models for problem solving using a systems approach.

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2 An example is the project Knowledge Politics and New Converging Technologies; A Social Science Perspective, funded by the European Commission under Priority 7 of the 6th Framework Programme; [http://converging-technologies.org/](http://converging-technologies.org/).
3 For example, the Kurchatov Institute Centre of Nano-, Bio-, Info-, and Cognitive Sciences and Technologies in Moscow, [http://www.kiae.ru/e/nbic.html](http://www.kiae.ru/e/nbic.html). The Kurchatov Institute is Russia’s National Research Center.
4 For example, see “NBIC–New Opportunity for China,” the National Natural Science Foundation of China, [http://www.nsfc.gov.cn/Portal0/InfoModule_584/37502.htm](http://www.nsfc.gov.cn/Portal0/InfoModule_584/37502.htm).
5 The IRGC White Paper on Nanotechnology Risk Governance (Renn and Roco 2006) notes that in the fourth generation of nanotechnology products and production process (after 2014/2020), “NBIC convergence will play an increased role” and addresses some of those issues, including their sociological components.
Figure 4.3 Number of publications in various domains of NBIC, 1990–2011 (courtesy of J. Murday).

Figure 4.4 Funding per various domains of NBIC (at least two NBIC domains in each award) by NSF, 1987–2012 (courtesy of M. C. Roco).

Another mechanism to stimulate convergence is evidenced in the increasing collaboration between academic, industry, and government sectors. As industry has reduced its investment in internal basic research, it has looked to the academic community for research discovery. While that has mostly been on an ad hoc basis, in one specific instance, the semiconductor industry has formed an extended partnership with Federal and state governments to co-fund use-inspired basic research pertinent to its interests. For example, the Semiconductor Research Corporation’s (SRC) Nanoelectronics Research Initiative (http://src.org/program/nri/) is mostly funded by industry but is supplemented by funding from NSF and the National Institute of Standards and Technology (NIST). Another SRC effort, the Focus Center Research Program (http://www.src.org/program/fcrp/), is funded by roughly 50/50 cost sharing with government.
Overall, in the past ten years, areas of NBIC convergence have been integrated within various U.S. Government R&D programs mostly by pairs, in a reactive mode, generally without a holistic system view. At the same time, the emerging technologies have developed both independently and jointly to a level that now more readily enables structured convergence. Examples in the United States of salutary program developments are the Information Technology Research for National Priorities program (ITR) and its successors (such as NITRD, http://www.nitrd.gov), the National Nanotechnology Initiative (NNI; http://nano.gov), and several large database initiatives such as ones in the medical, communication, and defense fields. In the same period, the 2001 NBIC study (NBIC 2003) and other studies also planted seeds for convergence. Simulations of reality are increasingly providing a method of evaluating possible integration efforts. International organizations such as the International Risk Governance Council (since 2005) and various international scientific communities have recognized the need for transformative interdisciplinary synergism. Despite their importance, systems approaches and corresponding methods of convergence, and connections between the transformative tools, nomenclature, standards, legislation, and policies of CKTS, have not received sufficient attention in scientific and public discourse.

Despite the fact that these kinds of inroads that have helped to partially advance convergence in the past 10 years, they are insufficient to enable the synergies and momentum that are critical if the potential benefits of convergence are to be realized. The differences between the rates of discoveries and economical outputs can be observed in most of the world economies, with some specific characteristics in each country. In the last decade, U.S. policy leaders began to realize that the 60-year dominance of the United States in science and technology is eroding, and national interests require a new perspective. In 2005 Thomas Friedman published his book *The World is Flat*, pointing out that the world was rapidly becoming a level playing field in terms of commerce, where all competitors have equal opportunity. In 2007 the U.S. National Academy of Sciences published *Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (NRC 2007b). It observed that without a renewed effort to bolster the foundations of U.S. competitiveness, we can expect to lose our privileged global position. The report was revised in 2010 to *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5* (NRC 2010b), which asserted that in the face of so many daunting near-term challenges, U.S. government and industry were letting the crucial strategic issues of U.S. competitiveness slip below the surface. Transformative technology, particularly in emerging areas, was identified as a critical component in retaining competitiveness. Systematic actions are needed to extract the full value out of convergence trends going into the future.

### 4.3 GOALS FOR THE NEXT DECADE

The main purpose in promoting a proactive and systematic focus on converging knowledge and technology is to increase creativity, innovation, and productivity in society, to enable people to solve both local and global problems that otherwise seem to defy solution. To achieve value-added goals, it will be necessary to create a portfolio of convergence methods or an expert system platform for selecting methods of integration and domains of application. A number of ten-year goals for reaching synergism and integration in CKTS are described below. They include methods applicable to the entire convergence–divergence cycle—a systems-based approach (see Sections 4.3.1 and 4.3.3) —and other methods more specific to one of the four phases of the knowledge development cycle: the creative, integration/fusion, innovation, and outcomes phases (see Figure 4.1 and Sections 4.3.2–4.3.9).

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4.3.1 Improve Systems-Based Convergence Methods

Improved systems-based methods for achieving CKTS will encompass the following kinds of approaches:

- **Support system science approaches**, including specific tools such as neural networking and logic model approaches to underline system interactions.
- **Support evolutionary approaches** for system convergence (see Section 4.8.1, Erik Goodman).
- **Develop knowledge mapping and network visualization techniques** for identifying large patterns in the knowledge, technology, and societal systems, as well as related work going on in other disciplinary communities and other hierarchical levels that might benefit from collaboration.
- Unify large sets of multi-topic databases and expert systems for the converging platforms, coupled with informatics, and linked computer simulations, including different phenomena, processes, scales, applications, and social events.
- Promote more integrated and interactive education programs (e.g., Khan Academy for large groups; the Integrative Graduate Education and Research Traineeship [IGERT], as described in Section 8.8.8 of this volume; and the vertical [from K–16], horizontal [disciplinary] and global [international] approach for education as described in Section 8.8.1 of this volume).
- Apply CKTS fractal patterns (similar patterns of contents and presentation but used in different contexts) in various areas of R&D, applications, and education.
- Combine organizations’ technical pushes and societal pulls for R&D planning and setting organization structures.
- Use S&T policy and directed investment to reach societal goals.
- Combine deductive (e.g., nanoscale to macroscale analyses; apply direct design; application of topical-based science and technology to society) and inductive (e.g., Earth- to human-scale, apply reverse design; societal goal-driven science and technology) approaches to long-term decision analysis.
- Apply scenarios development and research for uncovering the potential open issues that may be “invisible” at the beginning of societal planning.
- Encourage international sharing of models for exploiting R&D investments, based on mutual interests.
- Move to open publications on converging methods.

4.3.2 Create and Implement Higher-Level (Multidomain, Convergent) Languages

By convergence language we mean 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 of 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
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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 language is 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 efforts, steer the interest and efforts 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 tools 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 2000), foundational tools in 2002 (NBIC 2003), and CKTS (this study; see Figure 1 in Overview and Recommendations):

1. Nanotechnology – Integrate knowledge and disciplines for all sectors of the material world from the nanoscale.
2. NBIC – Integrate foundational and emerging technologies from elemental features (atoms, bits, DNA, and synapses) and integrate them into larger-scale systems.
3. CKTS – Integrate essential convergence platforms in human activities, including knowledge, technology, human behavior, and society, driven by societal values and needs.

4.3.3 Apply a Holistic Deductive Approach to Decision-Making

Human activities are interdependent through an evolutionary system (Figure 4.1a). When such a system is specified for a given goal, the most suitable approach in decision analysis and establishing partnerships is the deductive approach, where all system components and their causal evolution are considered. The results are different from coincidental collaborations or interdisciplinary work, where the collaborating parts and approaches are defined a priori.

The applicability of the deductive approach is a function of how well the hierarchical structure of the respective system is known and whether the bottom-up, top-down, interdisciplinary horizontal, and longer-range links and processes are well understood.

4.3.4 Improve the Creative Phase of the Convergence–Divergence Cycle

Several methods to improve the creative phase of the convergence–divergence cycle are:

• Open collaboration.
• Multidisciplinary education: Apply CKTS fractal patterns in education (similar patterns of content and presentation but used in different components of the convergence platform) in
various areas of R&D, applications, and education. For example, presenting nanoscale principles in chemistry, mechanical, and social sciences courses has created a foundation for collaboration and synergism in these several fields.

- Connect basic research projects based in different disciplines.
- Team science.
- Use social media and game theory to connect communities and increase the synergism of ideas.
- Explore concepts of new funding mechanisms conducive to convergent S&T ideas, e.g., processes for idea incubation prior to formal proposal formulation. Examples in the United States are the Integrated NSF Support Promoting Interdisciplinary Research and Education (INSPIRE) programs, the goal-oriented solicitations of the Defense Advanced Research Projects Agency (DARPA), and science-engineering-medical collaborative programs at the National Institutes of Health.
- Better understand psychological processes in creativity and human capabilities (for illustration of the role of intelligence, see Neisser et al. 1996).

4.3.5 Improve the Integration/Fusion Phase of the Convergence–Divergence Cycle

Several methods are:

- Use broad-based S&T platforms that offer more integration opportunities.
  - An example of the kinds of opportunities opened up through convergence–divergence processes is the cell phone platform, which has been underestimated throughout its history. It is rapidly becoming one of the most important technological platforms in mankind’s history, with 1.6–1.8 billion sold per year, over 5.6 billion subscriptions, and devices owned by >70% of the human race. Convergence of multiple disciplines and technology sectors yielded the cell system. It depends on high-frequency communications 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—all of which converged to create the “smart phone” about a decade ago. In turn, the platform has yielded a cascade of outcomes across science and society. There are thousands of applications scarcely imagined ten years ago, from social networks to ability to control swarms of very inexpensive miniaturized satellites, and many other examples. These impacts in turn have profound “cascade” implications for and secondary impacts on areas as diverse as national security, education, and cognitive science. In the area of healthcare, widely available “smart” portable devices are beginning to enable round-the-clock medical monitoring, and identification and interpretation, of data related to critical body functioning; these kinds of devices and their associated applications will accelerate highly personalized medicine, where nanoelectronics, sensors, cognition, and information technology are integrated. Soon they are likely to be connected through video devices in glasses, watches, and other portable devices in daily activities. Although such personalized information would serve initially for diagnostic and preventative purposes, it is widely acknowledged that such use of this platform is an important step toward improved quality in healthcare.
- Use multidisciplinary design methods.
- Make various manufacturing methods and phases of production compatible and synergistic by integration of knowledge and technologies.
- Develop advanced mind–cyber-physical systems.

4.3.6 Improve the Innovation Phase of the Convergence–Divergence Cycle

Several methods are:
4. Methods to Improve and Expedite Convergence

- Promote open science and innovation, and participatory design and governance (Section 10.8).
- Support the field of futures studies, including use of trend analysis, Delphi, scenario writing techniques, and virtual reality methods.
- Use specialized software providing alternatives in decision-making (NSF 2012).

To conceptualize the influence of convergence on innovation, we have defined an index of innovation rate \( I \). The three-dimensional innovation divergence spiral (Figure 4.1b) has a projection in the convergence platform plane (Figure 4.1a) that is characterized by a time scale \( t \) of information exchange in the respective convergence platform. The time scale of the convergence–divergence process (from the beginning of the creative phase “A” to outcomes “D” in Figure 4.1b) is \( T \). The index of innovation rate is estimated to be in direct proportion with the size \( S \) of the convergence platform from where information is collected (the domain circumscribed by the projection of innovation spiral; that is, the number of disciplines or application areas intersected by the circumferential spiral, in Figure 4.1a), the speed of information exchange supporting innovation in that platform \( (S/t) \), the speed of the convergence–divergence cycle \( (1/T) \), and the divergence angle in realizing the outcomes \( (O/T) \).

\[
I \sim k (S) (S/t) (1/T) (O/T) \sim k' S^2 O / (T T t) \sim k' S^2 O / T^3 (4.1)
\]

where:
\( t \sim T \) because they are the time scales on the normal and axial projections of the displacement on the innovation spiral; \( O \) is a measure of the outcomes; and \( k \) and \( k' \) are coefficients of proportionality.

This qualitative correlation shows that the innovation rate increases with the size of the convergence domain \( I \sim S^3 \) and is significantly affected by the time scale of the convergence-divergence cycle \( I \sim 1/T^3 \). This correlation has similarities with the Metcalfe's Law in information research (Shapiro and Varian 1999) that says that the number of possible cross-connections in a network grows as the square of the number of computers in the network increases, and the community value of a network grows as the square of the number of its users increase. Metcalfe's Law is often cited as an explanation for the rapid growth of communication technology and the Internet. The \( (O/TT) \) term in the equation is in agreement with the empirical exponential growth model for science and technology (for illustration see Moore’s Law and Kurzweil 1999).

4.3.7 Improve the Outcomes Phase of the Convergence–Divergence Cycle

Several methods and evaluation considerations are:
- Reevaluate and take steps to realign criteria for success in society by adding—besides economic output (such as GDP)—accumulations in knowledge and technology, preparation for the future, and changes in education and infrastructure
- Identify and pursue high-priority common values and goals
- Cultivate user-driven approaches such as use-inspired basic research
- Create top–down governance focused on convergence for specific goals
- Sponsor self-regulating convergence in self-reliant communities (with constraints for sustainable technologies and practices)
- Explore downstream activities as integrators (provide funding for application areas)
- Focus on computer-assisted policy design methods
- Pursue methods for distributed and hybrid manufacturing
- Investigate medical-cognitive advances; develop governance science
From one perspective that shaped the working group’s discussion at the U.S. NBIC2 workshop, policymaking progress will depend on better tools, including the inclusive rules themselves but also computer-assisted policy design methods. The equivalent of a computer-aided design tool for modeling the world’s service systems is much needed. The world’s service ecology is increasingly composed of major nested, networked service system entities. Modeling cities and their top universities is essential, because universities are the knowledge engines creating the next generation of workers, knowledge, and regional economic development. Flows of people, information, capital, technology, energy, water, waste, and other resources or products are also important to understand.

Convergence results also may be expressed in terms of increases in number of patents from converging technologies, number of new jobs created nationally, percent increase in GDP, as well as the emergence of new industries and academic disciplines.

4.3.8 Vision-Inspired Basic Research and Grand Challenges

Using forecasting, early signs of change, 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. Then, a recommended approach is to work backwards from the vision to investigate intermediate research steps and approaches. This approach was used in researching and writing the two nanotechnology research directions reports (Roco, Williams, and Alivisatos 1999; Roco, Mirkin, and Hersam 2010).

A typical knowledge and technology convergence–divergence process (Figure 4.1b) has four phases (creative assembling, system integration for known uses, innovation, and outcomes that lead to emerging new uses); the research approach has to adapt to the corresponding phase of the process. The CKTS methods can provide connections between the long-term knowledge and technology vision and basic research activities in each phase. An additional “Vision-Inspired Basic Research” quadrangle is proposed (Figure 4.5) that expands the existing four domains—particularly the Pasteur quadrangle—of the Stokes diagram of basic scientific research paradigms, to address new and emerging areas of research and applications (“new use” section of Figure 4.5).

![Figure 4.5](attachment:image.png)  
**Figure 4.5** Schematic for “Vision-Inspired Basic Research” quadrangle in the modified Stokes diagram: three basic research approaches (pure, use-inspired, and vision-inspired) are suggested as a function of the phase (Creative, Integration, or Divergence) in the knowledge and technology convergence–divergence process (figure based on that by Stokes [1997], courtesy of M. C. Roco).
To efficiently and responsibly achieve the benefits of research in new areas, the convergence processes need to be used to identify the vision and its corresponding basic research strategic areas, changing priorities periodically as interdependencies change, old goals are achieved, and new ones come within reach. The “vision-inspired” domain is extending the Stokes diagram to basic research in emerging areas where there solution and use are not known a priori. Different basic research approaches are needed as a function of the phase in the knowledge and technology convergence–divergence process (Figure 4.1b), that is, the Bohr approach for the creative phase (A), the Pasteur approach for the integration/fusion phase (B), and vision-inspired basic research for the divergent phase (C and D).

4.3.9 Change the Knowledge and Technology Culture

An overall goal of CKTS is supporting a culture that is guided by principles of interdependence and connectivity. Two approaches for changing the culture are discussed below: open science and anticipatory technology assessment.

Open Science

A key approach for the creative and innovation phase is “open science” consisting of virtual organization collaboratories and online citizen science. Already, scientists are beginning to talk about open science as the approach in which specialists, nonspecialist scientists, and nonscientists collaborate fruitfully by means of new methods of communication and novel research methodologies (Woelfle, Olliaro, and Todd 2011). Two important recent information technology developments are expected to converge in the near future, with marvelous benefits for the unification of the sciences towards open science:

- The evolution of scientific data archives into digital libraries in the 1990s and into virtual organization collaboratories in the 2000s. Prominent examples include The Protein Data Bank (http://rcsb.org/pdb/; Berman 2012), The Computer Tomography Virtual Organization (Tapia et al. 2012), and a computer-based archives network shared by astronomers (Djorgovski 2012).
- The emergence of online citizen science over the past decade, which began by using ordinary people as volunteer data collection and classification workers, but which is beginning to include people from a variety of technical backgrounds as volunteer collaborators. An example that has been used as an innovative information technology approach to unite biology with nanoscience is the Foldit project (http://fold.it/portal/info/science), in which nonscientist volunteers have been able to solve difficult problems in protein folding through an online game (Khatib et al. 2011). Another example is the 2010 Oregon Citizens’ Initiative (Gastil and Knobloch 2010).

Several future convergence scenarios come readily to mind; the following five suggest the range of possibilities, each organized around a new or existing virtual organization collaboratory:

- A professional scientist in one discipline volunteers as a citizen scientist for a project in a different discipline, thereby gaining greater awareness of that other science and growing into a professional collaborator with the scientists managing the project or with others in his/her field.
- A serious student in high school becomes a citizen volunteer for projects in two or more distinct sciences, gaining increased motivation to become a professional scientist and the experience to succeed as a double-major in college.
- A member of the staff of a college or university migrates from one project to another, after contributing significantly as a citizen scientist in each, and then becomes the official coordinator of citizen science projects at his or her educational institution on the basis of this extensive personal experience.
- Members of two high-quality scientific teams in adjacent fields volunteer as citizen scientists to contribute labor to the other's success as a conscious step in development of a permanent collaboration between the teams.
• A scientist in one field becomes a citizen science volunteer for a project in his or her own field but conducted in a different nation and using a different language, as preparation for increased international collaborations.

**Anticipatory, Participatory, and Adaptive Technology Assessments and Decision-Making**

The idea of anticipatory technology evaluation for CKTS fits within a larger national and global movement toward sustainable chemical, material, and product development and use. As an example, work on public responses to nanotechnology has included fine-grained comparative work with other contemporary merging/converging technologies like neurology and synthetic biology and with past technologies and risk controversies such as biotechnology and nuclear power. A key aim of risk perception and mental models research is to create an empirical basis for linking risk and benefit perception to risk and benefit communication. Anticipatory technology evaluation will require a reflexive approach to CKTS development. That is, it will be necessary to look critically at technology itself in terms of impacts as well as benefits.

### 4.4 INFRASTRUCTURE NEEDS

Changes expected in the next decade include accelerated developments in emerging and converging technologies, increased needs for sustainable development in a more crowded world, more rapid globalization of commerce, and aging of the world’s overall population. This section discusses several S&T infrastructure elements that are needed to adapt to these kinds of changes.

To effectively achieve integration and synergism in CKTS, an infrastructure is needed that can provide diverse networks and tools for communication and convergence across knowledge and technology domains. The primary objectives are to develop new convergence methods by exploiting expertise that already exists to build a specialized expert network infrastructure. The infrastructure is expected to provide platforms for:

- Creating specialized networks and tools for communication, with seed funding for converging of people and communities. Horizontal information systems in university, industry, and government organizations will have an increased focus on building knowledge versus conveying information.

- Developing methods for advancing convergence in planning, decision analysis, investment policy, and other areas.

- Building collaboration spaces that are free from geographical boundaries, organizational constraints, and single-domain restrictions. Examples of biology-centered convergence in the United States are the Arizona State University’s Biodesign Institute (see Chapter 1, Section 1.8.4), Stanford’s Bio-X Institute, Harvard’s Wyss Institute, and the University of Wisconsin–Madison’s Wisconsin Institute for Discovery (a public–private partnership).

- Drawing on international forecasts of science and technology trends. Forecasts of essential aspects in the world can be garnered by mining information from social network and news services such as Twitter, Facebook, Youtube, CNN, etc.

- Developing information systems for finding experts from different domains across the world, providing a communication space by adopting functionality from existing professional and social applications.

- Enabling the sharing of resources and exchange of knowledge by designing a knowledge profiling service with well-defined resources such as data, software, source code, documentation with standardized formats, publications, laboratories, etc.

- Creating collaborative groups and projects for solving real-world issues.

- Providing tools or services for analyzing and visualizing trends, networks, project progress, discussion topics, etc.
Convergence can be supported by rejuvenation of university laboratories and creating CKTS curricula early in the educational continuum. A number of researcher network systems have been introduced to expose high-quality institutional data via websites and semantically structured RDF (resource description framework) data. Several well-known systems are VIVO (the “Facebook-for-researchers”, http://vivoweb.org); Harvard Catalyst Profiles (http://profiles.catalyst.harvard.edu); Stanford CAP (http://med.stanford.edu/profiles); Academia.edu (the “Linked-In for academics”); and Elsevier Scival Experts (http://www.scival.com/experts). These systems are institution-based, and only the members of the system are able to access the information. International Researcher Network (IRN) visualization (http://nrn.cns.iu.edu) has provided a single interface that allows experts to find other experts across these systems. Since these systems are served as a profiling service where members can find expert members in the system, they lack the opportunities created by open-communication functionality and resource-sharing. Collaboration has to be done through email outside the systems. HUBzero® (http://hubzero.org/) has taken this web-based researcher network concept further by providing an online space for sharing resources and collaborating; however, it is still limited to members only, and each hub is only available for a specified expertise group. For example, nanoHUB (http://nanohub.org/) is for nano researchers and the c3Bio hub (http://c3bio.org/) is for researchers involved in energy and carbon efficiencies of biofuel production. Mendeley (http://www.mendeley.com/) has provided a space for experts from different disciplines to collaborate. (A visualization of the cross-disciplinary collaboration is shown at http://cns.iu.edu/research/2011_Mendeley_Binary_Battle_entry.pdf.)

Software, computer, and visualization equipment are needed for improved communication, information, and virtual reality environments to allow hybrid cluster facilities for manufacturing.

4.5 R&D STRATEGIES

The following strategies are suggested:

- Restructure “broader impact” requirements for projects to include convergence aspects such as manufacturability, planning, investment policies, education, and decision analysis. Establish positive closed-feedback loops across multiple technologies, medicine, education, and manufacturing, regulated appropriately.

- Expand the “science for science” programs to include a focus on “science for governance”, and institutionalize them to do so. The need may be illustrated by how different the approaches are toward grant proposals in different government agencies. Researchers who have spent the majority of their careers dealing with one agency should deal with various agencies that have completely different research philosophies. Plans for interdisciplinary centers should ensure that communications in calls for proposals are explicit about expectations for prior research and that evaluations of proposals are conducted by panels constituted of members who have multi- and interdisciplinary backgrounds.

- Promote mechanisms to engender more effective stakeholder involvement in improving education and research to support CKTS. One strategy is to support research grants that encourage universities to develop new programs and courses that address convergence-driven research that is holistic and personalized in concept. In plans for any new cross-disciplinary efforts for converging technologies, capturing and leveraging stakeholders’ enthusiasm and excitement should be a high priority.

- Provide open access to science and technology journals with the goal of widely disseminating best practices to promote accelerated advancement of converging technologies. Current efforts toward open access are being restricted by the need to resolve intellectual property issues, to compensate “publishers” for the effort and expertise to review and provide the resources to archive the publications, and to provide appropriate rewards systems for authors and their institutions. These difficulties about open access are being compounded by the increasing prices of journals (Sample 2012). Arguments have been put forth (Ross n.d.) that open-access
publications are beginning to garner prestige equivalent to conventional publications, and that taxpayers have already paid for the research results.

- **Extend NNI lessons learned for promoting interdisciplinary research.** There are some significant lessons learned from the National Nanotechnology Initiative in the efforts by participating agencies to promote interdisciplinary research among their multidisciplinary centers and programs. Nanotechnology development has been similar to CKTS in that researchers from all the physical, chemical, biological, and medical sciences participate, but CKTS broadens this expectation to include the geological, geospatial, social, neurological, environmental, and educational regimes.

- **Convene a group of agency and academic experts to identify and design appropriate centers around national research priorities.** Converging technologies imply cross-disciplinary efforts, and R&D centers provide a mechanism to locally house expertise derived from multiple disciplines. With the growing sophistication of information technology, virtual centers can certainly play a role, but unscheduled, informal meetings between people are often the more likely occasions for nurturing insightful, innovative ideas. This effort must explicitly engage the challenges of converging technologies.

- **Foster open innovation environments and innovation mechanisms for CKTS (Kim et al. 2008).**

- **Foster anticipatory and participatory governance integrating the four basic functions of CKTS (transformative, inclusive, responsible, and visionary) as a guiding vision for the next ten years.** Foster diversity in the pipeline of future researchers; this will promote innovation by providing differing perspectives. Devote attention to enabling participation by broader representation in the student population, including lower-income students (Osterman 2008) and students from segments of society that are underrepresented due to gender (NRC 2010a; Beede et al. 2010) and/or minority status (Frehill, DiFabio, and Hill 2008).

- **Define realistic “grand challenges” in problem-driven research for proper selection of converging methods.** Examples are the “mapping brain activity” project (Alivisatos et al. 2012) and the technology challenge project (Mills and Ottino 2011).

### 4.6 CONCLUSIONS AND PRIORITIES

The main priorities as they relate to the methods of convergence are as follows:

- **Proactively promote holistic and balanced convergence of knowledge, technology, and social developments** with a strong focus on problem-solving, transdisciplinary S&T platforms, stakeholder involvement, and use of emerging resources. Emerging resources include multidomain databases; cloud information, computing, and manufacturing; open-access publications; open innovation mechanisms and environments; and virtual reality methods.

- **Added-value decision-making and transformation of scientific knowledge** are based on the convergence–divergence process (see below) in science, technology, and applications. Methods are needed to improve and expedite each of the four phases of the process.

- **Develop a systematic approach for selecting the methods of convergence for synergy and integration,** with a focus on emerging technologies in society and enhancement of individual human quality of life in terms of both mental satisfaction (pursuit of happiness) and improved physical condition.

- **Identify the subset of problems likely to benefit most from the convergence approach.** Address priority large-scale imminent problems of fundamental concern to communities across the globe, Define specific, realistic “grand challenges” in problem-driven research, such as brain-inspired neuromorphic devices, digital and distributed manufacturing, Earth-scale interventions, and personalized health and education.
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- Establish methods for convergence suitable for a variety of self-reliant communities (sized from a thousand to millions of people) for sustainable development over time. Define specific, realistic “grand challenges” in problem-driven research proposed by various communities.

- Establish broad user “platforms” for interdisciplinary collaboration to support communication, inputs from various communities, international partnerships, and sharing of resources and expertise, e.g., portal websites serving diverse S&T communities.

- Fully involve social scientists and decision analysis procedures in CKTS projects.

- Incorporate dynamic feedback loops across multiple technologies in performance evaluation.

- Establish a common language for scientists, engineers, industry, regulators, and the general public, and develop compatible standards for different fields.

- Seek alternatives and modifications to the current peer-review system in R&D project selection in order to encourage converging technologies R&D, and consider a set-aside of funding for exploratory CKTS projects.

- Focus early in the innovation cycle on identifying potential risks and hazards. Support international collaboration to enhance value and reduce risk in high-return R&D projects for CKTS.

4.7 R&D IMPACT ON SOCIETY

Accelerating the beneficial use of CKTS in society to solve high-interest problems will deepen human insights into natural phenomena, offer significant new opportunities to increase quality of life, and bring an infusion of excitement into society concerning S&T similar to that seen for the Apollo Mission.

The United Nations goals for human development provide a good reference for guiding convergence methodologies (UN 2012). The methods of convergence need to enable the following kinds of outcomes:

- Affordable access of the world’s citizens to new knowledge, technologies, and products. Such access is anticipated through:
  - Increased and open access to the latest advances in S&T publications and databases in all disciplinary areas, including platforms for interdisciplinary collaboration, host communities, and shared resources and expertise.
  - Innovation for advanced manufacturing/jobs/competitiveness such as that provided in personalized (“mass customization” or “do-it-yourself”) manufacturing and the availability of manufacturing information as a service. These exemplify the integration of information, communications, materials, and economics in an evolving new paradigm for manufacturing. Downstream activities such as design and manufacturing can serve as important means of integrating diverse knowledge bases. Realizing artifacts and services of benefit to society necessarily requires the consideration of multiple facets: economics, technology, sustainability and the environment, societal effects, etc. A main goal is increasing worker efficiency.
  - Scalable models for distributed manufacturing: The emerging idea here is the integration of small distributed facilities to obtain scaled-up manufacturing. Crowd sourcing is one emerging idea related to this trend.
  - Information-technology-inspired communication and manufacturing systems (cores, buses, peripherals, operating systems, networks, etc.) following architecture similar to that employed in computer systems.

- Significant support for increased innovation through inclusion of multiple science paths, application areas, and societal targets.
• **Sustainable and equitable use of natural resources** (energy, water, sustainable food and nutrition security, climate, oceans, forests, biodiversity) and management of wastes.

• Universal access to high-quality healthcare and education.

• **Enhanced individual quality of life** through personalized medicine, education for the entire life span, and other measures.

• Use of new governance paradigms enabled by CKTS.

Sustainable development is a challenge for the world because current economic development models (i.e., development based on increases in global population and industrial output of all economies) will accelerate resource depletion and global warming. Piecemeal progress in different geographic areas, supported by advances in single areas of technology, could be counterproductive. This challenge can be met successfully only by treating the world as a single complex system, from the perspective of unified science based on convergence. A comprehensive approach is required to address the economic, social, and environmental dimensions of sustainable development (UN 2012). Methods of convergence have particularities as a function of goals, such as those listed in Section 4.6.

4.7.1 Additional Considerations

Much of the CKTS discussion concerns human beings working together to achieve convergence of the sciences, but it is also important for the sciences to work together to achieve convergence of humanity. This is obvious in the international context, and the CKTS discussions and workshops have been carried out explicitly as a global activity. Within each nation, convergence of people having a variety of native talents must also be achieved. There will be many challenges.

The world has already advanced several decades into a new form of economy, building upon the original Industrial Revolution and worthy of being called the Second Industrial Revolution, in which machines and physical products are still important but where information systems are paramount. At the beginning of this revolution, a number of theorists proposed very powerful ideas about this future, but we have largely failed to conduct the empirical scientific research needed to evaluate their ideas and to understand the new world we are rapidly entering. Whether the emerging world society is called technological, technetronic, informatics, or post-industrial, it places a high priority on the ability to handle complex systems of information (Ellul 1964; Brzezinski 1970; Bell 1973; Castells 1996). What, then, will be the place for people who lack the innate abilities or skills to do so?

Often, this question has been framed in terms of the **digital divide**, originally defined in terms of lack of affordable access to computers by economically disadvantaged people, but that also may apply to people having easy access to Internet but lacking the ability to use it effectively (DiMaggio et al. 2001; Attewell 2001). Universal access to quality education will reduce the number of people lacking essential skills, although very deep analysis will be required to design educational improvements that are really effective (Ray and Mickelson 1993) for all kinds of students. Ethical considerations must be addressed for providing equal opportunities for all kinds of individuals and communities to participate fully in the progress that CKTS is expected to bring.

4.8 EXAMPLES OF ACHIEVEMENTS AND CONVERGENCE PARADIGM SHIFTS

4.8.1 Evolutionary Approach for Convergence

Contact person: Erik Goodman, Michigan State University

The BEACON Center (Bio/computational Evolution in Action CONsortium) for the Study of Evolution in Action (http://beacon-center.org/) is a science and technology center funded in 2010 by NSF. It teams evolutionary biologists conducting experiments in the lab and field with computer
scientists and engineers experimenting with evolution of artificial organisms in the digital domain, where the organisms compete for resources and reproduce themselves with a specified mutation rate. Experiments are carried out that cast light on the mechanisms operating in the other domains.

4.8.2 Open Learning Systems for Convergence

Contact person: Clayton Teague, Consultant

The new online Internet learning efforts by the Khan Academy, MIT OpenCourseWare, Udacity, EdX (a joint venture of Harvard and MIT), Coursera (Stanford, University of Michigan, and University of Pennsylvania), 2Tor (UNC Chapel Hill and Georgetown University), and others are challenging conventional approaches to learning systems for students. These kinds of approaches to delivering high-quality lectures to individual students are being combined with such efforts as those by the Knewton Company to obtain real-time feedback from a student’s response in terms of his or her speed, accuracy, delays, keystrokes, click-streams, and drop-offs. In the future, one could envision a tutor watching a student via a camera and having the tutor respond with the intelligence of say a “Watson”-equivalent computer to the student’s responses, such as depicted in the novel The Diamond Age by Neal Stephenson (1995).

4.8.3 Convergence in Regional Partnerships: Oregon Nanoscience and Microtechnologies Institute (ONAMI)

Contact person: Skip Rung, ONAMI

Knowledge, innovation, and entrepreneurship converge in regional partnerships such as ONAMI to build better citizen futures and serve a diversity of stakeholders. ONAMI was formed (and funded by the State of Oregon) in 2003 to locally respond to the implications—both benefits and challenges—of accelerated technological advancement and global integration. The gifts of freedom, prosperity, and global peace (comparatively speaking) have raised the stakes for communities, regions, and nations to enable their citizens and institutions to create and deliver economic value commensurate with their consumption, as determined by a global marketplace that increasingly erodes the economic potency of political borders.

The current “state of play” calls for critical and apparently non-substitutable collaborative roles for (a) researchers/inventors, (b) entrepreneurs/early-stage investors, (c) large manufacturing and “customer-facing” businesses, and (d) governance at all levels in order to sustain and reasonably distribute the productivity and opportunity growth that has led to human flourishing in the leading economies—and to do so without undermining the human responsibility and initiative that made the productivity and opportunity possible in the first place.

Two important examples of these changing interdependent roles are (1) increasing outsourcing of early-stage R&D to universities and startups (which requires both early-stage capital and large-company customers and scale-up partners) and (2) “horizontalization” of large-company roles, e.g., even large original design manufacturers (ODMs) such as Apple and Hewlett-Packard have become customer-facing operations, relying on contract manufacturing firms for production and even supply chain operations. These developments are mature in the electronics and pharmaceutical industries and are moving to other sectors such as energy and materials.

Just as nanotechnology is a convergence of previously distinct science, engineering, and medical disciplines, the laws of the human ecosystem (economics) are becoming a convergence of knowledge and knowledge workers, innovation, and productivity enhancement in major industries and markets, and entrepreneurship and risky leadership and investment in disruptive advancements that at first threaten, but ultimately transform, large private and public organizations.

ONAMI’s chosen approach is project-centric. It funds collaborative developments involving research institution assets (intellectual property [IP], talent, and facilities), entrepreneurial ventures (with experienced management teams), a regional industrial base in materials and device
manufacturing, and public economic development functions that are rapidly evolving (from corporate recruiting from and assistance to “mom & pop” operations to cluster development, “gazelle” company, and “economic gardening”).

The crucial inputs to the process are technology IP, a startup business plan, and a project team to advance them both. The “gap project”\(^7\) consists of up to $250,000 in 3–4 installments of milestone-tranched grant funding and rigorous periodic technical and business review. The desired output is an “investable company” (Figure 4.6), as defined by terms acceptable to “super angels,” angel groups, venture capital firms, and (typically, later) private equity/capital management firms.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{onami_gap_fund_process.png}
\caption{The ONAMI gap fund process (courtesy of S. Rung).}
\end{figure}

In the simplest terms, what new technology startups need is a good chance for the kind of breakthrough economic performance that only significant innovations can achieve and that require a transition in orientation from “technology push” to “market pull” as evidenced by successful sales to and partnerships with significant (i.e., large) customers. With venture capital increasingly scarce (because of poor performance) and demanding (“capital efficiency”), the expectations for deal quality are bracing. Business community and local government assistance (in many forms, including limited partner investments) can provide the necessary edge.

ONAMI’s results with this process have exceeded expectations (see (Figure 4.7). As of 2012, approximately $6 million has been committed and $5 million disbursed, resulting in over $112 million in leveraged funds ($96 million in private capital, $16 million in SBIR/STTR and other government grants) to ONAMI gap fund portfolio companies (Figure 4.7). All of the companies are early-stage—two-thirds are pre-revenue—but most of them are candidates for making world-impacting differences in medical devices, cancer treatments, semiconductor fabrication, energy generation and storage, solid state lighting, flat-panel display manufacturing, and water resource management (see http://www.onami.us/commercialization/current_gap_projects).

Not every gap project has been successful, but the experience is consistent with the original intuition that deep collaboration between technical and business development talent (both of these guided by outstanding leadership and mentoring) is a critical factor in success. The “investment” criteria therefore remain unchanged: build a solid business plan oriented around customer/strategic partner needs, a clear definition of the “gap” to be crossed, and quantified success criteria for in-project milestones and end-of-project goals.

\(^7\) In general terms, the “gap” is the normally underfunded period in the evolution of a new technology development between the time it is funded at the R&D level and the time, when applied in a startup business, that it successfully attracts adequate commercial investment funding and/or becomes a profitable enterprise.
4. Methods to Improve and Expedite Convergence

4.8.4 ICTAS as an Exemplar of an Organization Built on the Foundation of Converging Technologies

Contact person: Roop Mahajan, Virginia Polytechnic Institute and State University (Virginia Tech)

Converging interdisciplinary research as a mode of discovery and learning is a powerful paradigm. It allows us to break down and restructure our knowledge about a subject in order to gain new insights into its nature and to use our imaginations to invent and innovate. A report from the National Research Council of the National Academies, *Facilitating Interdisciplinary Research* (NRC 2005), considers interdisciplinary research to be “one of the most productive and inspiring of human pursuits—one that provides a format for conversations and connections that lead to new knowledge” (p. 16).

Perhaps nowhere is the potential of interdisciplinary research more promising than at the intersection of the four converging NBIC technologies. As noted by Roco and Bainbridge (2003), this set of powerful technologies is poised to unleash a new understanding of matter at the atomic scale and of the complex working of the human brain, creating opportunities for new industries and jobs and enhanced human capabilities. While each of the original NBIC technologies is powerful, with the potential for huge impact, it is the interfaces between them that are most transformative and exciting. However, in harnessing these technologies, attention must be paid to unintended consequences, as well as to the short- and long-term implications of these technologies in a range of areas that include the environment, quality of life, and human dignity (Fisher, Mahajan, and Mitcham 2006).

Motivated by these considerations, the Institute for Critical Technology and Applied Science (ICTAS) at Virginia Tech formulated a vision to be a premier institute to advance transformative, interdisciplinary research for a sustainable future. To this end, ICTAS decided to focus its research on tapping the potential of the confluence of the NBIC technologies, anchored by the principles of sustainability (Figure 4.8), where sustainability is defined as a metadiscipline that integrates economic, social, and environmental processes to meet the needs of the present without compromising the ability of future generations to meet their needs.
The following research thrust areas selected for investment and advancement are either a subset of or at an intersection of these technologies: nanoscale science and engineering, nano–bio interface, cognition and communication, sustainable energy, sustainable water, renewable materials, and national security. Considering the nature of our times when technology progresses at breakneck speed, another thrust area, “emerging [disruptive] technologies,” was added as a focus. Each of these thrust areas is populated by interdisciplinary research teams ranging from a roster of twelve or more faculty members to smaller teams of four to six researchers. A minimum of two doctoral students per faculty member/researcher is the norm.

In the nano–bio thrust area, for example, research is carried out under the umbrella of six research teams engaged in investigating cellular interactions with nanostructured surfaces; the seamless union of computational and experimental models to drive the next generation of advances in tissue engineering and in systems biology; multiscale bio-engineered devices and systems; nanoscale assembly of biological building blocks to understand healing mechanisms; regenerative medicine in animals; and targeted delivery of multifunctional nanoparticles for imaging, therapeutic, and immunological applications.

It is estimated that the sphere of influence of ICTAS activities is at least 60% on the Virginia Tech campus, where 5 of the 8 major colleges are represented on the ICTAS Stakeholder Board: the College of Engineering, College of Science, College of Agriculture and Life Science, College of Natural Resources, and Regional College of Veterinary Medicine. ICTAS interacts with all of these colleges substantially (and to some extent with the remaining three colleges) and supports their faculty in the strategic areas of ICTAS (NBIC-based) research through facilities, seed grants, equipment, matching funds, start-up funds, and large proposal development.

Activity focus areas for the next years are included in the ICTAS strategic plan for 2012–2018; ICTAS holds frequent meetings with thrust leaders, who are leading scientists/engineers in their fields, to brainstorm where the technology/science is headed. Projects are then selected on the basis of members’ unique capabilities and a goal of being among the top three in the selected field. For example, Sustainable Agriculture was added as a thrust area to pursue in the next few years. “Black swan” seminars are held to help identify new areas of research to seed and grow. An example is the Virginia Tech project, the “Humanoid Hospital and Hospital Room of the Future.”

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8 Thrust leaders include Mike Hochella (nanoscale science and engineering), Marc Edwards (sustainable water), Jeff Reed (cognitive communications), and Naren Ramakrishnan (discovery analytics).
Supported by over 180,000 square feet of state-of-the-art collaborative laboratories spread over three buildings in Blacksburg and 6,700 square feet of rental space in the Virginia Tech Research Center at Arlington, ICTAS has grown significantly since 2006 in its contribution to the research and learning enterprises of Virginia Tech. Research expenditures over the first five years grew tenfold to a level of over $80 million/year in FY 2011. This has been made possible by the collaborative work of over 300 faculty members\(^9\) from a wide spectrum of disciplines spanning engineering; the physical, life, and social sciences; and the humanities.

Looking ahead, NBIC will continue to serve as platform technologies for ICTAS, at least for the next decade. However, these technologies will give rise to or will be supplemented by cutting-edge developments in various other technology fields, i.e., emerging technologies. In a *Wall Street Journal* op-ed, “The Coming Tech-led Boom” (January 30, 2012), Mark Mills and Julio Ottino named three grand technologies—big data, smart manufacturing, and the wireless revolution—poised to transform the 21st century as much as telephony and electricity did in the 20th century. Other novel technologies, so-called “black swans,” may not yet have been recognized but may still carry an extreme impact. Best-selling author Nassim Nicholas Taleb in his book *The Black Swan* (2010) defines a black swan as an event that has three characteristics: it is an outlier; it carries an extreme impact; it has retrospective predictability. He further makes a claim that our world is dominated by black swans. To identify future disruptive technologies, ICTAS holds a monthly “Black Swan” seminar series that generally focuses on a broad field of inquiry and is guided by the question, “What technology/innovation idea will transform your field in seven years?” These seminars are open to all who want to innovate and stay ahead of the times.

Built on a strong foundation of the converging technologies, ICTAS is well-positioned to integrate emerging technologies and sustainable practices to bring positive transformation in the lives of people locally and globally.

### 4.8.5 Knowledge and Technology Convergence and Decision Analysis

**Contact persons:** Matthew E. Bates and Igor Linkov, U.S. Army Corps of Engineers, Engineer Research and Development Center

Developments in transportation, information technology, and the physical, life, and social sciences have led to discoveries, knowledge, products, and capabilities that have revolutionized science and changed how we live our lives. Although independent progress in these fields has been invaluable, the increasingly complex nature of our world and its management requires additional fusion of information and intentioned synchronization between fields and across organizational, temporal, spatial, and social scales to develop converging technologies and knowledge capable of solving the most pressing economic, technical, and social problems facing humanity now and in the future.

Previous attempts to understand the convergence of disparate fields for social benefit have been largely qualitative and not well integrated across management levels. This NBIC2 study addresses the mechanisms of convergence where decision analysis can be adapted to align with convergence. For example, in previous studies, bottom-up approaches provided available technical information to organizational decision-makers as raw data or, at best, as visualized through the use of statistical tools and dashboards. Without additional decision tools integrating information across scales and domains and quantifying tradeoffs from stakeholders and top leadership, the ensuing decisions were limited to ad hoc treatment of the provided data based on management intuition, expert opinion, and often misleading oversimplifications (Hammond, Keeney, and Raiffa 1998).

Similarly, top-down approaches implemented by governments and leading scientific organizations as road maps and vision statements have been helpful in guiding various communities towards information fusion at the highest levels, but they have lacked concrete and prescriptive means to

\(^9\) This number does not include faculty supported in earlier years or through provision of laboratory space, equipment, etc.
guide the daily technology-development decisions through which convergence ultimately takes place. This lack of practical decision relevance in projects has been noted on several occasions by the scientific community, with calls for the adoption of quantitative decision-analytical frameworks that fuse relevant data and preferences from all levels of the management hierarchy and social structure and use transparent and replicable decision tools with this information to guide decisions from a holistic perspective (NRC 1996; NRC 2009d; OECD 2003; The Presidential/Congressional Commission on Risk Assessment and Risk Management 1997; NSTC 2011).

Decision analysis is a science with tools relevant for supporting a broad range of economic, social, and technical decisions at the organizational, national, and international levels. It aids knowledge and technology convergence for social or other benefit through the fusion of preferences and information across temporal, spatial, and organizational scales and domains. Decision analysis has developed over the past half-century drawing on ideas from operations research and the cognitive and management sciences to transparently and quantitatively identify the underlying values guiding decisions, map those values to data for comparing alternatives in a specific decision context, integrate all relevant preferences and information available from any level of the management hierarchy, and fuse this information to evaluate decision alternatives or potential product designs (Raiffa and Schlaifer 2008; Keeney and Raiffa 1993). These methods transcend the directional hierarchy of typical approaches by combining technical information and needs (bottom-up) strategies with broad organizational, national, or international objectives and tradeoffs (top-down) strategies to guide the creation and selection of alternatives from a holistic perspective.

Of particular interest are the Multi Criteria Decision Analysis (MCDA) and Value of Information (VoI) analysis tools. Based on available scientific information, MCDA identifies feasible alternatives (typically enumerated by experts) and decision criteria (typically from decision-makers), assess the performance (via experts) of each alternative relative to those criteria, and elicits or explores relative priorities (from stakeholders and decision-makers) among the continuum of incommensurable criteria (e.g., characteristics that cannot be reduced to single units, as in a cost-benefit analysis) (Linkov and Moberg 2012; Tervonen and Figueira 2008). VoI analysis extends MCDA by further identifying uncertainties whose resolution has a good chance of changing the decision or that most undermines confidence in the results. This leads decision-makers to guide knowledge and technology convergence for social benefit by quantitatively demonstrating how differences in the design of integrated products or technologies affect long-term, holistic social outcomes (Howard 1996; Linkov et al. 2011; Linkov, Bates, et al. 2012) (Figure 4.9).

The ad hoc nature of many current technological decisions is worrisome because knowledge convergence and the management of emerging technologies are filled with complicated, contentious, and risky decisions. For example, a manufacturer’s choice to use a specific type of nanomaterial in a new biomedical device may involve significant uncertainty about life-cycle material properties, dozens of potential process inputs and consequences, unknown human health and environmental risks, multiple stakeholder groups, competing objectives, and dynamic nonlinear interdependencies that test the limits of unaided human judgment. In situations like these, without structured decision processes that incorporate computational exploration of uncertainties and holistic trade-offs, human decision processes can often lead to erroneous, inefficient, or suboptimal outcomes that decision-makers may later come to regret (Linkov, Cormier, et al. 2012).

Formal decision analysis is useful for guiding knowledge and technology convergence because it is entirely transparent and quantitative (Raiffa and Schlaifer 1993; Keeney and Raiffa 1993). With all data, values, perspectives, and relevant information clearly specified in a governing framework and applied to the data of each unique decision, all parties now and in the future can be made aware of and deliberate the pros and cons of alternative pathways towards convergence.
4. Methods to Improve and Expedite Convergence

Figure 4.9 Example of a five-step decision analysis process to integrate quantitative and qualitative information across organizational, temporal, and spatial scales to develop alternatives, evaluate decisions, and prioritize research from a holistic perspective encompassing multiple decision criteria (Bates et al. 2012; ©NanoToday/Elsevier, permission for reuse through RightsLink).

This also enables scenario and sensitivity analysis, where impacts on individual decisions can be assessed based on possible differences in perspective or data (Karvetski, Lambert, and Linkov 2011; Montibeller, Gummer, and Tumidei 2006). Also, by eliciting and incorporating information from all relevant organizational, political, and social levels, applications of decision analysis transcend many limitations of traditional bottom-up and top-down approaches.

Applied at the organizational level, quantitative decision frameworks can help businesses and organizations efficiently navigate technological decisions and maintain consistent direction toward their organizational goals. At the national or international level, instead of letting organizations of scientists and engineers independently stumble towards convergence, governments and scientific authorities can aid the process by clearly specifying the objectives of technological progress.
Recognizing that convergence is not an end in itself but rather a means toward more sustainable and equitable social outcomes, decision frameworks can be used to clearly communicate and quantify the goals of the desired future. For example, governments and scientific academies can systematically explore their decision preferences, reveal their decision criteria (perhaps drawing from the three common economic, environmental, and societal pillars of sustainability), and quantify their values and the tradeoffs between criteria to provide practical and decision-relevant guidelines for individual scientific organizations to follow. These guiding frameworks can then be applied to evaluate the long-term net expected social or other benefits of specific variations of converging technologies being developed, drawing from knowledge and components in different scientific and engineering fields.

Decision analysis tools explicitly take into account data and preferences across many scales and domains and quantitatively relate this information to outcomes on multiple management criteria, helping decision-makers transparently and consistently create better alternatives, identify preferable decisions, and guide knowledge and technology convergence for holistic social benefit (Keeney 1992).

4.8.6 Achieving Continuous Operation of Huge, Complex, and Ever-Changing Systems in the Nanotechnology Era

Contact persons: Mario Tokoro, Professor, Faculty of Science and Technology, Keio University, and President and CEO, Sony Computer Science Laboratories, Japan

In the nanotechnology era, every system becomes smart, compact, and small, and at the same time huge in functionality, complex in structure, and ever-changing to meet the requirements of users. These systems are often connected to each other to form much more complex ones, and the boundary of a system becomes vague. Our daily lives are supported by such systems, from telecommunication to traffic and distribution, from manufacturing to financing, and from healthcare to defense. The prevention of a failure, and isolating a failure from propagation when it occurs, becomes crucial to achieve continuous operation of such systems.

Open systems dependability is a methodology of achieving continuous operation of huge, complex, and ever-changing systems. It sees such a system as an “open system” (as these words are used in scientific language), in which failures cannot be completely prevented, and therefore, minimizing the damage, identifying the causes, and achieving accountability have the highest priority.

The DEOS process (dependability engineering for open systems; http://www.dependable-os.net/) is defined as one that integrates the continuous development process (forever changing nature) and the operational processes that overlap with the continuous development process. It is applicable not only to ICT (information, communication, and technology) systems but also to a wider range of systems, including mechanical and cyber-physical ones.

4.8.7 Scenario Development Approach

Contact person: Cynthia Selin, Arizona State University

The future of emerging technologies is not preordained and can therefore not be predicted. There are critical uncertainties surrounding both the technological pathways and the societal implications of scientific discoveries. The development of emerging technologies depends on choices made today, choices that occur throughout society—in the boardroom, within the laboratory, in the legislature, and in shopping malls. There are numerous complex, interrelated variables that impinge upon what those technologies will ultimately look like in ten years’ time. Future-oriented methods like scenario planning provide a means to structure key uncertainties driving the co-evolution of technology and society. These critical uncertainties range from the health of the economy, to regulatory frameworks, to public opinion, to the actual technical performance of many of nanotechnology’s projected products. Anticipation and foresight, as opposed to predictive science,
provide means to appreciate and analyze uncertainty in such a way as to maximize the positive outcomes and minimize the negative outcomes of new technologies. The value of scenario development in particular is to rehearse potential futures to identify untapped markets, unintended consequences, and unforeseen opportunities.

4.9 INTERNATIONAL PERSPECTIVES

The following are summaries relevant to this chapter of discussions at the international regional WTEC NBIC2 workshops held in Leuven, Belgium, September 20–21, 2012; in Seoul, Korea, October 15–16, 2012; and in Beijing, China, October 18–19, 2012. Further details of those workshops are provided in Appendix W.

4.9.1 United States–European Union NIBIC2 Workshop (Leuven, Belgium)

Principal discussants:
Christos Tokamanis, European Commission (EU)
Françoise Roure, OECD (France)
Alfred Nordmann, Darmstadt Technical University (Germany)
Sylvie Rousset, Université Denis Diderot (France)
George Whitesides, Harvard University (U.S.)
Bruce Tonn, University of Tennessee (U.S.)
Jo De Boeck, IMEC (EU)
Barbara Harthorn, Center for Nanotechnology in Society, Univ. of California–Santa Barbara (U.S.)
Maurizio Salvi, European Commission (EU)
Mark Lundstrom, Purdue University (U.S.)
Mira Kalish, Tel Aviv University (Israel)
Todd Kuiken, Woodrow Wilson International Center for Scholars (U.S.)

This group of scientists found consensus around three important themes: (1) human development, (2) sustainability and human development, and (3) co-evolution of human development and technology.

Prof. Alfred Nordmann and colleagues (under the subtitle “Magic Moment in History – Sound Science Policy Concept”) presented the evolution of the concept, suggested a definition, and spoke about methods of convergence. Converging technologies are enabling technologies and knowledge systems that enable each other in the pursuit of a common goal—through neither emergence, nor planning, but through agenda-setting that achieves robustness through a political process. There are two ways of considering “converging technologies”: as a technological push and as a policy initiative. The main challenges are the following:

- Defining methods of convergence and essential technology platforms based on developing mechanisms for matching diverse research capabilities to societal needs.
  - Two core ideas here were (1) an emerging trend to use personalized and molecular information to enhance both medical treatment and cognition, and (2) individualized long-term education.
- Examining and assessing human–technology co-evolution, i.e., placing S&T research in the context of social science and humanities research (since all technologies structure human–human and human–nature interactions).
  - The core idea here was using convergent technologies to enhance human sustainability. It includes using recycled water and sea water as sources of clean water, nutrients, and materials; urban planning for megacities—maximizing positive effects; and renewable materials.
• Providing a knowledge generation-to-governance framework, i.e., allowing for inclusive agenda-setting processes.
  o The core idea here was the accelerating co-evolution between human development and technology by using the societal convergence approach. The image of robots as taking abilities and jobs away from people is changing: it is better to view robots as assisting and being complimentary to people; people are the robot creators and controllers.

An example of a convergence network in France was presented by Sylvie Rousset. Since 2005 in France, the Centers of Competence in Nanosciences for the Ile-de-France region (C’Nano IdF) has been established at the initiative of the National Research Centre (CNRS), the French Atomic Energy and Alternative Energies Commission (CEA), and the Ministry of Higher Education and Research (MESR). This network of 2700 researchers federates the largest European cluster in nanoscience and technology, coming from multidisciplinary fields that range from natural sciences to the human and social sciences (including physics, chemistry, engineering, medicine, biology, toxicology, law, philosophy, sociology, and economics). The existence of large technology facilities with technology platforms and a synchrotron plays a key role in the emergence of highly innovative interdisciplinary projects. Another example is the Interuniversity MicroElectronics Center (IMEC) with bio-nano-cogno programs in Leuven, Belgium.

The time has come for convergence between the USA-NSF NBIC initiative (2001 workshop) and the EU, owing to the numerous accomplishments in industry, academia, medicine, and government (see the EU report, Converging Technologies—Shaping the Future of European Societies [Nordmann 2004]). The formation of a meeting point platform to combine and bridge basic research (bottom-up) and the application-driven research (top-down) in the converged micro and macro environment will pave the way to ensure overall progress.

4.9.2 United States–Korea–Japan NBIC2 Workshop (Seoul, Korea)

Panel members/discussants:

Jo-Won Lee (co-chair), Hanyang University (Korea)
Mihail Roco (co-chair), National Science Foundation (U.S.)
Takahiro Fujita (co-chair), NIMS (Japan)

Others:

Hanjo Lim, Ajou University (Korea)
Y. Eugene Pak, Seoul National University (Korea)
Jian Cao, Northwestern University (U.S.)
Jim Murday, University of Southern California (U.S.)

Considering the enrichment of human life without our present concerns such as sickness, climate change, and running out of natural resources, NBIC would be a key technology to ease our concerns and may be a solution provider. Increasing scientific and technological complexity with all the necessary core capabilities cannot be sustained in one discipline. This vision has not been changed for the last 10–12 years since the first NBIC report was published (2003), even if many goals are only just getting under way. NBIC, robotics, virtual reality, avatar approach, human–machine interfaces, and other CKT approaches will become dominant in the next decade.

An example of a multidisciplinary platform is the International Center for Materials Nanoarchitectonics (MANA) in Japan. A general method to enhance convergence is creating environments to stimulate encounters with disparate disciplines.

Equipment is needed for communication and virtual reality to allow converging platforms and networks to operate.
Urgent global problems in the 21st Century are population growth, shortage of resources and energy, greenhouse effects, deterioration of biodiversity, shortage of food and water, and the aging population are given conditions in converging society planning. New technologies in the 21st century should be designed for meeting global issues and social wishes. A specific method of convergence for new technologies is inverse design based on science for design. Examples of visible social wishes for converging society are green innovation, life innovation, and recovery and reconstruction from a disaster, as illustrated, for example, in the Japanese 4th S&T Basic Plan (2011–2015). Potential/invisible social wishes, such as having an active aged society, are important (Yoshikawa 2012). The interaction between society and scientific community needs to be a closed loop, combining application of science to society with society tasks driving science and technology. A better science of science is needed.

An approach to advance convergence in a domain of activity is through the mission of dedicated organizations. An example for environmental aspects is South Korea’s Korea Environmental Industry and Technology Institute (KEITI), whose focus areas are shown in Figure 4.10.

Over the past decade, the R&D approach for converging technology has been generally “reactive” in achieving a collaborative approach (compared to the NBIC2 holistic, systematic approach). From “Priority R&D Areas” driven research we are moving to “Social-Issue Targets”-oriented research (i.e., from “seeds push” to “needs pull” science and technology). “Scientific challenges” make big breakthroughs for real applications, judging from history. “Social-issue targets” should be well translated to the scientific way of thinking and scientific approaches.

All twenty illustrations cited in the first NBIC report have seen significant progress (see Appendix D). The vision for the next ten years includes a systematic convergence (proactive and holistic) of various domains of knowledge, technology, and society. Creating a database with an expert system to select the method of convergence to accelerate unprecedented discoveries and innovation is a priority. Important drivers will be robotics, bionics, and road-mapping using a holistic view of human society. A higher-level convergence language needs to be developed that will facilitate integration into essential platforms and facilitate innovation (confluence of streams), improved manufacturing (hybrid methods, cyber-physical systems), and advances in all emerging technologies. Personalized, online, life-long education, combined with advances in neuroscience, communication, psychology, and understanding of learning, will be needed for the human-scale convergence platform. Observatories and simulation for Earth’s dynamic systems, new sensing, large data, etc., will be needed for Earth-scale convergence platforms. The focus will be on communities and on addressing major issues affecting those, using converging technologies. Self-regulating convergence among communities is facilitated by organizations such as professional societies and NGOs. Changes in governance will be needed, especially for changes that depend on a holistic view. There is a planned converging technologies organization to be created in the Office of the Prime Minister in Korea.

Several emerging topics and priorities emerged in the discussions:

- Self-reliant communities for sustainable development
- “Platforms” for interdisciplinary collaboration that include host communities and shared resources and expertise, e.g., portal websites serving diverse S&T communities
• Define specific, realistic “grand challenges” in problem-driven research, such as brain-inspired neuromorphic devices, digital and distributed manufacturing, Earth-scale interventions, and personalized health and education

• Enhancement of human quality of life enabled by individual “pursuit of happiness”

• International collaboration to enhance the value and reduce the risk in this high-return area

4.9.3 United States–China–Australia–India NBIC2 Workshop (Beijing, China)

Plenary speaker: Chunli Bai, Chinese Academy of Sciences (CAS)

Panel members/discussants:

Dongyi Chen (co-chair), University of Electronic Science and Technology (China)
Ron Johnston (co-chair), Australian Centre for Innovation
Mike Roco (co-chair), National Science Foundation (U.S.)

Others:

Xing Zhu, Peking University (China)
Jian Cao, Northwestern University (U.S.)
Ke Xu, Suzhou Institute of Nano-tech and Nano-bionics China)
James Murday, University of Southern California (U.S.)
Calum Drummond, CSIRO (Australia)

Convergence of important frontier technologies, such as those represented by NBIC, will be crucial to the ways in which we innovate, and eventually to the success of human society (Chunli Bai, plenary presentation on September 17, 2012). In China, important steps have already been made in tearing down the traditional boundaries of individual scientific disciplines. For example, the CAS has set up entirely new research entities to explore convergent technologies. In Shenzhen, Chongqing, and several cities, China is organizing research institutes that combine information science, advanced manufacturing, and biomedicine.

Developing compatible standards for different fields is an important tool for convergence. This may allow for establishing a common language for scientists, engineers, industry, regulators, and the public.

An approach to integration is supporting personalized, online education, combined with advances in neuroscience, communication, psychology, and understanding of learning. Another approach is to focus on communities and major issues affecting them using converging technologies and a self-regulating approach. Changes in governance (structures and measures to reach decisions and solve conflicts) will be needed for achieving societal benefits. Updating government organizations and regulations will be required.

Multidisciplinary teams are inadequate for the challenges of this century unless they are also transdisciplinary; knowledge of each team member should span multiple disciplines. There is a need for continual refinement based on both top-down strategies and bottom-up findings.

An illustration for a converging center is Suzhou Industry Park (China), co-located with the National Nano-tech Innovation Park, both focused on nanotechnology and nanobiology. It includes one institute of the Chinese Academy of Sciences, more than 20 universities, about 50 engineering research centers, and more than 1000 spin-off high-tech companies.

Several emerging topics and priorities are:

• Implement investment policy in multisector, multidisciplinary centers and networks

• Develop standards for various fields in convergence platforms

• Expand and institutionalize the programs “science for science” to “science for governance”
• Explore mechanisms to engender more effective stakeholder contributions towards improvements in personalized education

• Open access to all S&T journals, to promote accelerated advancement of converging technologies, resolution of IP issues, and exploration of the rewards system vs. the advantages of open access.

4.10 REFERENCES


4. Methods to Improve and Expedite Convergence


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