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

RETROSPECTIVE AND OUTLOOK SUMMARY
Summary of the international report

Mihail C. Roco • William S. Bainbridge • Bruce Tonn • George Whitesides
Study on Convergence of Knowledge, Technology, and Society:
Beyond Convergence of Nano-Bio-Info-Cognitive Technologies

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The cover picture (the “conductor”) suggests coordination through societal governance of the essential knowledge and technology platforms to realize a vision of their convergence to benefit society. The background is a view of the Romanian Athenaeum concert hall. (Image courtesy of Jackson Fine Art, Atlanta, and the artist. Image copyright, David Leventi.)

This booklet is a summary of the report, Convergence of Knowledge, Technology, and Society; Beyond Convergence of Nano-Bio-Info-Cognitive Technologies (M.C. Roco, W.S. Bainbridge, B. Tonn, and G. Whitesides), Springer, Dordrecht, 2013. This is a World Technology Evaluation Center (WTEC) study with sponsorship by the National Science Foundation. The complete text and image credits of the report can be found at http://www.wtec.org/NBIC2-Report. The logos above represent the U.S. Government agencies that supported the study.

RETROSPECTIVE AND OUTLOOK SUMMARY

For societal benefit, human development

Earth-scale platform

Foundational tools—NBIC

Human scale & quality of life

Innovative & responsible society and governance

Values system and morality

The conductor suggests societal governance of converging platforms for societal benefit

Mihail C. Roco, William S. Bainbridge, Bruce Tonn, and George Whitesides

NSF/WTEC report 2013
The full report is published by Springer
In their 2011 book *That Used to Be Us*, Friedman and Mandelbaum identify one of the main challenges for the United States as bringing activities together driven by a higher national purpose—to “act collectively for the common good.” This report on the Convergence of Knowledge, Technology, and (for the benefit of) Society (CKTS) aims to address that challenge in a general, long-term context by identifying the basic principles of convergence of human activity—including for knowledge creation and technological innovation—and proposing a transformative approach to benefit society. The report discusses an alternative to the focus on specialization.

The CKTS report outlines convergence principles, mechanisms, and possible system solutions for societal challenges in the next decade, including those of creating new knowledge, industries, and jobs; addressing population growth, massive urbanization and globalization; providing national security; improving lifelong wellness and human potential; achieving personalized and integrated healthcare and education; addressing environmental issues; and securing a sustainable quality of life for all.

This study originated with a set of research assumptions on convergence that were validated and enhanced during five brainstorming workshops that took place at the locations shown in the following map. Participating in the workshops were leading experts from

- the United States
- the European Union
- Latin America
- Japan and Korea
- China, Australia, and other countries.

The CKTS study was supported by U.S. Federal agencies: the National Science Foundation (NSF), National Institutes of Health (NIH), National Aeronautics and Space Administration (NASA), Environmental Protection Agency (EPA), Office of Naval Research (ONR), and U.S. Department of Agriculture (USDA), with co-sponsorship by international partners who co-hosted four of the brainstorming workshops. The study goals are to:

1. Understand how convergence works and how it can be improved and implemented
2. Chart trends for the next decade
3. Identify opportunities for transformative actions to improve societal outcomes.

More information on the CKTS study may be found at [http://www.wtec.org/NBIC2-Report/](http://www.wtec.org/NBIC2-Report/) and at the Wilson Center website [http://wilsoncenter.org/convergence](http://wilsoncenter.org/convergence), where interviews with numerous study participants may be found. Springer ([http://www.springer.com](http://www.springer.com)) has published the full CKTS report as part of its series of science policy reports.
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OVERVIEW AND RECOMMENDATIONS

CORE OPPORTUNITY
Convergence of knowledge and technology for the benefit of society (CKTS) is the core opportunity for progress in the knowledge society of the 21st Century. This report presents the principles of convergence and its implementation mechanisms in the main knowledge and technology platforms of the human activity system, with implications in nearly all sectors of the system. This would change the connections, networking nodes, and the system itself.

DEFINITION
CKTS is defined as the escalating and transformative interactions among seemingly different disciplines, technologies, communities, and domains of human activity to achieve mutual compatibility, synergism, and integration, and through this process to create added value and branch out to meet human needs and shared goals. It allows society to answer questions and resolve problems that isolated capabilities cannot, as well as to create new competencies, knowledge, and technologies on this basis.

Convergence has been progressing by stages over the past several decades, beginning with nanotechnology for the material world [1], followed by convergence of nanotechnology, biotechnology, information technology, and cognitive science (NBIC) [2] for emerging technologies. CKTS is the third level of convergence [3].

FIVE PRINCIPLES OF CONVERGENCE
CKTS suggests a general process to advance creativity, innovation, and societal progress based on five general-purpose principles: (1) the interdependence of all components of nature and society; (2) decision analysis for research, development, and applications based on dynamic system-logic deduction; (3) enhancement of creativity and innovation through evolutionary processes of convergence, which combines existing principles, and divergence, which generates new ones; (4) the utility of higher-level cross-domain languages to generate new solutions and support transfer of new knowledge; and (5) the value of vision-inspired basic research embodied in grand challenges.

The CKTS report outlines possible solutions for key societal challenges in the next decade, including support for foundational emerging technologies to create new industries and jobs, improve lifelong wellness and human potential, achieve personalized and integrated healthcare and education, and secure a sustainable quality of life for all. It provides a ten-year “NBIC2” vision within a longer-term framework for converging technology and human progress outlined in a previous study of unifying principles across nanotechnology, biotechnology, information technology, and cognitive science—the “NBIC” fields—for improving human potential [2].

Convergence is at the forefront of scientific discovery and technology development, promising to become a foundational and integrating knowledge and transforming field, as information technology and nanotechnology already have done.

MECHANISMS OF CONVERGENCE

Effective and managed convergence to benefit society will require (also see Section 4):

1. Advancing interdependence of the natural and human activity systems (Figure 1), comprising four platforms; these platforms constitute a key organizing theme in the CKTS report:
   - Foundational emerging tools and technologies (nano-, bio-, info-, and cognitive technologies) in a system approach
   - Human-scale platform, characterized by interactions among humans, machines, and their environment
   - Earth-scale platform—the broad environment for human activities at the Earth scale
   - Societal-scale platform, characterized by human individual and collective activities, organizations, and systems

2. Decision analysis based on dynamic system-logic using hierarchical, cause-and-effect deduction.

3. Use of the convergence–divergence evolution approach (Figure 2) to enhance creativity, invention, and innovation.

4. Adoption of high-level cross-domain languages to support transfer of new knowledge and to generate new solutions.

5. Vision-inspired basic research to advance long-view objectives and grand challenges (Figure 3).

CKTS VISION FOR THE NEXT TEN YEARS

Timeline

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

CKTS aims to provide approaches for added value and synergistic benefits for human endeavors over the next ten years and beyond to:

- Improve wellness and human development
- Stimulate productivity and economic development, for example, by building new platforms such as the cellular phone.
- Empower individuals and communities, and overall, support the emergence of a “Cognitive Society” (Figure 4 & Section 6) to enable focused solution of the world’s most pressing problems.
- Achieve environmental and societal sustainability. For example, plan, build, and maintain an “earth monitoring center” (Figure 5 & Section 9).
- Provide support for human knowledge and education.
- Achieve an innovative and equitable society.

OPPORTUNITIES FOR ACTION

Including an international network and a national CKTS initiative

The envisioned benefits of CKTS are most likely to be realized through deliberate planning and concerted action, based on the five convergence principles proposed in this report and aiming at the vision components listed above. The CKTS study panel identified opportunities for international collaboration and proposed an international network to identify and support opportunities for convergence. It also proposed establishing a national CKTS Initiative that may be organized by a suite of centers, technology platforms, programs, organizations, and government coordination, as outlined below.

Centers

Research and education institutions would host centers and networks to support formation and advancement of CKTS, with three initial priorities:
Figure 4. Creating a cognitive society will involve providing cognitive and social support for individuals and communities; improving our understanding of the cognome—the cognitive equivalent of the genome; and personalized and affordable genomics. Achievement of the Cognitive Society will also provide opportunities for global economic leadership.

Figure 5. A commitment to sustainability must address the interacting Earth systems and incorporate complex continual monitoring capabilities and CKTS solutions for mitigation of problems and achievement of life security within the Earth system’s critical boundaries.

1. Theory and methods for measurement, evaluation, and informatics approaches for convergence platforms and processes.
2. A distributed education network to address CKTS horizontal (across disciplines) and vertical (along years of a person’s life) system integration.
3. Biomedicine centers that bring together biology, medicine, science, and engineering for health.

**CKTS Technology Platforms**

Platforms would focus on areas of national interest:
- Sustainable, distributed converging NBIC manufacturing technologies such as cyber-enabled distributed manufacturing, nanobiotechnology, and mind-cyber-physical systems.
- Cognitive society, brain research, and cognitive computing.
- Sustainable urban communities.
- Environmental sensors.
- Systemics and data integration.
- Increasing human potential.

**Programs and Organizations**

Integration is needed for evaluating methodologies to support a convergence ecosystem’s performance, R&D results providing information spanning from the human brain to Earth-scale systems, and development of new paradigms for understanding and communicating science and monitoring increasing human potential at all levels.

**Government Coordination**

The Federal Government would have the role of evaluating and supporting convergence opportunities in the Federal Government and between Federal and local governments in areas such as wellness, aging, and decision-making processes. A Federal CKTS Convergence office would provide support and guidance to national initiatives and current developments.
1. CONVERGENCE PLATFORMS: FOUNDATIONAL SCIENCE AND TECHNOLOGY TOOLS

ADVANCES IN THE LAST TEN YEARS

- The 2003 report *Converging Technologies for Improving Human Performance* (Figure 6) placed the separate NBIC fields within a unifying concept that all four are based on the cohesive structure and behavior of matter at the nanoscale (Figure 7), and that research in each area benefits from synergies with the other three. This basic assertion has been borne out by rapid and stunning discoveries and tool innovations that have arisen from and been applied in all four areas, such that now almost no R&D advance is made by an individual in a solitary scientific field but rather depends on far-reaching interdisciplinary work.
- Two examples of this concept are *cell phones* and *gene sequencing* (Figures 8 and 9), whose dependence on the convergence of multiple technologies has led to rapid improvements in functions, decreases in functional costs, and unprecedented rates of societal acceptance.
- A host of new physical and theoretical tools in all NBIC fields now allow imaging, visualization, manipulation, simulation, and synthesis of matter. These promise to fundamentally reshape a multitude of science and technology fields ranging from electronics, optics, and materials science to healthcare delivery, cancer treatment, “smart” agriculture, remote sensing and data management, computing, communication, and manufacturing.

VISION FOR THE NEXT DECADE

- Multidisciplinary research will progress to transdisciplinary work that will create entirely new fields at the intersections of traditional disciplines.
- Each of the NBIC disciplines will continue to evolve, becoming increasingly interdependent and powerful, where there will be growing use of tools and methodologies originally developed for specific disciplines by experts outside those disciplines.
- An entirely new class of converging technology tools will emerge that is not tied to any specific NBIC discipline, helping to integrate the pursuit of shared scientific, technological, and societal goals.
- Spin-off technologies will be developed at the confluence of NBIC domains.
- New educational paradigms will be developed to give students and practicing scientists and engineers the depth and breadth of knowledge they need to build and use the new tools that will allow society to realize the promise of converging technologies.
- Communication and cognitive potential for individuals and groups will increase.
- Physical and health potential to advance wellness will increase.
- A list of twenty visionary ideas for longer time intervals, including ideas on increasing productivity, extending the limits of sustainability, and enabling human and societal potential, are listed in the appendix of the CKTS report.
Figure 6. Convergence trends were apparent by the 2000s.

Figure 8. 1980s image-acquisition board and 2010 smart phone (iPhone 4). Converging technologies in smart phones include CMOS transistors for logic, III-V semiconductors for radio frequency transistors, analog–digital and digital–analog convertors, geo-location, digital signal processors, microprocessors, ROM and FLASH memories, CMOS imagers, gyroscopes, high energy-density lithium-ion batteries, MEMS devices, magnetometers, speakers and microphones, LCD displays and touch-screens, all with usability/design improved by social science research.

Figure 9. Gene sequencing cost trends, 2001–2012. The introduction of electronics approaches—micro-arrays, massive parallelization, and adoption of CMOS tools in second-generation Ion Torrent sequencing techniques dramatically decreased costs within a very short period of time. As in smart phones and tablet computers, multiple converging technologies developed in disparate fields have so improved functionality and reduced costs that the rates of public acceptance of new technologies are faster than at any previous time in human history.
2. CONVERGENCE PLATFORMS: HUMAN-SCALE CONVERGENCE & THE QUALITY OF LIFE

ADVANCES IN THE LAST TEN YEARS

Figure 10 represents the Human-Scale Platform for convergence in knowledge, technology, and society. The NBIC field with the greatest impact in its direct effects on human lives today and in the near-term future is information technology, although it is progressing in concert with nanoscience, biotechnology, and cognitive science.

- Democratization of the Internet has occurred via “Web 2.0”, “cloud computing”, “social media”, open-source software, and other means for Internet content creation and management by individuals rather than by large companies or government agencies.
- There has been a reconceptualization of computing as a service (sharing of knowledge), rather than as the sale of hardware and software products.
- Developing nations have rapidly adopted mobile communications/computing systems.
- Advancement has taken place of shared scientific databases, collaboratories, and virtual organizations to support sharing of R&D, all enabled by CKTS.
- Government agencies have begun using “virtual panels” to review scientific research proposals (Figure 11) as an example of the broadly expanded use of distance meeting and document sharing systems.
- A new field of study has developed to improve human–robot interactions for human benefit.
- Quality-of-life conceptualizations have moved from strictly economic to broader, more abstract ones.

VISION FOR THE NEXT DECADE

- Scientific R&D performed within the open-source paradigm will accelerate development, reproduction, adaptation, and replication of participatory organizational forms.
- Convergence will benefit from:
  - transparent, open-source models and process representations that can be expressed in both human-readable and computational forms
  - models and representations that can be visualized and computationally simulated and used across fields with different types and amounts of data
- New combinations of NBIC technologies will be engineered for direct application in human lives, e.g., assistive robotics and robotics for education uses, including education of children.
- Robotics technologies will become more available, inexpensive, pervasive, and consumer-oriented (Table 2 and Figure 12). They will follow the trend of convergence in computing; that is, there will be a shift toward social and cognitive support for individuals.
- Social sciences will be better integrated into NBIC fields to connect them and increase benefits. This includes expanding “citizen science” and creating “citizen social science”.
- Long-term ethical, legal, and social issues will be more proactively addressed.
- More democratic rules and policies will be developed for wise management of CKTS, enabling overall better and more sustainable quality of life for all people.
Figure 10. The human-scale platform for CKTS addresses human-human, human-technology, and human-environment interactions.

Table 2. Consumer shifts in computing and robotics

<table>
<thead>
<tr>
<th></th>
<th>1960 Computing</th>
<th>2010 Computing</th>
</tr>
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<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Institute-scale</td>
<td>Consumer-scale</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>Room-sized</td>
<td>≤ Desktop-sized</td>
</tr>
<tr>
<td><strong>Training of User</strong></td>
<td>Ph.D. level</td>
<td>None</td>
</tr>
<tr>
<td><strong>Technology Requirements</strong></td>
<td>Fast, repeatable, durable</td>
<td>Easy to use, portable, flexible</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
<td>Cryptography</td>
<td>Social networking</td>
</tr>
<tr>
<td></td>
<td>Scientific computing</td>
<td>Entertainment</td>
</tr>
<tr>
<td></td>
<td>Engineering design</td>
<td>Personalized search</td>
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</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>1975 Robotics</th>
<th>2025 Robotics</th>
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</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Institute-scale</td>
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<tr>
<td><strong>Applications</strong></td>
<td>Factory automation</td>
<td>Human-robot interaction:</td>
</tr>
<tr>
<td></td>
<td>Remote sensing</td>
<td>physical &amp; social,</td>
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<td></td>
<td>Dangerous materials</td>
<td>language</td>
</tr>
<tr>
<td></td>
<td>handling</td>
<td>&amp; communication</td>
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</tbody>
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Figure 11. One of the areas where virtual review panels are held by the National Science Foundation.

Figure 12. The National Robotics Initiative “co-robot” concept is that intelligent machines should be designed to partner with human beings and expand human capabilities in a wide variety of contexts.
3. CONVERGENCE PLATFORMS: EARTH-SCALE SYSTEMS

ADVANCES IN THE LAST TEN YEARS

The Earth-scale platform (Figure 13) includes both global environmental systems and man-made platforms and their integration. CKTS planning and policy must take into account both global bio-physical needs and human cognitive needs.

- **Knowledge systems**: Complex and nonlinear systems; theoretical frameworks for global environmental systems; a new discipline, Earth systems science; high-performance computing, data mining, modeling, and visualization; crowd-sourced research; rise of neutral international and local “boundary” advisory organizations (e.g., Intergovernmental Panel on Climate Change); and regional networks to help farmers and others address water, crop, livestock issues.

- **Monitoring/management systems and tools**: Systems and models for air and water quality and temperature, traffic, land use, global electric (Figure 14) and magnetic circuits, Sun–Earth interactions, etc.; GPS technology for transportation management and tracking of key species; modeling/simulation for more reliable prediction of extreme weather, energy system, and telecommunications events.

- **Information technology**: Expansion of bandwidth and access to computer networks, adoption worldwide of mobile devices and myriad applications, greater collaborative computing, and widening access to Earth systems data.

- **Energy**: Renewable energy industries such as solar, wind, and biofuels, and energy-efficiency technologies driving job creation and new views.

- **Space programs**: Growth in investments by developing nations and the private sector.

VISION FOR THE NEXT DECADE

- **Knowledge systems**: Increasing globalization of Earth-scale systems research (especially environmental); increasing spatial resolution in global climate modeling to facilitate more effective policymaking; greater integration of analytical frameworks and systems analysis into theoretical disciplines and their use to identify CKTS challenges and opportunities; an increasing number of boundary organizations; advances in IT and cognitive science to facilitate collaborative public policymaking.

- **Monitoring systems**: Increases by several orders of magnitude as costs drop; increases in real-time coverage of air/water/transportation systems; expanded satellite coverage and tagging of key species to improve ecosystem monitoring; increased monitoring by individuals of their health and that of their surroundings.

- **Communication systems**: Growing capability, sophistication, and adoption of systems, backed up by growing data and visualization capabilities, and NBIC systems that facilitate both R&D collaboration and policymaking.

- **Management systems**: “Smart” electrical grids, intelligent transportation and transit systems; testing of global cooling schemes; more intensive management of natural systems; increased understanding of short- and long-term global implications of manufactured nanomaterials in comparison to nanomaterials in nature (Figure 15) to set regulations—all of these supported by more robust databases.

- **Other systems**, including globalization of space, will contribute to the above trends (Figure 16).
Earth-scale platform

Earth systems (communication / interaction / economy / monitoring)

Global cognitive needs

Earth scale

Global bio-physical needs

Earth-technology integration (astronomy / space exploration / oceans / infrastructure / climate)

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**Figure 13.** The Earth-scale platform is part of the human activity system outlined in Figure 1.

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Inventory of nanoparticle (NP) occurrence

Soils worldwide produce $10^5$ times more NP's annually than industry

$<< 1 \text{Tg/yr}$

(est. $0.2 \text{Tg/yr} = 200,000 \text{mt/yr}$)

1,000's Tg/yr

1 Tg = $10^{12}$ g = 1 million metric tons

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**Figure 14.** The global electric circuit and its effects on Earth are complex and interrelated.

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**Figure 15.** On the left, estimated industrial production of nanoparticles; on the right, estimated global soil production of nanoparticles.

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**Figure 16.** Artist rendition of the Orbiting Carbon Observatory-2, scheduled for launch in 2015, which will perform precise, time-dependent measurements of atmospheric CO$_2$ levels.
4. METHODS TO IMPROVE AND EXPEDITE CONVERGENCE

ADVANCES IN THE LAST DECADE
A key component of governing the societal-scale platform (Figure 17) is advancing methods to improve and expedite convergence to promote creativity, invention, innovation, and socio-economic projects.

- In R&D work and corresponding publications, there has been evidence of collaborative approaches within two or three NBIC areas, increasing with an annual rate of about 25%
- Globally, various programs and organizations have aimed to support convergence efforts, e.g.:
  - U.S. NSF funding of multidisciplinary research and science of learning centers
  - EC annual converging technologies program; bio-nano-cogno focus at IMEC in Belgium
  - Russia's Kurchatov Center for Converging NBIC Sciences and Technologies
  - India's Center for Converging Technologies
  - Several programs in Japan, Korea, China
- NSF awards covering three or more NBIC areas have increased significantly (Figure 18), e.g., in quantum information science, eco-bio-complexity, neuromorphic engineering, cyber-physical systems, synthetic biology, nanosensors in the environment, adaptive systems engineering, and enhanced virtual reality.
- First steps have been taken for convergence in education, following various methods, including full convergence centers, e.g., MIT, Arizona State University, Virginia Tech (Figure 19), and Seoul National University.
- Even limited convergence is driving discovery and innovation around the world—a new source of competitive advantage in the global economy.

VISION FOR THE NEXT DECADE
- Proactive, systemic, holistic convergence will develop in various domains of knowledge, technology, and society.
- Higher-level convergence languages will be developed to identify integrators among domains and facilitate integration among platforms for improved creativity and innovation.
- One focus will be on personalized education and self-regulating convergence within communities.
- Government organizations and regulations will be updated to enhance and enable convergence.
- A science of convergence will emerge in decision-making, manufacturing, and other contexts.
- Goals to enable these developments include:
  - Creating a broad portfolio of means to support convergence in all phases of the innovation spiral (Figure 2): improved systems-based methods, collaborative approaches such as mind–cyber–physical platforms, informatics, manufacturing approaches, a vision-inspired basic research funding model (Figure 20), self-reliant communities, and open governance
  - New funding mechanisms conducive to convergent science/technology ideas, e.g., idea incubation prior to formal proposals
  - Improving network visualization techniques for identifying synergistic opportunities within other disciplinary communities
  - International sharing of models for exploiting global R&D investments in areas such as hybrid manufacturing, medical-cognitive advances, and governance science.
**Societal-scale platform**

Governance, investment policies, regulations

Moral, ethical needs

Societal scale

Health, education, infrastructure needs

**Human – technology co-evolution**

**Figure 17.** The societal-scale platform, which is a part of the human activity system outlined in Figure 1.

**Figure 18.** National Science Foundation funding of various domains of NBIC (at least two NBIC domains in each award), 1987–2012.

**Figure 19.** The vision of the Institute for Critical Technology and Applied Science (ICTAS) at Virginia Tech is to be a premier institute to advance transformative, interdisciplinary research for a sustainable future, tapping the potential of the confluence of the NBIC technologies, and anchored by principles of sustainability.

**Figure 20.** Schematic for the proposed “vision-inspired basic research” domain in the modified Stokes diagram, where a new quadrangle is dedicated to basic research for new and emerging applications inspired by a vision (new use) beyond the Pasteur quadrangle, which in turn tracks to the Divergence stage in the knowledge and technology convergence–divergence process shown in Figure 2 (figure based on that by Donald Stokes [1997]).
5. IMPLICATIONS: HUMAN HEALTH AND PHYSICAL POTENTIAL

ADVANCES IN THE LAST DECADE

Coincidental (“passive”) convergence in biomedical fields was focused in areas with the largest human and economic cost of injury, infection, and disease (Figure 21). Population aging compounds the urgent need for innovative science-based healthcare solutions (Figure 22).

- Information systems and hand-held devices developed to the point where they are now ubiquitous in medicine; this is transforming the relationships between symptoms and diagnosis, doctor and patient.
- Significant proofs of concept of nanotechnology uses in medicine and biomedical devices were achieved.
- A six-fold growth occurred in the relative “scientific market share” of immunology and vaccine research from 1953–2012, with acceleration in the past decade. The shares of cancer and heart research have about doubled.
- A rapid change took place in the physical form of medical records, where individualized paper-based medical records were largely replaced with networked electronic medical filing systems.
- A new NIH Office of Physical Sciences-Oncology has established a collaborative network of 12 physical science-oncology centers at U.S. universities to unite experts in medicine, biology, physics, chemistry, mathematics, modeling, informatics, engineering, and nanotechnology to rethink biomedical approaches to understanding and curing cancer. Similar efforts have begun in Europe.

VISION FOR THE NEXT DECADE

- Low-cost, multiplexed point-of-care and integrated diagnostics of the human immune system will be harnessed to achieve a new generation of vaccines/procedures for averting infections, cancer, and autoimmune diseases.
- Targeted, individualized treatments for cancer other diseases with vastly reduced side effects.
- Round-the-clock health monitoring will be achieved through smart wearable devices and smart homes (Figure 23 & Table 3) to inform and assist individuals and advance systemic understanding of wellness and disease.
- Vastly improved regenerative medicine and prosthetics based on progress in in vitro cell, tissue, and organ growth, new materials and device functionality, advanced electronics and sensors, ability to monitor and tap into brain signals, and prostheses with intelligent interfaces.
- Globalization of CKTS-based medicine R&D. Democratization and personalization of medicine with growing healthcare efficiency, and equality across the globe.
- Private and academic research will increasingly leverage government seed funding for research in and public–private partnerships for commercialization of healthcare solutions, and public engagement in public health governance.
- Convergence of medicine with NBIC technologies will improve wellness and human capacity through distributed “P4” medicine that is personalized, predictive, participatory, and preventative.
Summary of the 2011–2012 International CKTS Study

Figure 21. The worldwide economic cost of disease: cancer and heart disease together account for about $1.65 trillion annually.

Figure 22. As shown here for the United States, an individual’s medical costs dramatically increase with age. Society’s healthcare costs also grow over time as its population ages. In the United States healthcare costs were 5.1% of GDP in 1960 and 17.6% of GDP by 2009.

Table 3. Sample organization of a health smart home

<table>
<thead>
<tr>
<th>Networked items</th>
<th>Components the user interacts with</th>
</tr>
</thead>
</table>
| Smart home (internal) | • Vital sign measurement devices  
                      | • Mobility activity detection sensors  
                      | • Assistive technology devices  
                      | • Home environment control devices  
                      | • Information communication devices  
                      | • Entertainment devices |
| Hospital | • Physicians  
           | • Therapists  
           | • Nurses  
           | • Medical staff |
| Safety services | • Formal providers  
                      | • Informal caregivers  
                      | • Home security  
                      | • Social services |
| Daily life services | • Education reminders  
                           | • Health programs  
                           | • Shopping, banking  
                           | • Library, civil services  
                           | • Entertainment – TV, movies |

Figure 23. Two of many types of smartphone-compatible or networked personal biometric monitors coming on the market: (left) watch-like Basis (http://mybasis.com/) measures heart rate, perspiration, and skin temperature, and counts calories burned and steps taken; (on the penny) implantable Senseonics devices (http://senseonics.com/) measure and track blood glucose data over time. These kinds of devices help wearers—and healthcare providers—to set, track, and keep individuals’ health goals and reduce the need for medical intervention.
6. IMPLICATIONS: HUMAN CONGNITION AND COMMUNICATION

ADVANCES IN THE LAST DECADE

Human society faces huge cognitive, physical, and communicative challenges, the solving of which depends on the effectiveness and extent of human vision and decision-making. These are in turn functions of human cognition and human–human interactions. Advances in understanding and managing these functions depend on all aspects of converging knowledge and technology; examples follow.

- Noninvasive brain imaging / stimulation gains:
  - Functional-MRI (fMRI) now dominating cognitive and neurophysiological studies
  - Recognition of nonverbal communication modes: spatial cognition, alternative sense modalities, brain–brain, and brain–machine
  - Emergence of neuromorphic engineering
  - Nanoelectronic emulation of some brain functions
  - Transcranial magnetic stimulation providing new ability to activate or inhibit specific brain areas, opening up new therapy options
- Mobile computing, social networking, and citizen journalism broadened possibilities for knowledge retrieval, communication, and participation of citizens in politics and science.
- Social enabling of Big Data.
- Low-cost, personal genomics (Figure 6).
- Distributed “Maker” design and manufacturing technologies (Figure 24) that empower creative people in individual and shared locations.
- All these advances share ubiquity: cutting-edge technologies have become smaller, faster, and embedded in daily life (Table 4).

VISION FOR THE NEXT DECADE

- Globally, augmented and embodied cognition will enhance and support human interaction and our understanding of society and nature.
- A new concept, the “Cognome”, will provide a blueprint for higher cognition (both individual and social) and enable a fuller understanding of our own human potential and limitations within the complete evolutionary human activity system.
- Robotics and other technologies increasingly will provide cognitive and social support to individuals and groups according to their needs.
- Brain sensor–activator technologies will become closely matched to the actual spatial–temporal dynamics of the human brain neural code, and they will be increasingly integrated into biological brain tissue as brain–machine interfaces become smaller and more sophisticated.
- National reinvention will be built on extended work lives, increased levels of safety/security due to reduced physical-cognitive decline, societal modeling to help keep life meaningful, and leveraging of NBIC and other CKTS advances in human health, national security, and national economic competitiveness.
- Transdisciplinary/team science will lead to a renaissance in human cognition and social communication—a cognitive science of science:
  - Better designs for science tools (Figure 24)
  - Improved education for future scientists
  - Insights to help science teams
  - New principles for convergence in sciences
- Combined, these elements will help us realize a “Cognitive Society” (Figures 4 and 25).
Table 4. Examples of CKTS achievements and paradigm shifts in support of cognition, communication, and human well-being

<table>
<thead>
<tr>
<th>Convergent Technology Domain</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communications</td>
<td>Smartphone revolution since 2007</td>
</tr>
<tr>
<td>Quality of Life</td>
<td>Personal genomics reach to ordinary citizens</td>
</tr>
<tr>
<td>Cognition</td>
<td>Transcranial magnetic stimulation to non-invasively activate/inhibit specific brain areas for neural therapeutics</td>
</tr>
<tr>
<td>Quality of Life</td>
<td>“Maker tools” (additive manufacturing, ...)</td>
</tr>
<tr>
<td>Communications</td>
<td>Twitter: searchable in real time</td>
</tr>
<tr>
<td>Communications</td>
<td>Facebook et al: converging of computing and social networking</td>
</tr>
<tr>
<td>Cognition</td>
<td>Brain imaging technology for new diagnostics and therapy tools</td>
</tr>
<tr>
<td>Computing</td>
<td>Cognitive computing</td>
</tr>
<tr>
<td>Cognitive Support</td>
<td>Assistive robotics technology</td>
</tr>
</tbody>
</table>

Figure 24. Collaborators at a tiled LCD tabletop display that supports interactive visualization of high-resolution data, examine a volume visualization of a Purkinje cell from a rat’s brain. Each layer is a mosaic of smaller, high-resolution images that were stitched together, and then the layers were stacked to create a volumetric view (http://scidacreview.org/0902/html/optiputer.html).

- Future global enhanced cognitive awareness
- An emergence of the current co-evolution/trajectory of multiple fields
- By analogy with “Genome” (and beyond the notion of Connectome) to a new concept: “Cognome” — the blueprint for higher cognition (individual and social)
- Renaissance in human condition and social communication (including unity of nature and society, and enhancing Team Science)

Figure 25. Dimensions of the cognitive society.
7. IMPLICATIONS: SOCIAEL COLLECTIVE OUTCOMES, INCLUDING MANUFACTURING

ADVANCES IN THE LAST DECADE
The foundational new tools and increasingly complex societal patterns of CKTS have profound implications for societal collective outcomes, including manufacturing approaches and long-term societal development. An immediate need is to understand and manage the rapid changes due to NBIC convergence.

• Flexible manufacturing processes and systems, such as additive manufacturing (AM), were applied in design/manufacturing for final functional products (Figure 26) and new modalities, e.g., 3D printing on soft materials, and bioprinting of single cells and growth factors.
• The semiconductor industry was successful in continuing Moore’s Law down to the nanoscale.
• Robotics increasingly advanced in accuracy, flexibility, and integration in various areas, including the manufacturing environment, the da Vinci remote surgical system, and humanoid assistants—a new “co-robot” concept (Figures 12 & 27).
• Universal Internet access to quality education has begun, e.g., EdX, Khan Academy.
• Different disciplines were successfully integrated within the clinical environment.
• Small-scale multifunctional manufacturing began to be broadly seen as having potential to enable localized, specialized production and reduced capital investment, leading to personalization of products, new modes of land and infrastructure utilization, more widely dispersed employment opportunities, and amelioration of some societal problems that attend concentrated urban living.

VISION FOR THE NEXT DECADE
• Science, technology, and applications will be integrated, and knowledge generation increasingly will originate from all these domains (schematic in Figure 28).
• Manufacturing development will evolve from the concentrated, urban, economies-of-scale model toward a routine “mass customization” dispersed model, upending the path of how knowledge is created.
• Distributed, point-of-need manufacturing will be supported by machines and systems integrated with IT that have a high degree of autonomy and include in situ metrology and remote diagnostics capabilities, among other functions that empower individuals and communities (Table 5). Examples include manufacturing of one-of-a-kind items only when needed, including in medicine, such as repair/replacement of nerve or muscle tissue or personalized prescriptions.
• Enhanced human sensing will extend current capabilities, e.g., human-friendly body-centered electronics/organic sensor networks for enhancing human–machine interactions.
• Brain research and manufacturing research will be integrated, e.g., electronic circuits/devices for understanding brain function with the knowledge used to enhance the speed and the process of determining successful outcomes for new materials or for creating new equipment.
• CKTS will help integrate various science, engineering, application, and ethical-legal-societal (ELSI) dimensions.
• Novel governance/regulation will be necessary.
Figure 26. 21st Century examples of additive manufacturing capabilities: (a) an Airbus hinge bracket in its original form (rear) and optimized form, which achieved a weight reduction of 64% by additive manufacturing; (b) a 3D micro-spring made by photolithography as proof-of-concept for microfabrication.

Figure 27. Honda's co-robot ASIMO “offers tea” and gestures. Such robots can provide assistance to humans in various situations.

Table 5. Examples of achievements and paradigm shifts in societal collective outcomes

<table>
<thead>
<tr>
<th>Convergent Technology Domain</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human factors</td>
<td>Hybridization of disciplines, and participatory design</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Distributed—from the hands of few into the hands of many</td>
</tr>
<tr>
<td>Knowledge development</td>
<td>Created from all levels: science, technology, applications</td>
</tr>
<tr>
<td>Robots</td>
<td>Complement human activities with multifunctional tasks</td>
</tr>
<tr>
<td>Empowered individuals and communities</td>
<td>Manufacturing process DNA; integrated social and physical sciences; individualized training</td>
</tr>
</tbody>
</table>
8. IMPLICATIONS: PEOPLE AND PHYSICAL INFRASTRUCTURE

ADVANCES IN THE LAST DECADE
Making deliberate progress toward convergence of knowledge and technology for the benefit of society will depend on proactively building the needed human, physical, and knowledge infrastructure.

Education
• Numerous multidomain (NBIC, mostly nano-bio-info, and in universities) transdisciplinary research and education centers were built (Figures 29 & 30).
• State, Federal, corporate, and foundation contributions grew to science, technology, engineering, and math (STEM) programs, including for establishing common standards.
• NSF established five Science of Learning Centers integrating research from brain processes to teaching and learning using NBIC.
• NBIC convergence originated from each of the four domains. For example:
  ◦ Penn State founded the NACK (National Nanotechnology Applications and Career Knowledge) Network, with NSF support for U.S. community colleges to prepare students for NBIC careers (Figure 31).
  ◦ The National Cancer Institute-funded Cancer Centers for Nanotechnology Excellence (CCNEs) and Physical Sciences Oncology Cancer Centers (PSOCs) brought physical scientists and engineers into medical schools.
  ◦ The use of IT-enabled teaching aids soared, including e-textbooks, web access to labs, online segments, and fully online programs.
• Boundaries have increasingly blurred between academic and industrial R&D, including industry’s expanded reliance on university research programs for novel ideas that might transition to new technologies and products.
• Public engagement with science increased in informal educational settings (e.g., Figure 33) and as a formal component of policymaking.

Infrastructure
• Huge strides were made in the United States and abroad in building dozens of university and national facilities, both physical and virtual, for R&D in two or more aspects of NBIC (Figures 29, 30) in Big Data science and engineering; in marine, terrestrial, and astronomical observatories; and in nanoscale characterization, fabrication, and simulation user facilities (e.g., NCN, Figure 32).
• The Human Genome Project, encompassing engineering, computer science, mathematics, biology, and social science, completed sequencing of the human genome, building new tools and launching a new era in health science.
• The U.S. defense global positioning satellite systems were significantly upgraded for accuracy and worldwide accessibility for civilian use, which enabled extraordinarily accurate positioning, timing, and synchronization globally, and thus sea-changes in mobile communications, banking, navigation, cartography, robotics, etc.
• Convergence in science and technology has brought the social sciences to the brink of a transition from a phenomenological basis to a basis in quantitative evaluation and scientific understanding beginning from the chemical/physical laws underlying brain function and cognition.
Figure 29. Examples of education-supporting infrastructure built since 2001 include the Nanoscale Science and Engineering Centers (NSECs), Materials Research Centers (MRSECs), Nanotechnology Undergraduate Education (NUE) program, National Center for Teaching and Learning (NCLT), Advanced Technological Education Centers (ATEs), Northeast Advanced Technological Education Center (NEATEC), Nanotechnology Applications and Career Knowledge network (NACK), and the College of Nanoscale Science and Engineering (CNSE) at U. Albany.

Figure 30. Examples of research and development (R&D) infrastructure built since 2001 that address overlapping needs in nanotechnology, biotechnology, and information sciences, especially at their interfaces, include centers and user facilities at the U.S. Department of Energy (DOE), National Institutes of Health (NIH), National Institute of Standards and Technology (NIST), University of Illinois at Chicago, and many other university centers. The Nanotechnology Characterization Laboratory, an NCI-FDA-NIST collaboration, is another example of an interagency facility.

Figure 31. NACK’s hands-on laboratory practice is part of the Nanofabrication Manufacturing Technology capstone semester; the program is available to regional and national community colleges (http://nano4me.org/).

Figure 32. The Network for Computational Nanotechnology, NCN (nanoHUB.org), was established by NSF and Purdue University in 2002. It has about 300,000 users annually (2013). (The map shows only U.S. users’ locations.) The HUBzero® website platform and Rappture graphical user interface are both open-source.
**VISION FOR THE NEXT DECADE**

**Education**

- An integrated cross-disciplinary approach to the education and participation of citizens, across disciplines, levels, and cultures (Figure 34), will lead to improved ability to devise solutions to societal problems, informed by new knowledge, information technology, and cognition insights.
- Digital information aids, including online education, networking, sensing, and automatic individualized testing and records-keeping, will grow from their present early-adopter implementation towards affordable, interactive, personalized education for all. Broad partnership structures will be established between universities (with facilities, equipment, and expertise) and community/technical colleges.
- Higher education will be increasingly structured towards transdisciplinary approaches to solution of societal problems, including in faculty reward structures, converging technology curricular concepts, and teaching aids to stimulate rapid migration of new knowledge into K–20 and community and technical college classrooms.
- The behavioral/social sciences will become increasingly based on fundamental physical–chemical laws and quantitative evaluations rather than on phenomenological observation.
- New insights into science communication, new informal education networks, and broader science museum mandates will more effectively engage the public in science (Figures 33, 35).
- Distributed knowledge and technology networks will include multidomain databases, education modules and facilities, and regional centers capable of leading efforts to foster converging technology education (see example, Figure 36).

**Infrastructure**

- The infrastructure will be expanded at research and development institutions that can enable rapid access of researchers and engineers to converging technology instrumentation, design methods, and fabrication facilities, with distributed user facilities.
- Geographically distributed user facilities will create converging knowledge and technologies clusters with a focus on using emerging NBIC foundational tools in various CKTS platforms and on providing additional test beds for invention and innovation to accelerate the translation of research discoveries into entirely new technologies.
- Advanced manufacturing facilities will be built with the diverse capabilities necessary to rapidly and efficiently transition cutting-edge converging technologies into products and services.
- Distance technology will be broadly used to give teachers and students direct access to, and control of, expensive university-based instrumentation within K–14 classrooms, to engage and train next-generation technology workers.
- Rapid development of international standards and reference materials coordinated by ISO and OECD in all four convergence platforms of human activity will facilitate reliable interpretation of instrumental results.
- A broad and well-informed public debate and decision-making approach based on convergence methods will aim to provide the balance required in benefit/risk analysis for novel converging technologies and services in order to effectively attain their benefits to society while minimizing their short- and long-term risks.
Figure 33. NISE Net (the Nanotechnology Informal Science Education network) began in 2005 to compile catalogs of programs, exhibits, forums, media, tools, and guides to support informal NBIC education. This effort culminates each year in distribution of “Nano Days” public activities kits to science and children’s museums and university centers all over the United States, as shown.

Figure 34. Schematic highlighting the axes of integration across levels, disciplines, and borders and cultures that is required for convergence of technology and knowledge to further education.

Figure 35. CKTS centers for education, outreach and public engagement envisioned by the Boston Museum of Science.

Figure 36. Components of Seoul University’s (Korea) Graduate School of Convergence Science and Technology, which is already up and running (http://gscst.snu.ac.kr/eng/).
9. IMPLICATIONS: CONVERGENCE OF KNOWLEDGE AND TECHNOLOGY FOR A SUSTAINABLE SOCIETY

ADVANCES IN THE LAST DECADE
One of the greatest challenges facing the world in the 21st century is to sustainably and equitably provide better living conditions to people while minimizing adverse impacts of their activities on Earth’s ecosystems and the global environment. The 1987 Bruntland Commission of the United Nations defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” The holistic approach of CKTS has direct implications on sustainability and is critical to realizing its goals.

- **Planetary boundaries** is a conceptual framework that defines a “safe operating space” for humanity in terms of measurable Earth System variables. Other frameworks look at societal variables such as the coupled interactions between population growth and human needs, societal and cultural values, and the human-built environment. It has been recognized that such concepts will require NBIC-enabled continual transformative and monitoring capabilities, and CKTS-enabled governance.
- Sustainability has been defined as key to humanity’s future as population rises to 8-10 billion by 2050—most living in urban areas (Figure 37)—and societal needs and expectations rise.
- New IT devices are using an increased amount of energy and critical metals.
- “Industrial ecology” has emerged to provide new tools to identify, assess, and minimize the impact of industrial activities on the environment.

VISION FOR THE NEXT DECADE
- CKTS will enable solutions to maintain life security while respecting societal values and observing the “planetary boundaries” of Earth systems. This is a daunting task as population and expectations increase and resources are limited.
- A goal is to realize what the United Nations System Task Team termed *The Future We Want For All*: inclusive social and economic development, environmental sustainability, and peace and security (Figure 38).
- Convergence solutions (based on physical and biological sciences, engineering, IT, and social sciences) will impact many aspects of Earth-system and societal sustainability:
  - Renewable energy generation, storage, and distribution, close-coupled with new clean water and sanitation solutions
  - Low-water food and agriculture models and new technologies, e.g., to avoid relying on reclaiming tropical rainforests for croplands
  - Environmental remediation and biodiversity
  - Cheaper and more universal (sometimes remote) access to healthcare
  - Climate stabilization
  - “Smarter” rural and urban communities based on “sustainable-community” thinking
  - Addressing materials supplies and their utilization, such as by tapping wastewater, seawater, and desalination plants as sources of critical materials, nutrients, and energy.
  - Routine application of supercomputer-enabled large-scale modeling to such challenges.
  - Involvement of social scientists and ordinary citizens will be critical to success.
Figure 37. Map showing urban areas with at least one million inhabitants in 2006. Only 3% of the world’s population lived in cities in 1800; 47% by 2000, and 50.5% by 2010. By 2050, the proportion may reach 70%.

Figure 38. An integrated framework for the future (UN Millennium Development Goals; for the original graphic see http://www.un.org/millenniumgoals/pdf/Post_2015_UNTTrreport.pdf.)
10. INNOVATIVE AND RESPONSIBLE GOVERNANCE OF CONVERGING TECHNOLOGIES

ADVANCES IN THE LAST DECADE

In an increasingly interconnected world experiencing unprecedented scientific and technological growth, the challenge will be to responsibly and proactively address humanity’s shared problems in an efficient, ethical, integrated, and balanced way. The CKTS convergence approach has the potential to increase creativity, invention, and innovation (Figure 39).

- In the last decade, there was a growing emphasis on advancing new technologies, innovation, sustainability, human potential, family wealth, and EHS/ELSI issues.
- Combinations of interconnected emerging fields (advances in areas such as imaging, electronics, genetics, and brain research) have created a fresh innovation environment. Examples of activities in this environment are the open innovation ecosystem approach (Figure 40); the Semiconductor Research Council’s system approach (Figure 41); Silicon Valley’s approach; regional S&T initiatives; the NSF Centers for Nanotechnology in Society; Korea’s cross-ministerial Convergence Research Policy Center; EU Horizon 2020; and United Nations Millennium Project consensus on societal goals.
- The viability of NBIC concepts has been confirmed in multiple settings and through various means: R&D programs in the United States, Japan, Korea, the European Union, China, and Russia since 2002; formation of an international community; founding of the Society for the Study of Nanoscience and Emerging Technologies in 2009; and social media enabled by NBIC.

VISION FOR THE NEXT DECADE

- Systemic convergence (Table 1) will bring global, essential changes in science, technology, and society, and will be a condition for competitiveness of individuals and groups, driven by accelerating scientific breakthroughs, and motivated by advancing human potential and quality of life.
- New CKTS governance organizations and programs are envisioned to be created to deal with: long-term and global issues (grand challenges such as wellness, brain and mind, sustainability, space, and nanoscale exploration programs); integrating knowledge and technology for increasing human capacity (more creative and productive, better learning, active aging); life security (sustainability, health, and safety); and improving the cultural balance between collaboration and confrontation, and work and personal satisfaction.
- Participation of individuals and public–private partnerships in the human activity system using new CKTS tools (such as multidomain informatics, system-logic deduction, and leaderless movements) is expected to increase.
- New CKTS supporting infrastructure will be built, using governance to advance convergence and convergence tools for societal governance.
- The roles of the CKTS transformative approach and governance are expected to increase, driven by the explosion in scientific knowledge and technologies, population growth accompanied by rising expectations, combined with growing global competition in an increasingly interconnected and rapidly evolving world.
Figure 39. CKTS innovation opportunities increase in direct proportion to: the number of M disciplines supporting R&D, the number of N application domains, and innovation improvements by applying convergence methods. The convergence–divergence approach offers multiple possible pathways from discovery to commercialization.

Figure 40. The concept of an “innovation ecosystem” can—and, when the results so intimately and broadly affect society as in the case of convergence, should—encompass the participation of all stakeholders in the full range of creative scientific and technological processes and products.

Figure 41. Schematic diagram showing the relationships among the key stakeholders in SRC research: SRC and its member companies, government partners, universities, and society at large. Arrows indicate flows of information between various forms and forums, people, and funding.
Convergence of Knowledge, Technology, and Society: Beyond Convergence of NBIC Technologies

U.S. AND INTERNATIONAL WORKSHOPS


AMERICAS WORKSHOP
Sao Paulo, Brazil. November 24-25, 2011
Hosted and co-sponsored by CGEE, RLPCT, and PROSUL
40 participants
Website: http://www.wtec.org/NBIC2-Americas

UNITED STATES WORKSHOP
Sponsored by NSF, NIH, NASA, EPA, DOD, and USDA
Hosted by WTEC
85 participants
Website: http://www.wtec.org/NBIC2-US

EUROPEAN UNION WORKSHOP
Leuven, Belgium. September 20-21, 2012
Co-sponsored by the European Commission
Hosted by IMEC
50 participants
Website: http://www.wtec.org/NBIC2Leuven

UNITED STATES-KOREA-JAPAN WORKSHOP
Co-sponsored by: NRFK, Korea; MEST, Korea; JST, Japan
Hosted by the Ministry of Education, Science and Technology, Korea
105 participants
Website: http://www.wtec.org/NBIC2Seoul

UNITED STATES-CHINA-AUSTRALIA WORKSHOP
Beijing, China. October 18-19, 2013
Co-sponsored by CAS, China; Australian Nanotechnology Network; Australian National University, and Department of Innovation Industry, Research, and Tertiary Education, Australian Government
Hosted by the Chinese Academy of Sciences (CAS)
41 participants
Website: http://www.wtec.org/NBIC2Beijing

ARLINGTON FINAL WORKSHOP
Arlington, Virginia, United States. December 11, 2012
Sponsored by NSF, NIH, NASA, EPA, DOD, and USDA
Hosted by WTEC
85 participants (63 in person and 26 via webcast)
Website: http://www.wtec.org/NBIC2
Webcast: http://www.tvworldwide.com/events/nsf/121211/

Interviews with several of the study’s authors may be found on the website of the Science & Technology Innovation Program at the Wilson Center: http://www.wilsoncenter.org/convergence (posted in 2013).

The convergence–divergence processes in knowledge and technology as reflected in art: “Endless Column” sculpture by C. Brancusi (1937).

Comments

This is truly an impressive body of work, which advances a transformative collection of concepts that could impact many areas of society and science. The ideas of this study are exciting.

*Tinsley Oden, University of Texas, Austin (April 2013)*

The CKTS study presents inspirational ideas behind the concept of convergence and identifies ground-breaking opportunities for human progress through such convergence.

*Christos Tokamanis, Nanotechnology and Converging Technologies, EU, Brussels (May 2013)*

The study provides a systematic and unified, internationally benchmarked framework for convergence that is relevant to policymakers, entrepreneurs, researchers, and the general public.

*Jo-Won Lee, Hanyang University, Korea (June 2013)*

I consider ... the first NBIC study in 2001 ... as an historical landmark that has caused a new dynamic in the reflection on these new technologies within the broad scientific and governmental community.

*Frank Theys, Co-producer for public broadcasters ZDF/ARTE, Germany & France (June 2013)*