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PERSPECTIVES

Possibilities for global governance of converging technologies

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Abstract The convergence of nanotechnology, modern biology, the digital revolution and cognitive sciences will bring about tremendous improvements in transformative tools, generate new products and services, enable opportunities to meet and enhance human potential and social achievements, and in time reshape societal relationships. This paper focuses on the progress made in governance of such converging, emerging technologies and suggests possibilities for a global approach. Specifically, this paper suggests creating a multidisciplinary forum or a consultative coordinating group with members from various countries to address globally governance of converging, emerging technologies. The proposed framework for governance of converging technologies calls for four key functions: supporting the transformative impact of the new technologies; advancing responsible development that includes health, safety and ethical concerns; encouraging national and global partnerships; and establishing commitments to long-term planning and investments centered on human development. Principles of good governance guiding these functions include participation of all those who are forging or affected by the new technologies, transparency of governance strategies, responsibility of each participating stakeholder, and effective strategic planning. Introduction and management of converging technologies must be done with respect for immediate concerns, such as privacy, access to medical advancements, and potential human health effects. At the same time, introduction and management should also be done with respect for longer-term concerns, such as preserving human integrity, dignity and welfare. The suggested governance functions apply to four levels of governance: (a) adapting existing regulations and organizations; (b) establishing new programs, regulations and organizations specifically to handle converging technologies; (c) building capacity for addressing these issues into national policies and institutions; and (d) making international agreements and partnerships. Several possibilities for improving the governance of converging technologies in the global self-regulating ecosystem are recommended: using open-source and incentive-based models, establishing corresponding science and engineering platforms, empowering the stakeholders and promoting partnerships among them, implementing long-term planning that includes international perspectives, and institute voluntary and science-based measures for risk management.

Keywords Nanotechnology · Biotechnology · Information technology · Cognition · Societal implications · EHS · ELSI · NBIC · Education · Global approach · Open-source organization · Risk governance

The opinions in this chapter reflect those of the author and do not necessarily represent those of NSF.

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Introduction

Converging Technologies refers to the combination of new and relatively traditional technologies. *Converging, emerging technologies* refers to the synergistic combination of nanotechnology, biotechnology, information technology and cognitive sciences (NBIC), each of which is currently progressing at a rapid rate, experiencing qualitative advancements, and interacting with more established fields such as mathematics and environmental technologies (Roco and Bainbridge 2003).

Fueling this convergence is the goal to use technology to serve peoples' needs, requiring development of more advanced products and services and the inclusion of cognitive and social sciences in the mainstream of emerging technologies. Advances in information technology, for example, are motivated by the human need to communicate and to do so with increasing ease and speed. A researcher developing an artificial organ, in another example, must use nanotechnology to understand and build the organ at the cellular level; must access biology to understand the organ's function within the body; and must use information technology to model and simulate the organ and its functions.

Thus, a main reason for advancing NBIC is to exploit unifying concepts of nature at the nanoscale, information, biology and system levels, and on this basis to identify better ways for serving people's needs. At the same time, key requirements are to pursue this advance while respecting the human condition and to encourage innovation within a long-term planning approach based on factual information, scientific principles, and full awareness of societal issues.

An earlier report on converging technologies (Roco and Bainbridge 2003, p. xii) recommended that "Ethical, legal, moral, economic, environmental, workforce development, and other societal implications, must be addressed from the beginning, involving leading NBIC scientists and engineers, social scientists, and a broad coalition of professional and civic organizations." It is better to address early the long-term issues related to revolutionary implications of converging technologies in a responsible government-sponsored framework, rather than trying to adjust to developments later.

Reaching at the building blocks of matter for all manmade and living systems, upon the broad nanotechnology platform, makes the transforming tools more powerful and the unintended consequences more important than for other technologies. Science based on the unified concepts of matter at the nanoscale and of information and biosystems at all scales provides new foundations for knowledge creation, innovation, and technology integration. The "fusion" of technologies is one goal. The other goal is integration of the resulting technology with human needs.

Despite the progress and promises for significant benefits, integration of converging technologies is not well understood. Now we are at the early stages of development, and many benefits and risks are functions of specific applications. A main, long-term concern is *a possible instability in development*, for several reasons. First, the transforming tools may create perturbations that could be difficult to control after the fact. Second, some perturbations might be created that affect the very foundations of life. Third, the systems enabled with converging technologies are complex and may exhibit emergent behavior.

These possibilities underline the need for an anticipatory and adaptive governance approach at the national and global levels. Furthermore, converging technologies are advancing on an accelerating path. An attempt is made here to identify the basic elements of a suitable governance approach for converging technologies. This framework would bring together several fragmented activities already underway. Governance efforts so far are integrated with and drive more traditional technologies.

Research on converging technologies in the United States, Canada, and several countries in Asia and Europe have been reported for a variety of applications (Roco and Montemagno 2004; THECiS 2007). Management of converging technologies recently has been reviewed (Bainbridge and Roco 2006) and is moving to the center stage of knowledge society.

Governance of converging technologies

In the common current usage of the term, *governance* implies a move away from the previous *government* approach, a top-down legislative approach that attempts to regulate the behavior of people and institutions in detailed and compartmentalized ways. *Governance* attempts to set the parameters of the system within which people, institutions and other stakeholders behave so that self-regulation or the social ecosystem achieves the desired outcomes. Put simply, governance is the replacement of traditional "powers over" with contextual "powers to." The dominant role of the top-down governing approach is replaced by dominant "bottom-up" and "horizontal" interactions.

Governance includes the processes, conventions and institutions that determine:

- How power is exercised in view of managing resources and interests;
- How important decisions are made and conflicts resolved; and
- How various stakeholders are accorded participation in these processes.

Integration of converging technologies needs to be done using a system approach and involving all stakeholders related to respective technologies. Within such a system, permeable and flexible boundaries facilitate communication and support the achievement of common goals, while the government role will continue in this context. These assumptions underline the switch from *government* alone to *governance* in debates about the modernization of policy systems, implying a transition from constraining to enabling types of policy or regulation—from "sticks" to "carrots" (Lyall and Tait 2005).

Democratic political leadership, social consensus, and knowledge-based economies are favorable environments for good governance. It is essential to support a global communication and participation system in all phases of converging technologies governance, facilitated by international organizations.

Core substance and principles of governance, along with the author's experience with the National Nanotechnology Initiative, Information Technology Research, Biocomplexity, NBIC, International Risk Governance Council, U.S. National Science and Technology Council and other related initiatives and organizations, are used to formulate key functions of the suggested global governance approach of converging technologies going beyond the risk governance alone.

Risk governance

Risk governance includes the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analyzed and communicated and with how management decisions are made (Renn and Roco 2006). Risk governance encompasses all the decisions and actions taken to minimize risk. It is of particular importance in situations where the risk is such that minimizing it requires that various stakeholders collaborate and coordinate because no single decision-making authority is available. Such is the case in the assembly of converging technologies.

Risk governance does not rely on rigid adherence to a set of strict rules, but calls for the consideration of contextual factors such as: (a) institutional arrangements (e.g., regulatory and legal framework and coordination mechanisms such as markets, incentives, or self-imposed norms); and (b) socio-political culture and perceptions.

Risk governance provides important concepts for assessing and managing the implications of converging technologies. There is genuine concern about the disruptive potential of interventions by the converging technologies, particularly NBIC technologies. These concerns resonate with long-standing social science analysis of technology running "out of control" (Winner 1977). Along with the relatively low levels of information about converging technologies available, and the low public trust in industry and government, these factors are leading to an increased risk of poor public perception. This perception could compromise the important phase of pre-assessment of possible implications. A particular concern is that insufficient formal and informal education will result in the misuse or inefficient application of converging technologies.

Converging, emerging technologies have several characteristics and long-term outcomes that reveal their potential benefits and also potential risks, which both require global governance:

- They can be described by complexity of large dynamic systems with many variables;
- They lead to powerful new tools;
- They offer a broad technology platform for industry, biomedicine, communication, knowl-

edge creation, environment, and an almost indefinite array of potential applications;

- They have broadened and changed manufacturing capabilities with the promise of more efficient outcomes;
- They reverse the trend of specialization of scientific disciplines, providing unifying concepts for research and education, and leading to system integration in engineering and technology;
- They have become one of the main drivers for technological and economic change, as well as industrial competition; and
- They have influenced the speed and scope of research and development (R&D) that exceeds for now the capacity of regulators to assess human, environmental and societal implications; and

The risk factors of converging technologies can be grouped into four categories, according to their sources:

- Technological (such as wireless communications, hybrid nanobiodevices, engineered and byproduct nanoparticles);
- Environmental (such as new viruses and bacteria, and ultrafine sand storms);
- Societal (such as management and communication, and emotional response); and
- Dynamic evolution and interactions in the societal system (including reaction of interdependent networks, and government's corrective actions through norms and regulations).

Governance of a changing system

The first focus of converging technologies should be on the benefits to individuals and society in general. Good indicators of success are the quality of life, health, safety, and how humanely and democratically the benefits are distributed.

The key decision processes for converging technologies—from knowledge to products to their implications to risk govenance policies—follow an open loop, similar to nanotechnology (Renn and Roco 2006). Figure 1 shows the decision processes in the open loop approach, in which each cycle generates new classes of products that determine different societal implications and require different decisions.

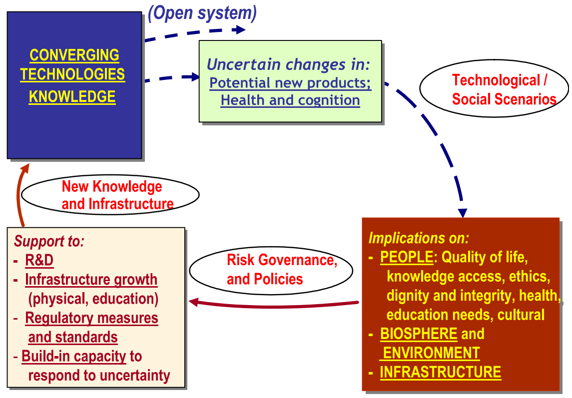


Fig. 1 Open system in the governance of converging technologies

Because of the fundamental changes in knowledge from one cycle to another, we have an "open system" in technological and socio-economical implications.

Emphasis must be given to "evidence-based," global-view, and results-oriented "pragmatic" governance (Pielke 2002). Changes are made through support for R&D and its infrastructure, regulatory measures and standards, and built-in capacity to respond to uncertainty.

Core governance processes and actors involved in or affected by converging technologies are shown in Fig. 2. The integration process and collective effects of converging technologies differ from those of any single technology. We have identified several core governance strategies:

- commitment to a long-term view;
- transformative approaches;

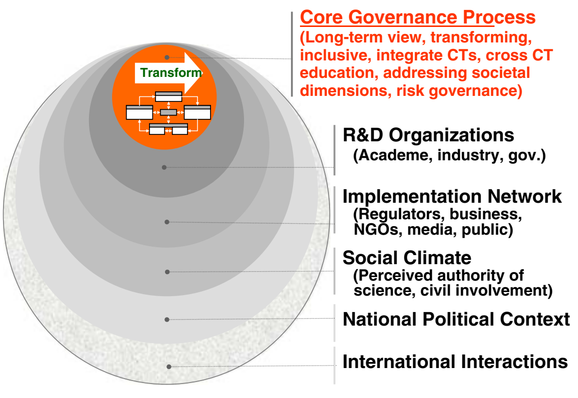


Fig. 2 Overview of governance of converging technologies

- inclusion in the decision process of both the innovators and those affected by the new technologies;
- integration of converging technologies;
- education that, like the converging technologies, crosses traditional disciplines;
- addressing societal dimensions upstream; and
- early adoption of risk governance.

Governance of converging technologies must deal with societal complexity, address many stakeholders, and use methodologies recognized globally for risk assessment and management. The key actors are the R&D organizations, implementation networks, civil society, national political organizations, and international organizations.

Currently, a linear, cause-and-effect approach is used to manage risk. The social ecosystem will need to adapt to ongoing changes and continuously put corrective measures in place. Thus, in addition to the current system, the complex societal system needs to also respond to change holistically. The corrective actions must take place on time scales comparable to the timescales of the disruptive events and, when possible, anticipate those events (Roco 2005). Special focus must be on the interfaces among regulations, institutions, and risk communication, interfaces where there is no clear jurisdiction or where responsibilities overlap.

The International Risk Governance Council provides an independent framework for identification, assessment and mitigation of risk in general and of nanotechnology in particular (IRGC 2006a). The basic approach identifies two frames: one for the first generation of products (passive nanostructures) and another for future generations (active nanostructures and nanosystems) where the products with higher complexity have broader societal implications.

An illustration of progress made in bringing various stakeholders together to pursue coordinated governance methods is the IRGC report on nanotechnology (2006a, b), which extends classical theories, such as theories of decision-making (Hammond et al. 1999), to managing an emerging technology field. Figure 3 illustrates the steps in the IRGC risk assessment and management framework for nanotechnology. The initial framing of risk is important for public perception and decision makers. Eventual government regulations will be dedicated to various areas of application of converging technologies. In dealing with conflicts in risk management, it is preferable to adopt constructive solutions, such as making changes in technology, than to implement additional regulations.

The Converging Technologies Bar Association offers an integrative approach in addressing the legal aspects of introducing emerging technologies based on nanoscale science and engineering.[1] The American Bar Association has issued a series of position papers on statutory authority and the implications of nanotechnology on the Comprehensive Environmental Response, Compensation and Liability Act (risks to human health and the environment posed by uncontrolled release of hazardous materials; ABA 2006a) and the Clean Water Act (ABA 2006b); and has also issued suggestions for new regulatory approaches (ABA 2006c).

An attempt to categorize the risk governance activities is presented in Fig. 4 (with illustrations for nanotechnology). Issues related to changes of nanoscale components of larger systems used in applications (such as nanoparticles in painting of a car) typically can be addressed by adapting existing regulations and organizations to the respective systems. Issues related to changes in a technological system (such as a new family of nanobiodevices) can be best addressed by new R&D programs, and eventually setting new regulations and establishing new, suitable organizations. At the national level, typical actions are policies and legislative actions. At the international level, typical actions are international agreements, collaborative projects, and multistakeholder partnerships.

Industry is a key stakeholder, and the success of governance will depend on industry practices. Among countries, industry cultures, and thus industry practices, differ. U.S. corporations are more likely to adopt decentralized approaches and rely on outsourcing and cross-functional business and R&D steering committees. Asian corporations are more likely to have explicit strategies aimed at achieving first-to-market status, with CEO and board members aware of technological developments. European corporations are more likely to take a “watch, wait, and

[1] www.convergingtechnologies.org

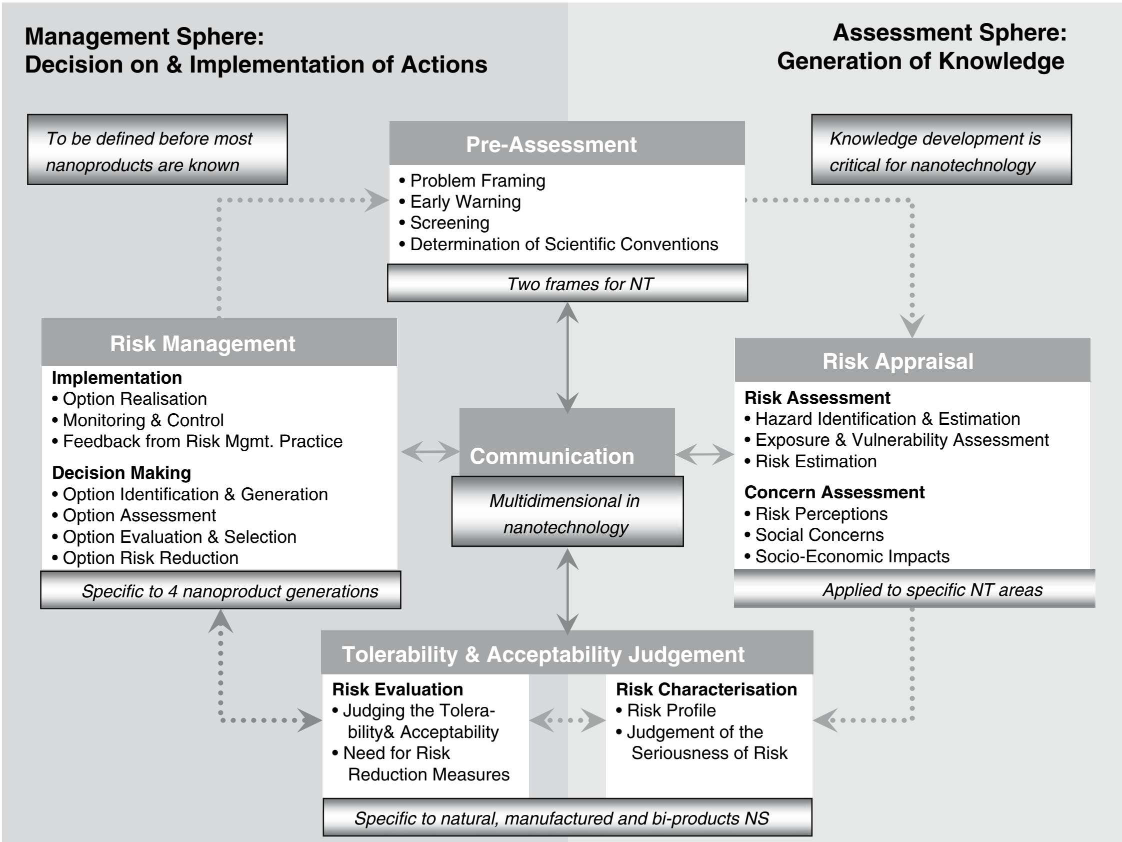
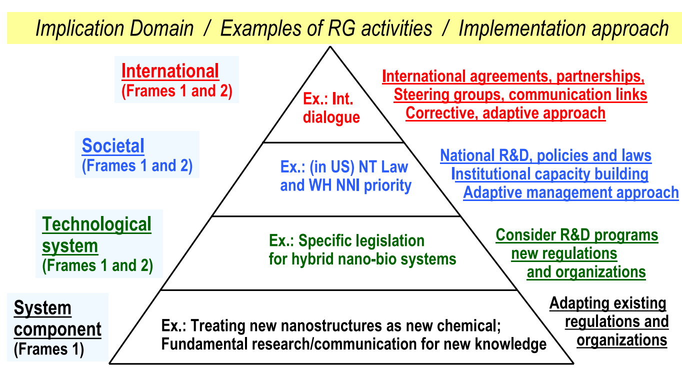


Fig. 3 Steps in IRGC risk assessment and management framework for nanotechnology (NT) (Renn and Roco 2006)

Fig. 4 Multi-level structure of risk governance for converging technologies



follow fast" approach rather than commit large R&D resources (Lux Research 2004/2006, personal communication).

A key issue is developing policy approaches for making credible governance decisions on nanotechnology when only scarce data are available and some data are uncertain. Such decisions need to be accepted by stakeholders. Transparent methodologies in addressing this issue will give confidence in the decision process. A first priority is an approach for the first generation of manufactured products already in production (passive nanostructures, which have quasi-steady properties). Dealing with uncertain or unknown product characteristics will become more important after 2010 when even more complex products enter the market. Furthermore, understanding the national political and international context is important for nanotechnology development, especially when decisions need to be made without complete data.

Governance must:

- be transformational,
- be responsible,
- be inclusive and
- allow visionary development.

These governance functions are discussed below, and several examples are provided in Table 1.

Transformational governance

The concept of transformative governance means that organizations and processes aim at substantial enhancement of the outcomes or impacts enabled by converging technologies in economy, health, quality of life, and security. The transformative function of governance is realized through four main mechanisms:

- investment policies,
- science and technology and business policies,
- education and workforce training, and
- supporting the needed transformational tools.

(i) Investment policies

The investment policies for converging technologies currently are fragmented, just as nanotechnology policies were before 2000. The integration of converging technologies needs to be done using systemic analysis and design. Effective development and implementation of emerging technologies may require broader foundations and longer term commitments than did classical technologies.

Investments must have reasonable returns, and the benefit-to-risk ratio must be justifiable and respect societal concerns. Key goals of investment policies are increasing productivity, improving quality of life and ensuring equity, while government organizations remain efficient and trustworthy. Several examples of investment policies are given below.

It is essential to *establish a broad and long-term R&D and infrastructure framework* for accelerated techno-economical development using converging technologies. One must ensure the availability and synergism of investigative tools, knowledge creation and production means supporting various converging technologies components. For example, large companies, or groups of smaller companies, would need to develop laboratories and facilities with multidisciplinary expertise to efficiently engineer and develop new products.

Converging technologies must *serve with priority key sectors of the economy that benefit the general population.* Examples are: supporting availability of natural resources (water, energy, food, materials, sustainable environment), designing technologies that are driven by general public benefit, rather than being market focused, advancing nanomanufacturing as a means for assuring social progress and welfare, and advancing medical improvements for public health and the well-being of all citizens. *Priority on manufacturing in converging technologies* is an example for taking advantage of the R&D investment. For example, nanomanufacturing has been paced as a priority in the National Nanotechnology Initiative since 2002, and a specially dedicated research and education funding program was established in the Directorate for Engineering at the National Science Foundation (NSF).

Convergence can *create intelligent systems and environments* as a means for improving everyone's quality of life and creating access for people with special needs. For example, a combination of wireless technology and nanoscale sensors could allow blind people to walk alone and eventually drive.

Implement new structures and methods of coordination for converging technologies, including those that promote participation of all those affecting and affected by the new technologies. Examples are multi-stakeholder advisory boards and empowering the public through science shops and periodical feedback processes in the research programs and investments concerning emerging technologies. Also included are new expertise and education domains, and new ways to structure investments.

Use new economic indicators other than the Gross Domestic Product (GDP). Instead, measure progress in terms not only of dollars but also of social benefits, societal accumulations (such as new knowledge, research and production facilities), human development including education, and security. We must

Table 1 Examples of recent developments in converging technologies (CT) governance

CT governance aspect	Example 1	Example 2	Example 3
(i) Investment policies	Support CT industries with high economic return and societal relevance	Support availability of natural resources (water, energy, food, clean environment)	Support priorities on human health and developing CT R&D infrastructure
(ii) Science, technology and business policies	Support discoveries through competitive peer-reviewed, multidisciplinary programs that are driven both by investigators and by specific strategies	Support innovation in converging technologies (*American Competitiveness Initiative* 2006); Support CT informatics	Support CT integration; New organizational and business models (Radnor and Strauss 2003)
(iii) Education and training	Creating the pipeline for CT workers through earlier education	Extend CT informal education to museums and internet (ex: NSF's Nanoscale Informal Science and Engineering network)	New university and community college curricula supporting CT (ex: NSF's Nanoscale Center for Learning and Teaching)
(iv) Technology and economic transformation tools	Create integrative CT technology platforms	CT research clusters for various applications; CT manufacturing R&D programs	Reduce the delay between inventions, technological development and societal response
(v) Environmental, health and safety (EHS) implications	U.S. Nanotechnology R&D Act of Dec 2003, including EHS policies	Identify research needs by diverse stakeholders	Develop new systemic knowledge for a life-cycle approach of CT products
(vi) Ethical, legal and social issues (ELSI) and other issue (ELSI+)	Ethics of CT (Roco and Bainbridge 2001; NGOs and UNESCO reports 2006a)	Equitable benefits for developing countries (ETC 2005); Public comments to EPA nanotechnology documents (2007)	Nanotechnology for the poor (Meridian project 2006); NSF's Nanotechnology in Society Network
(vii) Methods for risk governance	Risk analysis including the social context	Multilevel risk governance in global ecological system (IRGC 2006a)	Multi-criteria decision analysis (Linkov et al. 2007)
(viii) Communication	Increase interactions among experts, users and public at large	Public participation in the legislative process for CT funding	Coordination of regulatory agencies and research organizations
(ix) National capacity	Support interagency partnerships; NanoConnection to Society and NanoEthicsBank databases (IIT 2007)	Address societal infrastructure deficits for dealing with CT	Address social issues, such as workforce displacement
(x) Global capacity	International Dialogues on Responsible Nanotechnology (2004)	International Risk Governance Council reports	OECD working groups on emerging technologies
(xi) Long-term, global view	Strategic plans in U.S. for nanotechnology, information technology, health and neurosciences research	Long-term effect of technology on human development (UNESCO reports); Humanity and the Biosphere: The next 1,000 years (UNESCO report 2006c)	Studies on changing societal interactions because of CT; Long view on potential effect of nanotechnology on global warming
(xii) Support human development	Research on brain and nervous system evolution	Research connecting brain functions, education, and mind	Provide feedback based on public and expert surveys

OECD is the Organization for Economic Cooperation and Development

identify *new evaluation criteria* to include the NBIC contribution in the national infrastructure. The criteria of progress must include infrastructure accumulations, advancements in citizen education and training, improved working capabilities and quality of life. Structuring the investments in new areas of NBIC will be a drive and enable the *knowledge society.*

The rates of investment in converging, emerging technologies are generally increasing faster than the GDP, and resources need to be planned accordingly. For example, the worldwide GDP rate of increase was about 3.9% in 2005 and 2006, while the rate of increase for semiconductors, a primary product using nanotechnology, was 8% and it is expected to be about 10% in the next decade because of the increased semiconductor contents in new products (IC Insights 2006).

(ii) Science and technology and business policies

Science and technology and business policies play an important role in converging technologies. Science is reaching closer to technological applications in the emerging fields, and has an increased impact on society. There is the need to systematically *support converging technology integration through long-term strategic planning by addressing R&D gaps and key "bottleneck" research areas*. Establishing stakeholder coordinating groups at the national and international levels may help such integration.

In the United States, the NSF, the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency (EPA), the Department of Defense (DOD), the National Institutes of Health (NIH), the National Institute of Standards and Technology (NIST), and the Department of Energy (DOE) have R&D projects in the area of converging technologies. These projects are at the confluence of two or more NBIC domains, such as developing neuromorphic engineering, improving everyday human performance, "learning how to learn," and preparing for societal implications of converging technologies. A special challenge is understanding the dynamics and patterns of interactions within research fields, in particular how major research trends in converging technologies arise and evolve.

Encouraging discovery and innovation by competitive, peer-reviewed programs at the confluence of disciplines and areas of application in converging technologies is an effective approach for increasing societal implications. For example, the confluence of the research initiatives within Information Technology Research, the National Nanotechnology Initiative, Biocomplexity, the Human Genome Project and social and behavioral sciences have stimulated innovative research. In the United States, the *American Competitiveness Initiative* encourages innovation in emerging technologies. Other national programs for stimulating innovation have been adopted or considered within the European Union, Japan, China and other countries in the last year.

Innovation is the fuzzy process of transition from fundamental discovery to commercialization through the introduction of new knowledge to economical applications.

One way to encourage innovation is creating incentives, empowering stakeholders, and facilitating mechanisms to promote innovation in education, industry and business. An example is the European Union Science Shops program. These small research centers are aimed at addressing concerns "expressed by civil society" (see www.scienceshops.org).

Another way is to reduce the gap between discovery and commercialization by activities such as funding pre-competitive platforms and changing legislation.

Actions to better understand and facilitate innovation may focus on bridging diverse ideas and allowing individual and group creativity to flourish, creating suitable communities and social context.

The innovation culture can be strengthened by support for "integrators," such as goals that encompass the human dimension, approaches based on and addressing complex systems, tools for combining information technology and nanotechnology, and development of global-all-domains databases crossing societal sectors and international borders.

Combining major strategic programs with bottom-up investigator-initiated funding opportunities is needed to synergize support for major R&D trends with creativity and innovation.

Establishing converging technologies informatics is another way to better use the existing data and advance communication among contributors involved in various technologies. At this moment, there are separate efforts in each emerging technology such as bioinformatics and more recently nanoinformatics. The potential synergism created by such development would support converging technology development in areas such as new discoveries, design and manufacturing, and addressing the common environmental, health and ethical implications. Also, converging technologies informatics would help better overcome the "valley of death" between the creation of new knowledge in research and policy decisions by improving information transfer and framing of new technologies.

S*tates and local organizations* can contribute with specific actions to reach national goals. For instance, for nanotechnology, 19 U.S. states had enacted legislation on nanotechnology by January 2006 in support of NNI. This legislation ranged from allocating direct funding for nanotechnology research (e.g., Illinois, California, New York and Oregon), providing tax incentives to nanotechnology companies (e.g., Arkansas and Michigan), creating groups or boards to oversee the promotion of nanotechnology (12 states including Connecticut and Virginia), or implementing other measures to encourage interest in nanotechnology.

Reliable application of converging technologies requires development of suitable means of science and technology communication, that is: terminologies, metrologies, standards, patent evaluation, databases, risk assessment methodologies, and cultures in various supporting disciplines. Neglecting these aspects would create potential barriers limiting rapid discovery, exchange and assimilation of data and knowledge.

Support for developing and deploying *new business models* should aim at increasing productivity and other outcomes in the new context of accelerated global collaboration and competition. For example, rather than being company-centric, businesses could shift focus to networks centered around converging technologies. Businesses could also aim to manage an ecosystem of production clusters pursuing diverse technologies and a large variety of products. Another aim would be establishment of collaborative capacities as a part of business innovation networks. Communication could rely more on large multidisciplinary databases for common use by industry, academe, finance government, NGOs, and civil communities. Spohrer and Engelbart (2004) show an increased connectivity between science and business for emerging technologies. Policies must encourage stewardship for the future, because markets cannot account well for the future. A promising business model for encouraging innovation and increasing productivity is the "open organization," for topics such as open knowledge in R&D networks, open source for software, and open communication (National Academies 2007).

Policies on intellectual property for converging technologies are necessary because of several particularities, including longer time intervals between discovery and applications, the literally basic materials involved (genes, building blocks of matter, neural system, etc.), and more powerful societal implications.

(iii) Education and workforce training

Qualified workers will need to handle new converging technologies knowledge, will need to integrate, and will need to promote innovation. Creating a pipeline for such workers through earlier education is essential. For illustration, the NSF-funded Nanoscale Center for Learning and Teaching at Northwestern University plans to reach 1 million students in its 5 years of operation. Another example is the Nanoscale Informal Science Education, an NSF-funded network. Several universities have reduced the disciplinary barriers through new curricula supporting converging technologies. Multidisciplinary projects have been supported, such as the NSF-NIH multidisciplinary workforce preparation, and the Science of Learning Centers.[2]

Special educational activities are necessary in the context of the worldwide activities to enhance public understanding of sciences and humanities.

Preparing tomorrow's workforce to use and advance emerging and converging technologies is an essential contribution toward knowledge dominated economies.

(iv) Technology and economic transformational tools

Technological convergence requires the creation and development of integrative science, engineering and technology NBIC platforms, through priorities of infrastructure investments and production incentives. Such research and manufacturing platforms are already in development at several companies (such as General Electric) and government laboratories (such as Sandia National Laboratories). Also valuable will be multifunctional research facilities and man-

[2] http://www.nsf.gov/news/news_summ.jsp?cntn_id=100454&org=NSF&from=news

ufacturing capabilities (converging technologies clusters).

The efficient introduction and development of converging new technologies will require new organizations and business models, such as those in development through collaboration between the Industrial Research Institute (IRI) and NSF. It will be essential to reduce the usual delay between inventions, technological development and societal response. Harmonious introduction of technology should address societal acceptance, dialogue with the public, and research in response to societal needs.

Responsible development

Societal implications of converging technologies should be judged *using a balanced approach* between the goals (aiming at societal benefits) and unexpected consequences (which could be a combination of unexpected benefits and risks). Implications apply in a variety of areas, including technological, economic, environmental, health, educational, ethical, moral and philosophical. Responsible development includes respect of life and ethics, support for improving quality of work and quality of life, sustainable development and overall respect for the human condition. Because of the open loop and complex characteristic of converging technologies governance, decisions must be taken while the information about technology and products are not yet completely known.

Development with priority of applications of nanotechnology of general benefit to society such as increasing productivity, sustainable nanomanufacturing, and low cost healthcare, is a key feature of responsible development of the new technologies.

The responsible development function of governance implies addressing societal concerns in the general context of potential benefits and pitfalls in the short term and long term (Roco and Bainbridge 2006). The co-evolution of society and converging new technologies is a long-term trend. Several groups call for cultural changes and an international “code of conduct” or “code of ethics” for scientists, industry, and other stakeholders. However, the terms are not sufficiently well defined for possible implementation, and the concept of “good ethics” has different meanings in various countries.

A growing interest is on reducing the gap between developed and developing counties, and seeking how nanotechnology may bring benefits to the underdeveloped regions. In the shorter term, scientific research, studies of societies, regulatory measures and government policies must address environment, health and safety issues. The people’s needs and concerns should be addressed from various perspectives: knowledge society (intellectual drive), industrial society (help industry and other productive means), and civil society (help civil society goals). The International Risk Governance Council (IRGC 2006a, b; Renn and Roco 2006; www.irgc.org) is an example of international organizations aiming to address overarching risk assessment and management issues. IRGC goals are to develop an independent methodology framework for risk management and the principles for “good governance” for consideration by the national governments and international organizations.

(v) Environmental, health and safety (EHS) issues

The potential benefits of converging technologies are large—but so are the perceived risks to environment, health and safety. These risks must be addressed early. Specific areas for assessing and managing potential EHS risks are (a) instrumentation, metrology, and analytical methods; (b) effects on biological systems and human health; (c) effects on the environment; (d) monitoring methods for health and environmental surveillance; and (e) risk assessment and management methods.

Assessments must consider the entire life cycle of converging technologies products, including their eventual disposal, rather than just the effects of manufacturing and operating them.

There are challenges in developing nomenclatures, definitions and regulatory measures. Appraisal of research needs must include perspectives from government (see for illustration NNI 2006), industry (CBAN 2006), NGOs and civil groups.

Several national governance activities have been established per technology domains. For example, since 2000, several national research and development programs focused on nanotechnology have been created, notably in the United States (after 2001); in countries in the European Union and European Commission (after 2003), and in Japan (after 2002).

Existing regulations applicable so far by these programs are based either on products (as in the United States) or processes (as in the European Union). The converging, emerging technologies often cross existing jurisdictions and geographical boundaries. A clearer separation between science-based opinions and political judgment needs to be made when adopting regulations.

International activities have been launched for various emerging technologies. For example, the Asia-Pacific Economic Cooperation (APEC 2002; APEC Nanoforum 2006), the Organization for Economic Cooperation and Development (OECD 2006) and UNESCO (Study on nano ethics 2006) have supported studies and organized working groups on nanotechnology. In 2006, OECD has established the "Working Party on Manufactured Nanomaterials" in the Environmental Directorate, Chemical Committee and Working Party on Chemicals, Pesticides and Biotechnology, and in March 2007 a "Working Party on Nanotechnologies (on development and use of nanotechnology applications)" in the Science, Technology and Industry Directorate, Committee for Scientific and Technological Policy. The International Dialogue on Responsible Research and Development of Nanotechnology was first organized by NSF and the Meridian Institute in United States in 2004, and it was followed by meetings in Brussels and Tokyo. This forum allows an informal approach for addressing longer-term issues with diverse international participation.

(vi) Ethical, legal, and social issues

Ethical, legal and social issues (ELSI) are called ELSI+ if they include policy and security, and issues around gaps in education. These concerns must be answered to the satisfaction of both the public and experts. Without professional ethics, it would not be possible to ensure efficient and collaborative development of converging technologies and cooperation between people and organizations, and it would difficult to make the best investment choices, prevent harm to other people, and diminish undesirable socio-economic implications.

There is a *dilemma of choices* in the complex societal system where converging technologies and social interactions develop. Beyond a few very simple principles, no single set of rules of ethical behavior is universally accepted. Also, policy toward a given technology is not a decision to be made necessarily by scientists using a systematic approach, but by elected leaders and by civil and many other organizations tasked to make decisions about governance in a complex, evolving society. Should we give priority to societal benefits or individual rights? For example, it would be unethical to fulfill the interest of smaller groups by limiting the development of technologies meeting the basic needs of a large cross-section of the population. Addressing food, water and energy needs should have priority over improving luxury products. However, it is also unethical to affect others without consent. Medical treatments such as using tissue engineering and regeneration may have religious implications.

Application of democratic principles for equal opportunity, access to information, knowledge and development are other challenges. Experts, the public and others need information and must participate in order to make the best choices. Long-term progress cannot be derailed even if the road is not straight. Progress is faster with proper vision and when choices are guided by moral values, transformative goals, collective benefits, and professional ethics.

First, we must identify the moral values. Emerging technologies create imbalances in the initial phase of development when first products may be used only by a small proportion of the population, and measures should be taken to address such unbalances. A system oriented approach is needed to effectively address moral, ethical and other social issues (Kushf 2004).

Cultural, ideological and political influences color reports from the scientific community, non-governmental organizations and governments. Examples are debates on stem cell research, research on increasing life span, climate change, and even the original NBIC report itself (Roco and Bainbridge 2003). This report is based on scientific evidence and underlines the need to respect the human condition, democracy, and serving human needs. Subsequent reviews either followed this direction and appreciated the transformative power of NBIC (in several countries in Europe; Japan; Korea; and several EC directorates), or made connections to the political positions in the respective countries and played down the message of the scientific contents of the NBIC report (one working group in the European Community; Netherlands Department of Justice).

ELSI+ should not be used primarily as a "defensive approach" against concerns but as an approach to help innovation and positive outcomes by responsibly applying converging technologies. That 2003 report stressed the need for including the human dimension and social science studies in technology development, as well as the need for anticipatory planning including for technology implications and for "upstream" public engagement discussed later in other reports (Wilston and Willis 2004). Dialogue among science, engineering, medicine, and social and humanistic sciences must be reinforced earlier in the introduction of converging technologies in order to have synergistic outcomes and avoid mutual misunderstandings.

Examples of ELSI+ issues include the need for science and data to be reported in the public domain, and transparency in all phases of planning and execution. Privacy and confidentiality are key concerns within information and medical issues.

Since no specific moral norms are formally accepted at the global level, the positions taken by various organizations have different flavors. For instance, UNESCO prepared the report *The Ethics and Politics of Nanotechnology* (2006a, b), with a cautionary approach to the development of emerging technologies. In its methodology, the UNESCO report suggests that, before taking potential actions, we must first identify the moral dimensions, then test the relevancy of potential actions, and then enhance the political feasibility of potential actions. The Center on Nanotechnology in Society (IIT, Chicago) and Center for Responsible Nanotechnology (New York) are two NGOs that look to longer-term implications while others (Environmental Defense) are focused on more immediate concerns. The International Risk Governance Council attempts to address both short- and long-term aspects of governance of global risks.

A key concern is the equitable distribution of benefits, such as access to computers and the Internet and access to natural resources (water, energy, food and a clean environment). In dealing with such difficult issues, one needs a neutral, constructive platform where all actors can interact. Particularly important is to adopt a balanced view and avoid unjustifiable "utopian dreams and apocalyptic nightmares" (Gordijn 2003). The need of interactions among experts of various disciplines supporting converging technologies and between science and technology, creates a good ethical climate for cooperation. A little-noticed but noteworthy trend already underway is a broad-based shift from mass production to mass personalization and distribution, with effects on how equitably benefits are distributed.

(vii) Multi-stakeholder, multi-criteria and internationally recognized methods for risk governance

The policies and regulatory frameworks of the various countries have remained fragmented. International calls for addressing global challenges in R&D and for addressing the societal dimensions of emerging technologies at the international level have contributed to the collaborative developments, but have had so far a relatively limited effect on both governance of converging technologies and the global coordination of risk governance methods and structures.

Given the opportunities of converging technologies, there is the danger that necessary risk governance precautions will not be taken internationally in the race to gain economic advantage and to grasp economic benefits. Such an oversight could lead to an international backlash in emerging technologies development and diffusion if, due to lax standards and practices, an incident with negative repercussions on human health or the environment occurs. The fear around such an event could be quickly amplified by the global media, and such an incident could trigger worldwide attention and increase public concern. National regulatory agencies could feel propelled to tighten regulatory rules even if the incident occurred in a different country and would not have been possible or probable in any system with working standards and effective control.

The potential of this problem is beginning to be recognized. Despite an increase in international interactions and developing knowledge for the safer use of converging technologies, an international accord toward coordination of regulations and standards is still lacking. The risk governance of emerging technologies, including risk policies and regulatory structures, continues to follow separate paths in various countries. An attempt to address this issue is the IRGC (2006a, b) project (Fig. 3).

Balancing various factors and interests of different stakeholders is a challenge. Multi-criteria decision and mapping analysis (Linked et al. 2007) offers a structural approach for making justifiable and transparent decisions with explicit trade-offs between the large variety of factors of relevance, and it can be applied well to nanotechnology.

It is recommended that industry analyzes the value of risk information and then establish voluntary measures for ensuring that new products are safe and that decisions are based on scientific evidence.

An open issue is the question of combining formal meetings, such as those held under APEC, OECD and United Nations aegis, with informal international meetings to set up the main issues in a creative manner with a diversity of stakeholders. For example, the series of International Conferences on Nanotechnology Cooperation and Collaboration (INC) cover the nano-bio-info convergence with involvement from industry, government and academia.

(viii) Communication and participation

The goal is to include all those creating, using and being affected by the converging technologies. The complexity of the subject, the differing types of actors, the scope of responsibilities and accountability, and the trans-boundary nature of converging technologies offers many benefits and risks and requires that people working in government, business, science, civil service and communication cooperate for the purpose of optimizing the converging technologies governance in all phases of its development. There is a perceived gap between science communities and manufacturers, regulators, the public, NGOs, the business community, and the media. The following forms of communication should be included:

- *Documentation:* this ensures transparency. In a democratic society it is absolutely essential that members of the public not participating in the governance process learn of the reasons why the regulators opted for one policy and against another.
- *Information*: information serves to enlighten the communication partner. Information should be prepared and compiled in such a way that the target group can grasp, realize and comprehend it, and can integrate its message into their everyday life. The role of media and the Internet has increased in the last decade, even if the media focus has been mostly on the short-term and newsworthy information. Informing the public about both the real and perceived implications of converging technologies is important.
- *Two-way communication or dialogue*: this form of communication is aimed at two-way learning. There must be willingness on both sides to listen to and learn from the other. Mechanisms for improving the dialogue are needed. DEMOS in the United Kingdom (Kearnes et al. 2006) argue the key component in nanotechnology governance would be two-way 'upstream' communication, the dialogue between scientists and the public.
- *Participation in risk analyses and management decisions*: in a pluralistic society people expect to be included adequately, directly or indirectly, in decisions that concern their lives. Not all affected people can participate in governance, but it must be ensured that the concerns of the stakeholders will be represented in the decision-making process and that the interests and values of those who will later have to live with risks will be taken up appropriately and integrated into the decision-making process.
- *Increase citizens' inclusion and public participation:* this goal entails actions such as: support for both formal and informal science education about converging technologies; empowering citizen input in research investments; funding R&D programs with bottom-up investigator- and public-initiated funding opportunities; and facilitate citizen participation in international debates and decision processes.

Communication among all stakeholders is essential. For example, the public should be informed about the principles and procedures used to test converging technologies products, to assess potential health or ecological impacts and to monitor their effects. Perhaps large transnational companies should be required internationally to disclose information about health risks, even if some of the information is proprietary and connected to a company's competitive position. Scientists need to take courses on communicating risk.

Other issues include generating international standards, dictionaries for nomenclature and best practices applicable to both developing and developed countries. Communications should involve experts, regulators, legislators, the public, civil organizations and media.

Creating "open source" databases that are improved by users is an increasingly recommended approach. For example, the "Global Ethics Observatory" (UNESCO 2006b) is concerned with ethics for introduction of new technologies, and includes five databases: who's who, institutions, teaching programs, legislation and policies, and codes of conduct for scientists.

Inclusiveness

Stakeholders involved in converging technologies are operating within a dynamic societal system with close dependencies. Rather than monitoring in detail the interactions, it is more efficient to support various parties to play their roles in the overall system, encourage partnerships, and facilitate mechanisms for interactions and conflict solving. Various stakeholders and levels of governance that are inclusive part of the societal system are schematically presented in Figs. 2 and 4. Multi-stakeholder partnerships at the national and international levels are sought from planning phase to execution. The current governance measures generally deal with a single event, cause-and-effect, and do not consider long time intervals, secondary effects and interactions with other events. The governance organizations and measures are fragmented from the area of jurisdiction, type of product or process, intervention levels, and national and international harmonization of assessment and management procedures. An integrated governance approach for anticipatory and corrective measures is, however, necessary for an emerging technology that will have trans-boundary and global implications.

Using an open source approach is a way to increase participation of various stakeholders, and develop a collaborative working environment. This concept fits well with the establishment of an ecosystem where developed and in developing countries, multinational consortia, international organizations, and broad view experts can play an important role.

(ix) Building national capacity to govern converging technologies development

Coordination is necessary for activities that are too big for a single societal sector or region. For instance, the National Nanotechnology Initiative was conceived as an *inclusive process* in which various stakeholders would be involved. In 1999, "a grand coalition" of academic, industry, federal government, states, local organizations, and the public was envisioned that would advance nanotechnology and related technologies. The focus was on horizontal interdisciplinary research and education including most of the disciplines and areas of relevance.

Examples of challenges are developing corresponding infrastructure and institutional capacity, education and training, and coordinating all stakeholders in planning and implementation. An increased attention is necessary for involving civil organizations in key governance processes, including decision-making.

(x) Building global capacity and leveraging

While knowledge and products do not know borders, the policies and regulatory frameworks of the various countries have remained fragmented. Most of the wealth and capabilities to develop NBIC remain within developed countries. Formal and informal approaches are necessary for global governance. A special need is for more aligned global infrastructure initiatives and coordinated risk regulations. Leveraging international private sector and government research and education, as well as global communication, are needed for covering the major gaps in knowledge.

Agreements on nomenclature and standards are in preparation by the International Standard Organization (ISO) and its national members, International American Society for Testing and Materials (ASTM), International Council on Nanotechnology (ICoN), American Institute of Mechanical Engineers (ASME), Institute of Electrical and Electronics Engineers (IEEE), and other organizations, particularly since 2004. Also, while work and dialogue is underway at various national and multinational patent offices, more progress is needed for uniform treatment of patents in converging technologies areas.

Developing countries such as Brazil, China and India have gained standing in converging technologies research because of better international communication (Internet, travel, etc.).

Visionary function

Detecting early signs of change, development of scenarios, real-time technology assessment, and commitment to long-term planning with human development in perspective are necessary for the complex development and integration of emerging technologies.

(xi) Long-term and global view in planning, R&D, and investments

The anticipatory role can be realized by envisioning scenarios in scientific, economic and societal domains. Another way is creating the capacity to address the identified issues, such as research priorities, technology trends and economic cycles. For example, the World Economic Forum (WEF 2006) has developed scenarios for global risks in five interrelated areas: technological, economic, geopolitical, environmental, and societal. The identified highest technological risks were related to converging technologies, nanotechnology, electromagnetic fields, and pervasive computing. In another example, in 1999, *Nanotechnology Research Directions* (Roco et al. 1999) evaluated possible scenarios for the following decade. The time sale of scenarios may be related to the nature of the topic: for broader topics, longer term scenarios have been developed. For instance, the effect of nanotechnology on environment, global change, economy and Earth's biosphere are envisioned for intervals from several years (Hollins 2007) to the next 1,000 years ("Humanity and the biosphere: the next 1,000 years," UNESCO 2006c). Several trends for emerging and converging technologies are estimated up to 10–20 years. Examples are nanotechnology implications on markets (Roco and Bainbridge 2001; Lux Research 2004/2006, personal communication), four generations of nanotechnology products and processes by 2020 (Roco 2004), and introduction of nanotechnology in the semiconductor industry (ITRS 2004).

The technology view considers science and engineering advances, the innovation process, and potential changes in industry because of converging technologies. The macroeconomic view considers the economic growth and productivity changes. The social view considers interaction of technology with social factors. Scenarios may help identify issues, hypotheses, and possible paths in technology evolution.

National or international exercises for constructing scenarios that appear relevant to the context of the diffusion of converging technologies and the likely social reactions to it should also take place. Academic researchers, developers, potential users and other important actors should be actively involved in building scenarios in order to ensure the inclusion of an adequate representation of societal forces that ultimately shape the future of converging technologies. Successive changes ("cascade" effect) in a highly interactive and global environment as well as on an accelerating path (exponential growth after many, for example: "the amount of scientific data is doubling every year", Szalary and Gray 2006) need to be considered in the open-loop decision process discussed earlier.

(xii) Support human development

The long-term goal of supporting human development is well described in *Human Development Report 2001* issued by the United Nations Development Programme (UNDP 2001). The report begins with the effects of technology on changes in the economy, organizations, quality of life, security and environment. Examples of implications of converging technologies on human development are: understanding aging and maintaining working capacity, increasing learning capacity, developing brain-machine interfaces, increasing life-span, controlled gene therapy, and including converging technologies in formal and informal education and preparation of the workforce. Means of resolving possible ideological conflicts generated by technological development are also important. In the longer term, we will need to explore evolution of human cognition and cultural trends.

Good governance should cover all four basic functions described above, in a balanced manner. Focusing the attention on only one function may increase the chances that governance does not prevent some risks:

- Focusing only on the transforming function may raise risks to the human dimension and development.
- Focusing only on responsible development aspects may generate too restrictive approaches to risk and delay economic benefits.
- Disregarding the need to include all stakeholders may lead to slower development and even isolationism.
- Focusing on short-term issues (not visionary) is not good for longer term goals and future generations.

Concluding remarks

Big-picture and long-term governance of converging technologies and particularly of the emerging components (NBIC) is essential for obtaining efficient societal outcomes from the unifying science advances. A main challenge is integrating converging technologies. Another challenge is developing cognitive technologies. Needed is an adaptive, anticipatory and corrective approach within the societal system in addressing societal implications for each major R&D program. Deliberate and proactive measures should be adopted in order to accelerate the benefits of converging technologies. User and civic group involvement is essential for taking better advantage of the technology and developing a complete picture of its societal implications. Optimizing societal interactions, R&D policies and risk governance for the converging new technologies can enhance economic competitiveness and democratization.

There are choices in deciding the governance objectives and respective approaches. A distinction must be made between scientific and fact-based governance on one hand and ideology-based policies and advocacy on the other. *A multidisciplinary forum or a coordinating group involving academia, industry, government and civil organizations from various countries is needed* in order to better address globally the NBIC scientific, technological and infrastructure development challenges.

All four key functions of governance identified in this paper—transformational, responsible, inclusive, visionary—need to be addressed for a successful implementation. An important component in realizing the transformative function of converging technologies is governance that promotes innovation, entrepreneurship and informatics. The 2005 American Competitiveness Initiative and the 2006 EU Communication on Innovation illustrate policies supporting such governance. A key focus should be on safety by considering the profound transformative implications of converging technologies and the need to avoid damage to third parties. Both benefits and potential risks need to be presented in a balanced manner. There are real and perceived negative implications. Global stakeholder communication and partnerships in all phases of governance are needed to address both. Without a long-term view it will be impossible to address the governance issues of the transformative and rapidly growing converging technologies.

Five of the most relevant possibilities for global governance of converging technologies are listed in Table 2. Seeds for global governance of emerging

Table 2 Five key possibilities for global governance of converging technologies (CT)

1	Establish open-source and adaptive models to enhance CT discovery, education, innovation, informatics, and commercialization in the global self-regulating ecosystem
2	Create science and technology converging technologies platforms in areas of highest societal interest and for common resources
3	Develop internationally recognized EHS and ELSI requirements, including risk management methods and voluntary and incentive-based approaches
4	Support global communication, empowered stakeholder participation and partnering in all phases of governance, facilitated by international organizations and consultative groups of experts
5	Commitments to combined short- and long-term planning and investment policies, using global scenarios and anticipatory measures

technologies are already created but they are incipient and fragmented. There are opportunity for a more systemic approach in areas such as innovation, informatics, standards, EHS and ELSI measures. Increased interactions are needed for addressing the common and long-term human goals (such as basic discoveries on the mechanisms of life), sustainable common resources (water, energy, food, and environment) and healthcare (treatment of cancer and chronic illnesses).

The suggested converging technologies governance functions apply to various levels of societal change enabled by technology. Issues related to changes of nanoscale components of technological systems typically can be addressed by adapting existing regulations and organizations. Issues related to changes of a technological system can be best addressed by new R&D programs, setting new regulations, and establishing new, suitable organizations. At the national level, typical actions are policies and legislative actions. At the international level, typical actions are international agreements and collaborative projects.

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