VISIONS AND REALITIES IN CONVERGING TECHNOLOGIES
Exploring the technology base for convergence[1]

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This paper analyses the relation between visions and real technology developments in the debate on converging technologies (CT). Based on the analysis of the main documents of the CT debate, a structuring of CT into eight application areas is advanced. The eight application and technology development areas are described in more detail. The analysis shows that convergence is actually happening in different technology fields but that research in most areas does not explicitly refer to the convergence concept. We also found that, within the respective fields, the distance between visions and real developments is quite different. In the field of brain enhancement, one of the most prominent within the CT debate, the gap between visions and the state of the art is greatest.

Introduction

Defining the term 'converging technologies' (CT) and determining the areas where convergence actually takes place is not an easy task. The concept was brought up by technology visionaries; it was picked up and promoted by research funding organizations around the globe; and it has fuelled high expectations concerning the consequences of convergence for science and society among policy makers. Although the concept as such comes from the policy arena in the wider sense, it claims to reflect and reinforce developments occurring in many technology fields. However, it remains unclear which are these technology fields and how research and development is concretely affected by convergence.

The main documents that have informed the CT debate over recent years provide some indication as to what these technology fields might be. These are the four conference documentations from the United States and the reports from the High Level Expert Group (HLEG) in Europe. The conferences in the United States took place in 2001 in Washington, DC (Roco & Bainbridge, 2003), in 2003 in Los Angeles (Roco & Montemagno, 2004), in 2004 in New York (Bainbridge & Roco, 2006a), and in 2005 in Hawaii (Bainbridge & Roco, 2006b). In the United States, convergence is called NBIC convergence, claiming synergies from combinations of nano, bio, info and cognitive science. In Europe the High Level Expert Groups (HLEG) produced a series of documents analysing convergence, and suggested a European approach to the topic (HLEG, 2004a,b; Key Technologies Expert

Innovation, Vol. 20, No. 4, 2007
ISSN 1351-1610 print/ISSN 1469-8412 online/07/040375-20

DOI: 10.1080/13511610701767932
Routledge Taylor & Francis Group

Group, 2005; Stamann *et al.*, 2004; Ringland *et al.*, 2004; Bibel *et al.*, 2004). The European activities are subsumed under the heading CTEKS that stands for 'Converging Technologies for the European Knowledge Society'.

In these documents the concept of convergence is applied to a wide variety of scientific fields and technology areas and the authors claim such a general applicability of the concept that it seems that almost all technology fields are about to converge. Following the political and research planning activities, some attempts have been made to identify concrete convergence fields and to describe the genuine character of convergence. For example bibliometrical analyses were carried out to trace convergence or to identify so-called 'hot spots' of convergence, e.g. research institutes allegedly very active in convergent research (van Lieshout *et al.*, 2006; Malanowski & Compano, 2007). However, since the concept is so new, approaches that exclusively follow a bottom-up science and technology strategy – and do not take into account visions and plans of research management and governmental bodies – have not come up with a convincing characterization of convergence. There is still a need to clarify what is understood by convergence and to determine the concrete areas where convergence is taking place or is expected to take place in the future.

Therefore, we will suggest a combined top-down and bottom-up approach to identify core convergence fields and to characterize technological convergence in these fields. Our conceptual contribution can also be read as a discourse analysis since its starting point is not the development of science and technology on its own but the array of technologies and visions brought about by the main actors of the CT debate. The influence of visions and expectations on the development of research and technology has been intensively discussed within the social sciences (see for example Dierkes & Hoffmann, 1992; Lösch, 2006; Grunwald, 2007)

After identifying eight central CT fields, in the second part of this paper we attempt to provide a reality-check, trying to separate science fiction from science by confronting the visions and anticipated scientific breakthroughs with the state of the art of current research in the respective areas.

Converging Technologies: Concepts and Delineations

The starting point for the analysis of convergence is the so-called NBIC tetrahedron (Figure 1), originally proposed by Roco and Bainbridge in the documentation of the first NBIC-conference (Roco & Bainbridge, 2003, p. 2). In their introductory article they claim that convergence is taking place as a synergistic combination of four major provinces of science and technology, each of which is currently progressing at a rapid rate: (a) nanoscience and nanotechnology; (b) biotechnology and biomedicine, including genetic engineering; (c): information technology, including advanced computing and communications; and (d) cognitive science, including cognitive neuroscience (Roco & Bainbridge, 2003).

The assertion is that these sciences have now 'reached a watershed at which they must combine in order to advance most rapidly' (Roco & Bainbridge, 2003, p. 2). As structuring principles or building blocks for future technologies respective research objects of the NBIC fields like atoms, genes, neurons and bits are accounted for (Roco & Bainbridge, 2003, p. 71f). What remains undecided in the article of Roco and Bainbridge is whether convergence is something already under way, or something which is called for in

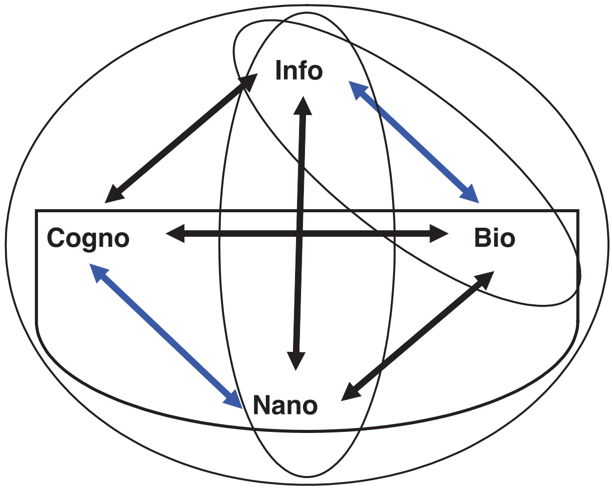

FIGURE 1
Convergence of nano, bio, info and cogno (NBIC) on a general level (source: Roco & Bainbridge, 2003, p. 2)

order to facilitate scientific breakthroughs in the future. The book presents a mixture of these two aspects, blurring vision and current research, thus making it difficult to identify areas where convergence is really taking place. Nevertheless, the structure of the documentation suggests some concrete areas where convergence might be taking place or is required:

- expanding human cognition and communication;
- improving human health and physical capabilities;
- enhancing group and societal outcomes;
- national security; and
- unifying science and education.

In about 70 separate articles and statements, the different authors try to find evidence of convergence taking place or advance arguments why convergence should take place in these selected fields.

In the European discourse, the question about which concrete research areas are affected by convergence and the guiding principles, has also been discussed. Bibel *et al.* (2004) list a series of concrete research fields like artificial intelligence, sensors for smart environments and DNA compression, and classify these into the different overlapping areas of nanobio, nanoinfo, nanocogno, etc. (Bibel *et al*., 2004).

In their report *Converging Technologies – Shaping the Future of European Societies*, the High Level Expert Group takes a different approach: of main interest are not the application areas where convergence might occur, but rather those fields in which convergence should function as a pacemaker for scientific breakthroughs and innovations. The authors suggest that the European version of NBIC, called Converging Technologies for the European Knowledge Society (CTEKS) should focus on research topics that are highly valued, thus initiating technology developments in the desired areas. Five areas were identified where progress through convergence is considered to be desirable (HLEG, 2004a):

- *health* with the applications: 'lab-on-a-chip' technologies for fast screening and early diagnosis of diseases; intelligent prostheses interacting with brain signals from patients and transmitting sensory information back to them;
- *education* with applications like invisible knowledge space, learning objects and smart surroundings;
- *ICT infrastructure* with environmental monitoring through ambient sensing devices to alert agencies of pollutants and inform individuals about the distribution of allergens; integration of information about food products, purchasing and consumption patterns and individual states of health;
- *energy* with new energy carriers and forms of storage, new energy sources emulating nature, exploring renewable energy sources, photovoltaic, hydrogen, geothermal and solar energy researchers should work together with geologists, geographers, anthropologists, and economists.

Conceptual Framework

The existing approaches on convergence exemplify themselves the different meanings of convergence and show a heterogeneity of application fields. One of the central problems with the CT concept is that it is not clear whether convergence is an observation of something already happening or a claim that something will happen if only the different approaches and methods of the different scientific and engineering fields are adequately combined.

A combined approach is necessary in order to achieve a convincing structuring of the field and answer the question of what are the concrete impacts of CT visions on scientific work. Thus, we analysed the central documents of the debate in the United States and Europe and extracted those scientific disciplines, research fields, technology development and application areas that are potentially relevant for convergence. Taken together we identified more than 100 individual fields. With the help of experts from different technology backgrounds, we managed to cluster the identified R&D fields according to thematic similarities, common methods, mutual closeness and frequency of occurrence in the main policy documents. The clustering exercise resulted in eight areas in which almost all research and development fields could be subsumed. The eight areas are shown in Figure 2.

Our approach reflects the fact that convergence can generally be seen from two perspectives: it can be seen as an abstract concept providing guiding principles for the general scientific development (top-down) in the sense of a guiding vision (Dierkes & Hoffmann, 1992; Dierkes, 1990; Lösch, 2006). Or it can be considered as something that is already occurring in concrete application areas without a comprehensive planning and principally even without knowledge of the concept (bottom-up, see Weingart *et al*., 1990).

The problem with these two perspectives is that the top-down approach is too general for a technology analysis at this early stage of the development, while the bottom-up approach has not yet been systematically applied. Figure 3 translates these observations into an overview. It shows three levels of concreteness, starting at the top from the least concrete level showing merely the four core fields of convergence. From the

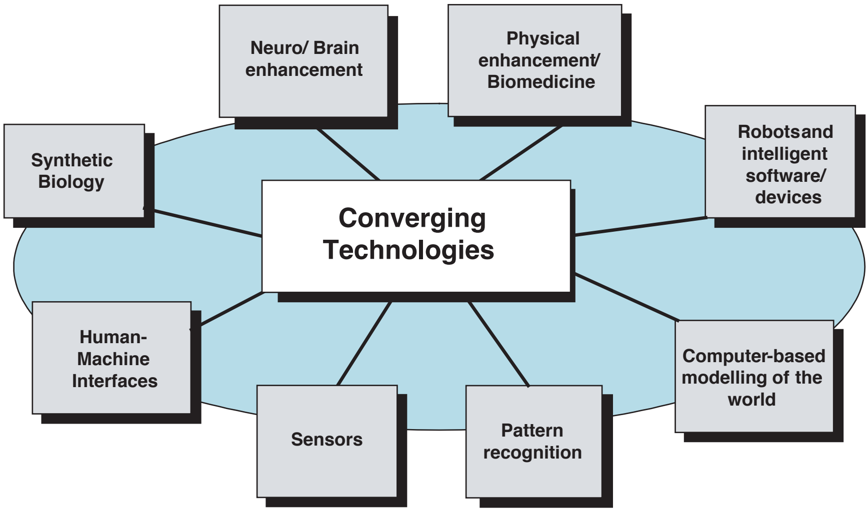

FIGURE 2
Application areas in the CT debate as a result of the clustering exercise

sheer notion of convergence, a series of ideas and visions may originate which, in turn, might stimulate specific research at a more concrete level or in concrete application fields. On the other hand, there is the bottom-up perspective where new research results give rise to new visions, as singular successes in the application fields may generate more general expectations about what might be achievable in that area in the future.

Our approach is to take the bottom-up approach seriously and to examine research and technology development at the level of single researchers, research groups, disciplines or technology development areas. In the following section we look at the concrete technology development fields and assess their 'grounding' in real developments, in order to establish the real impact of the convergence concept.

Method and Sources

The results presented in the following sections stem from an extensive analysis of the relevant literature as well as many internet sources. In addition, we carried out a series of interviews with researchers and engineers in the different fields.

First, we analysed the visions in the official CT documents. One important source was Bainbridge (2006). His collection of visions will be used in the following as an entry point, adding more visions from other CT-related documents as we proceed.

In order to assess the state of the art in technology development, we used scientific overview articles as well as reports on special areas covering certain parts of the NBIC subject matter. The overview articles include Silberglitt *et al.* (2006), Shmulewitz *et al.* (2006) and Grillner *et al.* (2005). For assessing advances in single application areas, articles mainly from the Institute of Electrical and Electronics Engineers (IEEE, engineering) and *Nature* (natural sciences) were used.

Second, we included know-how from experts of the Fraunhofer-network in Germany and from several external experts whom we interviewed for this project. The intention of the interviews with researchers and engineers in mostly German research institutes and

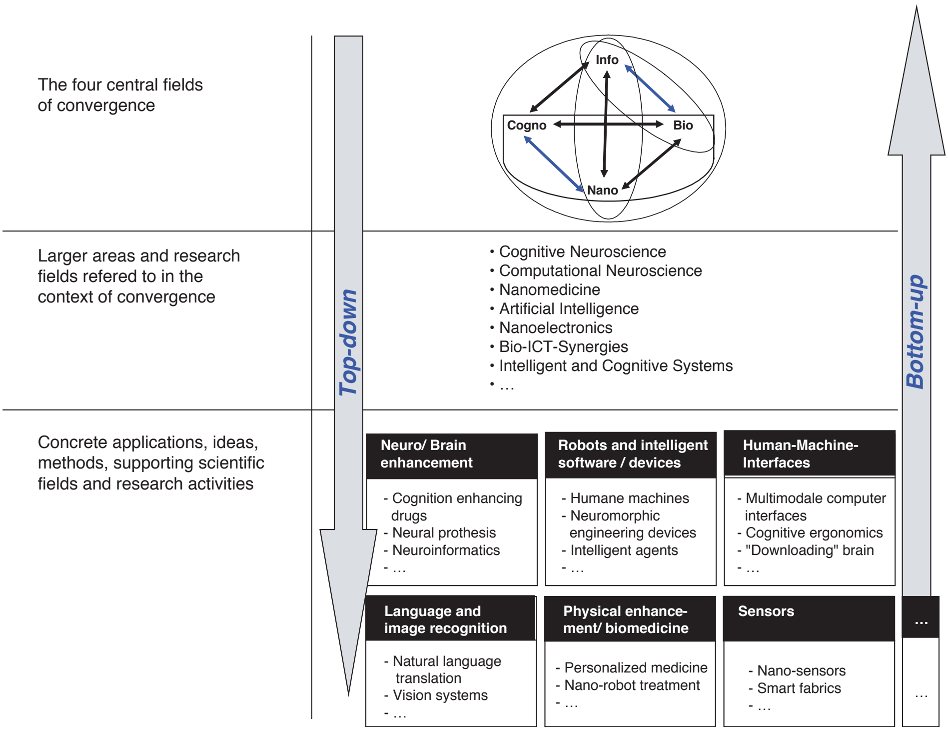

FIGURE 3
Top-down and bottom-up approaches in the debate on converging technologies

universities was to get informed about the extent to which scientific practice is affected by the notion of convergence, and in what ways technological convergence is actually taking place. The results of the expert interviews were incorporated into our assessment of the state of the art in the different fields and the general impact of the convergence concept.

Confronting Visions and Realities in the Eight Core Fields of CT

Neuro/Brain Enhancement

Visions. Recent neuroscience research results have triggered high expectations regarding the understanding, modelling and enhancing of the human brain. The central vision in the neuroscience field is that one day scientists will be able to completely understand and describe the biochemical and neuroelectrical processes associated with human intentions, impulses, feelings and beliefs, and be able to transfer that knowledge in terms of formally well-defined processes (Bainbridge, 2006). A comprehensive understanding would finally contribute to overcoming disabilities such as blindness, deafness and immobility states through assistive technologies (Bainbridge, 2006, p. 343).

In addition, the stimulation and enhancement of the human brain with the help of pharmaceutical products, genetic modifications or technical devices, such as implants or neural prostheses, is envisioned for the future. Pharmaceutical products could prevent sleep deprivation, stimulate creativity or enhance memory and cognition (Goldblatt, 2003, pp. 339–340). Another long-term goal is the development of technical devices that may function as surrogate brain structures or even as external memory extensions. (Robinett, 2003, p. 168).

Memory extensions or skill modules (for example Chinese language modules) to be implanted into the brain could enhance human capabilities just like computers can be upgraded by plugging in additional hardware components or by upgrading software. The most radical vision in this context is to download the complete contents of a human brain on a computer chip, thus preserving memories and thoughts after the death of that individual person.

State of the art. Neuroscience has been successful in locating areas in the brain responsible for certain functions by using new imaging techniques. It has also managed to gain a deeper understanding of the biochemical processes at the level of the single neuron by using new techniques. Despite these achievements over the last 10 years, the brain is still only very partially understood.

This is especially the case for the functioning of combined cell structures consisting of up to several thousand neurons. To make progress in this area, neuroscientists state that it is necessary to develop a multi-level approach which links together the different fields of investigation (Elger *et al.*, 2004, p. 31; Grillner *et al.*, 2005, p. 614). Interdisciplinary cooperation is foreseen in new brain-related areas such as neurocomputing, biomechanics or psychology.

Concerning the enhancement idea, there are already several pharmaceuticals commercially available which influence the functioning of the human brain in different ways. The most famous examples are pharmaceuticals like the anti-depressant Prozac or the sleep-regulating drug Provigil. In fact, some of these drugs are already called 'cosmetic psycho pharmaceuticals' because they are used by people who are not ill. Instead, they are used in order to overcome shyness or to be able to work up to 40 hours without sleep (Welan, 2005; Merkel *et al.*, 2007).

Regarding technical devices, the most established non-invasive technique to influence neuronal processes in the brain is the transcranial magnetic stimulation (TMS) method, where rapidly changing magnetic fields induce currents in the brain and thereby activate brain nerves. The potential of this method for treating severe depression, drug-resistant epilepsy, auditory hallucinations and tinnitus are currently being investigated. Apart from that, Sandberg and Bostrom, who provide an overview of the state of the art in neuroscience, are of the opinion that TMS could positively influence motor learning-tasks, visio-motor coordination, finger sequence tapping and even declarative memory consolidation during sleep (Sandberg & Bostrom, 2006).

Apart from the non-invasive techniques, there are invasive therapeutic approaches which aim at the restoration of senses or certain physiologic functions. For instance, Shmulewitz *et al.* (2006) list a series of companies which have succeeded in producing or are trying to produce such devices: 'The combination of miniaturised microelectronics, novel biomaterials and adaptive signal processing techniques has created the possibility of building artificial neural implants – spurring new ventures such as Intelligent Medical

Implants (Zug, Switzerland), Optobionics (Naperville, USA) and Cyberkinetics (Foxborough, USA)' (Shmulewitz et al., 2006: 278).

With regard to the restoration of senses, two important areas are implants for the restoration of hearing and vision (cochlear implants and retinal implants), which have been around for some time and are continuously improved as the understanding of the functions of the brain increases (Bolz *et al*., 2005; van Lieshout *et al*., 2006). In addition, certain possibilities of drug-based brain enhancements already exist. Examples are pharmaceuticals like the anti-depressant Prozac, memory drugs for the treatment of age-related cognitive decline (e.g. memantine to treat Alzheimer's disease) or amphetamine for the improvement of learning abilities. Furthermore, first approaches for genetic enhancement have already been tested on animals – demonstrating the possibility to create fearless or smarter mice with the help of targeted genetic manipulations of certain receptors in the brain (Shumyatsky *et al*., 2005; Sandberg & Bostrom, 2006).

Neuroscience involves a variety of scientific disciplines like biology, psychology, computer science, physics and medicine and utilizes methods and tools from different research areas. Neuroscience researchers are convinced that progress can only be made through an intelligent combination of disciplines like nano- and biotechnology, information technology, genetic engineering and cognitive science. Thus, 'neuro/ brain enhancement' as a research field stands at the centre of the CT debate. It attracts the largest share of attention due to its plans to simulate and manipulate brain processes, which – if realized successfully – could directly affect our concepts of the human self and identity.[3]

Physical Enhancement and Biomedicine

Visions. The central vision in the field of physical enhancement and biomedicine is that advances in bio- and nanotechnology will lead to novel therapy methods and the enhancing of the physical capabilities of humans. The most prominent visions here are nanorobots performing surgery and administering treatments deep inside the human body (Freitas, 2005), the breeding of 'spare parts' for the human body, muscles that do not fatigue and enhancing persons to the point where they can run way faster than 'normal' individuals or carry heavy loads, exceeding 'normal' dimensions (Bainbridge, 2006). Also, extreme longevity should be achieved with these methods, allowing persons to live longer than 200 years. Shorter-term visions foresee nano-sized sensors and lab-on-a-chip systems for patient monitoring and diagnostic purposes. These devices should be the basis for decentralized point-of-care applications – making central laboratories more and more obsolete.

State of the art. Concerning the current state of physical enhancement and biomedicine research, it can be said that the first nanotechnology-based drug-delivery systems which release drugs in particular locations of the body are already commercially available while another 100 products are currently in the pipeline (Wagner & Zweck, 2005). But as research on the interaction of nanomaterials and living organisms has just begun, it has to be kept in mind that only limited information concerning long-term effects and the potential toxicity of nanoparticles inside the human body is available at the moment.

Pharmacogenomic and pharmacogenetic studies, which both deal with the influence of genetic variations to drug response, have already enabled the development of a small number of genetic tests which predict the response of individuals to certain pharmaceuticals

(Weatherall *et al*., 2005). In the long run, this development might lead to drugs that are tailored to the individual genetic makeup. In contrast, gene therapy has not yet been very successful in the case of humans (some patients even died) despite quite successful experiments with genetically modified animals. With animals, treatments have been tested which gave mice muscles that did not fatigue. Concerning gene therapy it is estimated that it may take about 10 years until the first effective nanobased solutions become available (ESF, 2005, p. 20).

Research in the area of the artificially enhanced exoskeleton, envisioned by former DARPA-manager Michael Goldblatt (Goldblatt, 2003, p. 338), has already made considerable progress. In early 2004 researchers at the University of California at Berkeley presented a self-powered exoskeleton, which enabled its 'pilot' to carry about 30 kg (70 pounds) as if it were merely 2 kg (5 pounds). The system consists of mechanical legs that are connected to the user at his feet and a vest that is attached to the frame of a rucksack. A network of more than 40 sensors is used in order to control the hydraulic actuators within the exoskeleton, such that the system takes its own weight and ensures that the centre of gravity stays within the pilot's footprint. Although this special prototype is not a suitable application in the battlefield, it could be seen as a proof-of-concept.

Like in the brain research field, in the field of 'physical enhancement/biomedicine', convergence of different scientific fields and methods is clearly visible and widely applied. The area of biomedicine has a history of convergence already: its recent breakthroughs and products, like inhaled insulin or therapies combining devices and medication, were only possible by combining different scientific and engineering methods.

Synthetic Biology

Visions. The central vision of the relatively new field of synthetic biology is to design, construct and engineer biological systems or devices to be able to process information (the DNA computer), manipulate chemicals, fabricate materials, produce energy, provide food and maintain and enhance human health and the environment. This should be done by artificially re-designing existing biological systems.

Expectations on synthetic biology and future applications are high and range widely across scientific and engineering disciplines, from medicine to energy generation. Rationally engineered organisms might be designed to make useful materials (such as biodegradable plastics) from cheap and renewable raw materials, or to convert feedstock to fuels such as hydrogen and methanol. The ability of biological systems to control the structure of materials at the molecular level could also provide access to materials with new and improved properties, or devices such as machines and electronic circuitry structured at ultra-small scales. Synthetic biology might even have an impact comparable to the IT-revolution.

State of the art. Currently the main task in the field of synthetic biology is to develop building blocks for future biological devices. Compared with electronic components like resistors or capacitors, the aim is for biological components, so-called 'bioparts', to be assembled into devices to work inside living cells. In an engineering sense, the cells must act as 'power supplies' and 'chassis', providing materials, energy, and other basic resources that are needed for proper system function. However, the industrial fabrication of such biological systems in series is still out of reach. One reason for this is that the tools available for building with biological components still have to reach a level of standardization and utility equal to that in other engineering fields. Another reason has to do with methods and mindsets in biology. Until now, mostly scientists in the field have worked together in closed teams on isolated applications for special problems.

Even though most of the components developed so far have been important as proof-of-concept at the level of basic research, R&D in Synthetic Biology is still in its infancy. Currently, there are a number of concepts and ideas which yet have to be realized but some niche products are already commercially available, since there is a handful of companies and organizations applying engineering principles and tools to commercial biological manufacturing. Examples are the non-profit BioBricks Foundation (Cambridge, MA), which is promoting open tools, standards and parts for biological engineering; the firm 'Blue Heron Biotechnology' (Bothell, WA) focusing on DNA synthesis; Codon Devices (Cambridge, MA), which is building artificial biological devices; the Foundation for Applied Molecular Evolution (Gainesville, FL), which is generating novel proteins and materials; and the firm Synthetic Genomics (Rockville, MD), which is engineering microbes to produce fuels (Bio FAB Group, 2006; Bio-Fab-Gruppe, 2007).

The idea of biological computing was initially developed by Leonard Adleman of the University of Southern California, who demonstrated a proof-of-concept use of DNA for massively parallel computation problems (Adleman, 1998). A DNA computer or molecular computer is basically a collection of specially selected DNA strands whose combinations will result in the solution to some problem. Technology is currently available both to select the initial strands and to filter the final solution. The promise of DNA computing is massive parallelism by taking advantage of the many different molecules of DNA to try many different possibilities at once. This can be much faster than a conventional computer, for which massive parallelism would require large amounts of hardware, not simply more DNA (Adleman, 1998; Kari, 2001). At this stage, the establishment of a methodology for DNA computing dominates research efforts.

Synthetic biology combines nano, bio and information technology and has recently been seen as part of the converging technologies development. A recent report even states that synthetic biology may be the converging technology par excellence: 'Delve into the biographies of synbio's luminaries and you'll find Ph.D.s in chemical, electrical and biochemical engineering, physics and pharmacology (and surprisingly few biologists)' (ETC Group, 2007). Indeed, experts from numerous different research areas, such as engineering and production, molecular biology, systems biology, organic chemistry, informatics, nanobiotechnology, etc. have to work together. They have to take existing biological pieces and transform them into micro-machines, thus creating artificial systems that mimic the properties of living systems.

Human–Machine Interfaces

The following five CT areas can be considered sub-fields of the main fields 'neuro/brain enhancement', 'physical enhancement and biomedicine' and 'synthetic biology'. They constitute integral parts of the three main fields and are presented separately because there is already a research tradition in these fields linked to convergence and receiving corresponding attention.

Visions. The main goal in the research field of 'human–machine interfaces' is to develop interfaces that enable direct connections between the human brain and artificial limbs as well as between humans and computers or other machines. The envisioned interfaces will possibly enable a large set of applications – ranging from the restoration (e.g. artificial hands) to the augmentation of human performance by direct neural control of complex machines, connecting the brain to sensors for UV-light and ultrasound or to external memory extensions (Robinett, 2003; Bainbridge, 2006).

In the context of the CT debate the field of human–machine interfaces has acquired a peculiar importance: visions range from devices that may link directly to nerves, to record and replay sensations (Bibel *et al.*, 2004, p. 27) to broadband connections between brain and machines that will 'transform work in factories, control automobiles, ensure military superiority, and enable new sports, art forms and modes of interaction between people' (Bainbridge, 2006, p. 339).

State of the art. Regarding non-invasive human–machine interfaces, current research focuses on the possibility of monitoring cerebral activity via the electroencephalogram (EEG). About 100 electrodes are placed externally on the scalp in order to record electric signals, which can be converted into simple commands like the movement of a cursor on a computer-screen (Blankertz *et al.*, 2006). Using another non-invasive method based on real-time functional magnetic resonance imaging (fMRI) of brain activity, it has become possible to control a robot hand by thoughts (Knight, 2006). Regarding invasive interfaces, multi-electrode recordings from electrode-arrays, as for example the so called Utah electrode array (UEA), consisting of 100×1.5 mm long electrodes assembled on a 4 mm^2 chip permanently implanted in the brain, represent the state of the art. During recent experiments a quadriplegic patient was able to control a robotic arm with the help of such an implant (Hochberg *et al.*, 2006).

Given the fact, that the majority of these experiments are still one-directional, e.g. from the brain to artificial devices, the development of bi-directional interfaces would be beneficial for envisioned applications like the control of paralysed limbs or complex prosthetic devices. This can be achieved only by combining computer science and information technology with research fields like cognitive science and psychology but also material science, biomechanics and engineering.

Sensors

Visions. Apart from the general goal of sensor development like the miniaturization of components or the improvement of sensor sensitivity and specificity, a set of specific visions is connected to this field. In the NBIC documents there is a strong focus on the detection of chemical and biological warfare agents or poisonous substances in general and also on information about the environment like temperature, UV levels and concentrations of pollutants (Roco & Bainbridge, 2003; Pierce, 2003, p. 118). Related to this vision is the idea to build systems which could identify hijackers and terrorists via 'remote detection of heart rate, adrenaline on the skin, and perhaps other chemicals connected with the "fight or flight" reaction' (Fainberg, 2003, p. 345).

In the medical sector, visions encompass fast and ultra-sensitive sensors for enabling improved diagnostics and better treatment of diseases. Ideas range from wireless sensor networks and wearable sensors for medical self-monitoring to biochips or lab-on-a-chip systems and nanosized imaging and diagnostics agents (Connolly, 2003, p. 185; van Lieshout *et al.*, 2006, pp. 67 and 80; Bainbridge, 2006).

State of the art. Concerning military or terrorist defence applications, the state of the art in sensor-related R&D is difficult to determine. However, research progress in the civil areas might also become important for defence applications.

Within the area of wearable sensors, the commercially available heart rate sensors that are integrated in wristbands or chest-belts are well known examples. A more advanced device is the so-called smart shirt developed by researchers at Georgia Tech. This is a T-shirt with integrated optical and conductive fibres which enable the monitoring of heart rate, electrocardiogram (ECG), respiration and temperature. The technological maturity of nano-sized imaging, diagnostic agents and biochips still varies significantly. Nevertheless one could say that recent research efforts on diagnostics agents and miniaturized biosensors have led to a significant improvement of analyses of processes at the cellular and the molecular levels (molecular diagnostics) and also of more sensitive tests, like the detection of bio-molecules, e.g. target DNA-sequences (Wagner & Zweck, 2005; De Groot & Loeffler, 2006). Moreover, the development of more precise and faster diagnostic methods is an important part of the current trend towards point-of-care testing and the so-called personalized medicine. Concerning wireless sensor networks, one could conclude that research is still at an early stage of development, although the first experimental projects (environmental monitoring, seismic detection, military surveillance or even 'smart mine fields') seem to be successful (Chong & Kumar, 2003). With regard to monitoring health or human activity in general, the research field 'sensors' indicates the need for convergence of nano and biotechnology with information technology.

Computer-based Modelling of the World

Visions. This research field has to be understood as the modelling, simulation or mapping of 'the real world' with the help of computers. Visions and ideas in this field range from the prediction of computer-generated virtual environments, perfectly reproducing reality based on developments in virtual and augmented reality (VR and AR), to deep insights into living nature by making use of bioinformatics and computational biology, neuroinformatics and computational neuroscience (Batterson & Pope, 2002; Bainbridge, 2006; Bibel *et al.*, 2004). This category reflects the strong belief of the US-dominated debate of convergence that formal rules, natural science research and computer-based models can be developed to a state where the functioning of the human brain and body can be completely understood and manipulated in order to enhance performance and well-being.

State of the art. Research on VR and AR systems has already resulted in technologies which allow the interaction with immersive high-fidelity three-dimensional simulations (VR) and which also make it possible to combine 'the real world' and computer graphics (AR). One example is the visualization of assembly steps during maintenance and construction activities using a head-mounted display. However, research within both areas still focuses on the improvement of display technologies. Virtual retinal displays which scan low-energy laser light directly onto the retina are state-of-the-art in AR. The exact tracking of the position and orientation of the user's head, which is necessary for the correct matching of the overlaid graphics with the view of the surrounding world, is still a challenge for AR-related R&D.

Besides the steady improvement of computing power, the idea of building local or distributed computer clusters to create supercomputers has made it possible to address more and more complex or computing intensive problems in physics, chemistry, biology and neuroscience. Areas within computational science, such as bioinformatics or computational biology, deal with the management and analysis of biological data and the application of computational approaches to biological phenomena. They are linked to the vision that, one day, it will be possible to develop a multi-scalar simulation of biology ranging from the molecular to the societal level. At the moment, one can observe a movement of this field of research from structural analyses of genes and proteins towards analyses of interactions between genes and proteins, which is expected, in the long run, to lead towards research activities on cellular and ontogenetic functions (Shoji & Mogi, 2002). Yet, it is still not possible, for example, to simulate the kinetics of protein folding. Neuroinformatics and computational neurosciences deal with the management and analysis of neuroscience data and the application of computational methods to study the function and mechanisms of the nervous system. Current projects like the Blue Brain Project aim to simulate a rat's cortical column built of 10,000 neurons on the world's fastest supercomputer (by November 2006), the IBM Blue Gene/L, running at 280.6 TFLOPS (280.6×10^{12} floating point operations per second). The hope is that it will be possible to understand brain functions by modelling the cerebral cortex, which for humans consists of about 1,000,000 cortical columns and is involved in functions like sensory perception, conscious thought, speech, etc. (Markram, 2006).

The research field 'computational modelling of the world' is relevant for all scientific disciplines today. Here, convergence can be observed in the sense that within all natural sciences computers are used to manage databases or develop models in order to obtain deeper insights about fundamental mechanisms. This might also help to better understand diseases or develop new pharmaceuticals.

Pattern Recognition

Visions. The majority of visions in this field is related to automatic speech recognition and the detection of visual patterns (image recognition). The visionary application ideas are quite diverse and encompass applications like automatic translation systems of natural language, speech-driven vehicles and surveillance systems which can identify people and even detect what activities they are carrying out.

State of the art. Some examples for successful speech recognition-based products already exist, like medical reporting systems or 'reading tutors' for illiterate people. However, current software programs still fail 2–5% of all words. Regarding image recognition and computer vision systems, certain applications like industrial quality control systems for the inspection of manufactured goods or systems for forest surveys and crop/land-use identification are well established. Yet, more complex tasks like the computer-based assessment of the aesthetic appearance of products or the recognition of faces remain difficult (van Lieshout *et al*., 2006). In the field of surveillance systems based on pattern recognition, a variety of biometric methods like fingerprint, iris, face and voice recognition have already been established on the market. An up-to-date example is the biometric passport (ePass), which was introduced during the last two years in many states worldwide. The ePass is a combined paper and electronic identity document using biometric data stored on a radio frequency identification tag (RFID-tag) to authenticate the citizenship of travellers. For authentication, the stored reference data like the digital photo is compared with actually acquired data. A key factor for the quality of biometric systems is the probability of errors. Thus, error rates like the false acceptance rate (FAR) or the false rejection rate (FRR) have to be optimized. Given that the existing mathematical modelling approaches and algorithms for pattern recognition are still deficient, some researchers conclude that multi-modal recognition methods might be a solution (Zhao *et al*., 2003).

For the development of successful pattern recognition systems as part of the CT development, scientists and engineers from disciplines like linguistics, computer science, software programming and hardware development have to work together.

Robots and Intelligent Systems

Visions. This area of CT embraces visions and approaches that are predominantly influenced by concepts like artificial intelligence (AI), sociable technologies or ubiquitous computing. Central to the concept of AI is the idea that one day it will be possible to develop intelligent devices that are functionally equivalent to the human brain, and which could be used for a wide range of purposes and functions like sensing, perceiving, memorizing, controlling, acting and learning (Moravec, 1999, Kurzweil, 2005). Sociable technologies aim at the development of intelligent devices and robots which offer people new forms of social relationships, e.g. medical care robots which could provide personal contacts or household robots that are able to support aging people. The idea of ubiquitous computing is that everyone will be surrounded by computing and networking technologies embedded in his or her respective environments. Therefore, ubiquitous computing will make it possible to access needed information everywhere and will also provide different forms of distributed services and support (Bainbridge, 2006).

State of the art. Even though it still lags behind its self-imposed expectations, AI has already achieved certain advances in different sub-domains like expert systems, autonomous robots (e.g. 'Stanley' the robot which won the DARPA Grand Challenge in 2005) and in AI theory and algorithms, such as search and planning algorithms, machine learning or pattern recognition algorithms. Furthermore, AI has developed from a separate part of computer science to an area of research which influences other disciplines like the cognitive sciences, psychology, robotics etc. and vice versa (Waltz, 2006; van Lieshout *et al*., 2006).

Regarding sociable technologies, first examples of this kind of technology were toys like Tamagotchies or Sony's AIBO. Moreover, certain positive effects caused by the use of such robots in hospitals and in homes for the elderly have already been demonstrated in different experiments, such as mood improvement by interaction with a seal robot (Wada *et al*., 2004). Nonetheless, it is emphasized that a deeper theoretical understanding of emotions is necessary for the advancement of emotional robotics. Until now, the ubiquitous computing concept is still in its infancy, but nevertheless some functioning proof-of-concept systems exist. They include for example different kinds of wearable computers, e.g. fabrics that incorporate electrical circuits and which could be used for health monitoring, or the 'smart environment' of the so-called Gator Tech Smart House, which is based on connected sensors, actuators and computers (Helal *et al.*, 2005).

In the field 'Robots and intelligent software/devices', the scientific disciplines that have to come together and combine methods are computer science, cognitive science, psychology and hardware development.

Summary

The analysis of the visions and the state of the art research in the overlapping fields of nano, bio, info and cogno has shown that convergence is indeed under way in various fields. Central impulses for convergence are coming from the field of neuroscience. Multi- and interdisciplinary research and development is at the core of technological convergence.

The investigation into the applications fields of NBIC has shown that the central fields of CT, e.g. neuro and brain enhancement, physical enhancement and biomedicine, and – with some restrictions – also the relatively new field of synthetic biology, have incorporated and combined existing research fields. We found that convergence is indeed beginning to take place. Indicators are new potential applications, interdisciplinary cooperation and research projects.

However, the analysis has also shown that visions and the state of the art research are considerably distant from each other in all eight fields. The gap is especially wide in the two human enhancement fields (brain/neuro and physical enhancement) and in synthetic biology. In almost all of the remaining fields, the distance is not as significant and visions can be expected to turn into concrete applications in the not too distant future.

In neuroscience and biomedicine there is a strong focus on medical applications and improvements of treatments and therapies. This was confirmed in the interviews conducted with researchers. Clinical research and the focus on healing the human mind and body are not as present as in the other six areas. Current research priorities in these three fields do not mention enhancement as an explicit goal.

Looking at all eight fields, it can be stated that convergence is needed almost everywhere encompassing very different sub-fields and sub-disciplines. From a technological perspective, there is no 'lead' convergence to be found. However, it became obvious that 'pacemakers' of convergence are indeed neuro enhancement, physical enhancement and synthetic biology.

In all eight fields, the need for interdisciplinary cooperation is considered of central importance. In a certain way, convergence and interdisciplinarity could be used synonymously. In some areas, such as artificial intelligence, convergence does not describe a new approach but includes an existing research field, which could profit from a more rigid trans- and interdisciplinary approach, as suggested by CT. As such, convergence has to be understood as a dynamic and ongoing process that is accompanied by a continuous reorganization of disciplinary sub-fields.

Table 1 summarizes the results and lists areas and disciplines which are supposed to work together in the eight CT areas. The distance between visions and state of the art indicates the probability of the respective field remaining in a basic research state as opposed to becoming an important application area in the near future.

Although brain enhancement, brain modelling and brain manipulation have a strong appeal and are well suited for public discussion, it cannot be ruled out that the

TABLE 1
Summary distance between visions and state of the art research and main new combinations

Area of technological convergence	Distance between visions and state of the art	Expected benefit from inter-disciplinarity cooperation	Main new combinations to be found
1. Neuro/brain enhancement	High	Very high	Neuroscience, computer science and mathematical models, nano- and biotechnology, medical research, genetic engineering software development, cognitive science, neuroscience and psychology, biomechanics, material sciences
2. Physical enhancement and biomedicine	Generally high but medium in some concrete areas	Very high	Medical research, bioengineering, nanotechnology, material sciences, engineering human limbs, drug delivery methods, engineering, physics, pharmacology, nanobiotechnology
3. Synthetic biology	High	Very high	Nano-, bio- and information technology, chemical, electrical and biochemical engineering, physics, pharmacology engineering and production, molecular biology, systems biology, organic chemistry, informatics, nanobiotechnology
4. Human–machine interfaces	Medium with some exceptions	Very high	Computer science, information technology, cognitive science, psychology, material science, biomechanics, engineering
5. Sensors	Medium	Very high	Medicine, material science, electrical engineering, computer science, engineering
6. Computer-based modelling of the world	Medium	Very high	All natural sciences using computers to produce models from databases, especially medicine, pharmaceutical research, bioinformatics, computational biology
7. Pattern recognition	Low[a]	Very high	Computer science, linguistics, software programming and hardware development
8. Robots and intelligent software	Medium[b]	Very high	Computer science, cognitive science, mathematics, psychology, hardware development

[a]With the exception of automatic language translation.
[b]Due to earlier disappointments in artificial intelligence research.

convergence development might lead to scientific breakthroughs in totally different fields. The direction and thematic scope of convergence is much broader than some CT proponents suggest. The consequent application of the convergence concept may lead to very different results – even to results not thought of today. For example new understandings of the brain may have effects on the development of new IT-applications. But it could also work the other way round, namely when new computer hardware and data processing techniques lead to a better understanding of the brain.

Another point is the awareness among scientists of the concept of convergence. Given the uneven picture of real science and technology developments we conclude that the convergence concept works first of all as a political concept or a concept of research managers. In our interviews we found that the term is so new that researchers are mostly not aware of convergence, even if they work in the middle of a converging discipline, busy with technology developments in the conceptual overlapping of nano, bio, info and cognitive science. Thus, the concept of technological convergence still has to go a long way from vision to guiding actions of scientists and finally to concrete technology development.

NOTES

1. A significant part of the work for this paper was carried out in the context of the European project 'CONTECS' (converging technologies and their impact on the social sciences and humanities, see: www.contecs.fraunhofer.de).
2. Axel Thielmann from Fraunhofer ISI contributed to the text.
3. For a more comprehensive description of the state of the art research see the two papers produced for the CONTECS project: Deliverable 1.1 Part A (Beckert et al., 2006) and Deliverable 3.1 Part 1 (2007) entitled *R&D Trends in Converging Technologies* (Rader et al., 2006). The deliverables can by downloaded at www.contecs.fraunhofer.de

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