

# CONVERGING TECHNOLOGIES FOR IMPROVING HUMAN PERFORMANCE

June 2002



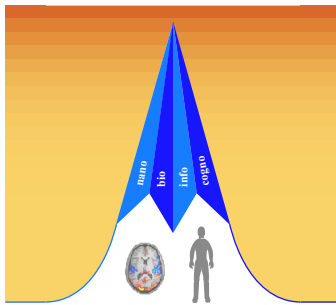
## **National Science Foundation Department of Commerce**

At the request of the National Science and Technology Council (NSTC) Subcommittee on Nanoscale Science, Engineering and Technology (NSET), the National Science Foundation (NSF) and the Department of Commerce (DOC) organized a workshop on December 3-4, 2001. This report incorporates the views expressed at the workshop of leading experts from government, academia, and private sector, and detailed in contributions submitted thereafter by members of the U.S. science and engineering community.

NSTC is the principal means for the U.S. president to coordinate science, space and technology ideas across the Federal Government.

### **Acknowledgements**

The contribution of all participants in this study in developing a coherent vision for Converging Technologies for Improving Human Performance is acknowledged. The initial group that began planning this study in Spring 2001 is composed W.S. Bainbridge, J. Canton, M.C. Roco, R.S. Williams and G. Yonas.



About the cover: The arrow suggests the combined role of nanotechnology, biotechnology, information technology in accelerating advancement of mental, physical, and overall human performance.

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# **Converging Technologies for Improving Human Performance**

**NANOTECHNOLOGY, BIOTECHNOLOGY, INFORMATION  
TECHNOLOGY AND COGNITIVE SCIENCE**

*NSF/DOC-sponsored report*

Edited by Mihail C. Roco and William Sims Bainbridge, National Science Foundation

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**CONVERGING TECHNOLOGIES FOR IMPROVING HUMAN PERFORMANCE:  
NANOTECHNOLOGY, BIOTECHNOLOGY, INFORMATION TECHNOLOGY AND COGNITIVE SCIENCE**

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*Changing the societal “fabric” towards a new structure  
(upper figure by R.E. Horn)*

The integration and synergy of the four technologies (nano-bio-info-cogno) originate from the nanoscale. This picture suggests the implications of the converging technologies by remapping the main societal paths, towards more functional and coarser pathways instead of the less organized and finer mesh we have now, and with an increased focus on people. New patterns are envisioned in working habits, in economic activity, and in human civilization.





## EXECUTIVE SUMMARY

*Mihail C. Roco and William Sims Bainbridge*

In the early decades of the twenty-first century, concentrated efforts can unify science based on unity in nature, thereby advancing the combination of nanotechnology, biotechnology, information technology, and new humane technologies based in cognitive science. With proper attention to ethical issues and societal needs, converging technologies could determine a tremendous improvement in human abilities, societal outcomes, the nation's productivity, and the quality of life. This is a broad, cross cutting, emerging and timely opportunity of interest to individuals, society and humanity in the long term.

The phrase “convergent technologies“ refers to the synergistic combination of four major “NBIC“ (Nano-Bio-Info-Cogno) 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; (d) cognitive science, including cognitive neuroscience.

**Timely and Broad Opportunity.** Convergence of diverse technologies is based on *material unity at the nanoscale and on technology integration from that scale*. Revolutionary advances at the interfaces between previously separate fields of science and technology are ready to create key *transforming tools* for NBIC technologies. Developments in systems approaches, mathematics and computation in conjunction with NBIC allow us for the first time to understand the natural world and scientific research as closely coupled complex, hierarchical systems. At this unique moment in the history of technical achievement, *improvement of human performance through integration of technologies* becomes possible.

Examples of payoffs will include improving work efficiency and learning, enhancing individual sensory and cognitive capabilities, revolutionary changes in healthcare, improving both individual and group creativity, highly effective communication techniques including brain to brain interaction, perfecting human-machine interfaces including neuromorphic engineering, enhancing human capabilities for defense purposes, reaching sustainable development using NBIC tools, and ameliorating the physical and cognitive decline that is common to the aging mind.

**This report addresses key issues:** What are the implications of unifying sciences and converging technologies? What visionary ideas can guide research to accomplish broad benefits for humanity? What are the most pressing research and education issues? How can we develop a transforming national strategy to enhance individual capabilities and overall societal outcomes? What should be done to achieve the best results over the next 10 to 20 years?

This report underlines several broad, long-term implications of converging technologies in key areas of human activity, including working, learning, aging, group interaction, and human evolution. If we make the correct decisions and investments today, many of these visions could be achieved within twenty years' time. Moving forward simultaneously along many of these paths could achieve a golden age that would be an epochal turning point in human history.

**Strategies for Transformation.** It is essential to prepare key organizations and societal activities for the changes made possible by converging technologies. Activities that accelerate convergence to improve human performance must be enhanced, including focused research and development, increased technological synergy from the nanoscale, developing of interfaces among sciences and technologies, and a holistic approach to monitor the resultant societal evolution. Education and training at all levels should use converging science and technology and prepare people to take

advantage of them. We must experiment with innovative ideas to motivate multidisciplinary research and development, while finding ways to address ethical, legal, and moral concerns. In many application areas, such as medical technology and healthcare, it is necessary to accelerate advances that would take advantage of converging technologies.

**Towards Unifying Science and Converging Technologies.** The evolution of a hierarchical architecture for integrating natural and human sciences across many scales, dimensions, and data modalities will be required. Half a millennium ago, Renaissance leaders were masters of several fields simultaneously. Today, however, specialization has splintered the arts and engineering, and no one can master more than a tiny fragment of human creativity. Convergence of the sciences can initiate a new renaissance, embodying a holistic view of technology based on transformative tools, the mathematics of complex systems, and unified cause-and-effect understanding of the physical world from the nanoscale to the planetary scale.

**Major Themes.** Scientific leaders and policy makers across a range of fields prepared written statements for a December 2001 workshop, evaluating the potential impact of NBIC technologies on improving human capabilities at the microscopic, individual, group, and societal levels. During the workshop, participants examined the vast potential in six different areas of relevance:

- *Overall potential of converging technologies.* Representatives of government agencies and the private sector set forth the mission to explore the potential of converging technologies to improve human performance, as well as the overall potential for changing the economy, society and research needs. They identified the synergistic development of nano, bio, information and cognition-based technologies as an outstanding opportunity at the interface and frontier of sciences and engineering in the following decades, and proposed new visions of what it is possible to achieve.
- *Expanding human cognition and communication.* Highest priority was given to “*The Human Cognome Project*,” a multidisciplinary effort to understand the structure, functions, and potential enhancement of the human mind. Other priority areas were: personal sensory device interfaces; enriched community through humanized technology; learning how to learn; and enhanced tools for creativity.
- *Improving human health and physical capabilities.* Six priority areas have been identified: nano-bio processors for research and development of treatments, including those resulting from bioinformatics, genomics and proteomics; nanotechnology-based implants as replacement for human organs or for monitoring of physiological well-being; nanoscale robots and comparable unobtrusive tools for medical intervention; multi-modality platforms for increasing sensorial capabilities, particularly for visual and hearing impaired people; brain to brain and brain to machine interfaces; and virtual environments for training, design, and forms of work unlimited by distance or the physical scale on which it is performed.
- *Enhancing group and societal outcomes.* An NBIC system called *The Communicator* would remove barriers to communication caused by physical disabilities, language differences, geographic distance, and variations in knowledge, thus greatly enhancing the effectiveness of cooperation in schools, corporations, government agencies, and across the world. This includes enhancing group creativity and productivity.
- *National security.* Given the radically changing nature of conflict in this new century, seven opportunities to strengthen national defense offered by technological convergence deserve high priority: data linkage and threat anticipation; uninhabited combat vehicles; war fighter education and training; responses to chemical, biological, radiological and explosive threats; war fighter

systems; non-drug treatments to enhance human performance; and applications of human-machine interfaces.

- *Unifying science and education.* To meet the coming challenges, scientific education needs radical transformation from elementary school through post-graduate training. Convergence of previously separate scientific disciplines and fields of engineering cannot take place without the emergence of new kinds of personnel who understand multiple fields in depth and can intelligently work to integrate them. New curricula, new concepts to provide intellectual coherence, and new forms of educational institution will be necessary.

Beyond the 20-year time span, or outside the current boundaries of high technology, convergence can have significant impacts in such areas as: work efficiency, the human body and mind throughout the life cycle, communication and education, mental health, aeronautics and space flight, food and farming, sustainable and intelligent environments, self-presentation and fashion, and transformation of civilization.

### Synopsis of Recommendations

The recommendations of this report are far-reaching and fundamental, urging the transformation of science, engineering and technology at their very roots. The new developments will be revolutionary and must be governed by respect for human welfare and dignity. This report has educational and societal transforming goals. Building on the suggestions developed in the five topical groups, and the ideas in the more than fifty individual contributions, the workshop recommended a **national R&D priority area on converging technologies focused on enhancing human performance**. The opportunity is broad, enduring, and of general interest.

- a) **Individuals.** Scientists and engineers at every career level should gain skills in at least one NBIC area and in neighboring disciplines, collaborate with colleagues in other fields, and take risks in launching innovative projects that could advance NBIC.
- b) **Academe.** Educational institutions at all levels should undertake major curricular and organizational reforms to restructure the teaching and research of science and engineering so that previously separate disciplines can converge around common principles to train the technical labor force for the future.
- c) **Private Sector.** Manufacturing, biotechnology, information and medical service corporations will need to develop partnerships of unparalleled scope to exploit the tremendous opportunities from technological convergence, investing in production facilities based on entirely new principles and materials, devices and systems, with increased emphasis on human development.
- d) **Government.** The Federal Government should establish a national research and development priority area on converging technologies focused on enhancing human performance. Government organizations at all levels should provide leadership in creating the NBIC infrastructure and coordinating the work of other institutions, and must accelerate convergence by supporting new multidisciplinary scientific efforts while sustaining the traditional disciplines that are essential for success. 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.
- e) **Professional Societies.** The scientific and engineering communities should create new means of interdisciplinary training and communication, reduce the barriers that inhibit individuals from working across disciplines, aggressively highlight opportunities for convergence in their

conferences, develop links to a variety of other technical and medical organizations, and address ethical issues related to technological developments.

- f) **Other Organizations.** Non-governmental organizations that represent potential user groups should contribute to the design and testing of convergent technologies, in order to maximize the benefits for their diverse constituencies. Private research foundations should invest in NBIC research in those areas that are consistent with their unique missions. The press should increase high-quality coverage of science and technology, on the basis of the new convergent paradigm, to inform citizens so they can participate wisely in debates about ethical issues such as unexpected effects on inequality, policies concerning diversity, and the implications of transforming human nature.

A vast opportunity is created by the convergence of sciences and technologies starting with integration from the nanoscale, having immense individual, societal and historical implications for human development. The participants in the meetings that prepared this report recommend *a national research and development priority area on converging technologies focused on enhancing human performance*. Technology will increasingly dominate the world, as population, resource exploitation, and potential social conflict grow. Therefore, the success of this convergent technologies priority area is crucial to the future of humanity.