OVERVIEW

CONVERGING TECHNOLOGIES FOR IMPROVING HUMAN PERFORMANCE:

Nanotechnology, Biotechnology, Information Technology, and Cognitive Science (NBIC)

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1. Background

We stand at the threshold of a New Renaissance in science and technology, based on a comprehensive understanding of the structure and behavior of matter from the nanoscale up to the most complex system yet discovered, the human brain. Unification of science based on unity in nature and its holistic investigation will lead to technological convergence and a more efficient societal structure. In the early decades of the twenty-first century, concentrated effort can bring together nanotechnology, biotechnology, information technology, and new humane technologies based in cognitive science. With proper attention to ethical issues and societal needs, the result can be a tremendous improvement in human abilities, societal outcomes and quality of life.

Rapid advances in convergent technologies have the potential to enhance both human performance and the nation's productivity. 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 efficiency, highly effective communication techniques including brain to brain interaction, perfecting human-machine interfaces including neuromorphic engineering for industrial and personal use, 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 several main issues: What are the implications of unifying sciences and converging technologies. What should be done to achieve the best results over the next 10 to 20 years? 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? These issues were discussed on December 3-4, 2001, at the workshop on Convergent Technologies to Improve Human Performance, and in contributions submitted after that meeting for this report.

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; and, (d) cognitive science, including cognitive neuroscience.

Accelerated scientific and social progress can be achieved by combining research methods and results across these provinces in duos, trios, and the full quartet. Figure 1 shows the NBIC tetrahedron, in which each field is represented by a vertex, each pair of fields by a line, each set of three fields by a surface, and the entire union of all four fields by the volume of the tetrahedron. This progress is expected to change the main societal paths, towards a more functional and coarser mesh instead of the less organized and finer one we have now.

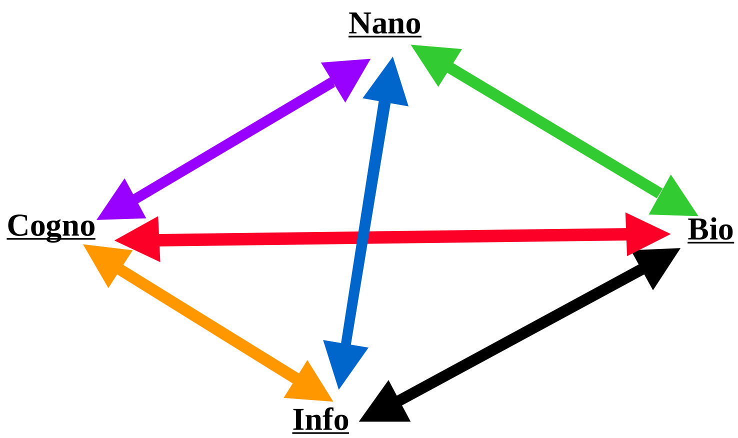

Figure 1. NBIC tetrahedron.

2. Timely and Broad Opportunity

The sciences have reached a watershed at which they must combine if they are to continue to advance. The New Renaissance must be based on a holistic view of science and technology that envisions new technical possibilities and focuses on people. The unification of science and technology is achievable over the next two decades, and can be realized during that time span on the basis of four key principles: material unity at the nanoscale, NBIC transforming tools, hierarchical systems, and improvement of human performance, as described below:

a) Convergence of diverse technologies is based on *material unity at the nanoscale and technology integration from that scale*. Science can now understand the ways in which atoms combine to form complex molecules, and these in turn aggregate according to common fundamental principles to form both organic and inorganic structures. Technology can harness natural processes to engineer new materials, biological products, and machines from the nanoscale up to the scale of meters. The same principles will allow us to understand and when desirable to control the behavior both of complex microsystems such as neurons and computer components, and macrosystems such as human metabolism and transportation vehicles.

b) Revolutionary advances at the interfaces between previously separate fields of science and technology are ready to create key *NBIC transforming tools (nano-, bio, info-, and cognitive based technologies)*, including scientific instruments, analytical methodologies, and radically new material systems. The innovative momentum in these interdisciplinary areas must not be lost but harnessed to accelerate unification of the disciplines. Progress can become self-catalyzing if we press forward aggressively, but if we hesitate the barriers to progress may crystallize and become nearly insurmountable.

c) Developments in system approach, mathematics and computation in conjunction with NBIC allow us for the first time to understand the natural world, social events and humanity as closely coupled unifying concepts of natural sciences *complex, hierarchical systems*. Applied both to particular research problems and to the over-all organization of the research enterprise, this complex system approach provides holistic awareness of opportunities for integration, in order to obtain maximum synergism along main directions of progress.

d) At this unique moment in the history of technical achievement, *improvement of human performance* becomes possible. Caught in the grip of social, political and economic conflicts, the world hovers between optimism and pessimism. NBIC convergence can give us the power to deal successfully with these challenges by substantially enhancing human mental, physical, and social abilities. Better understanding of the human body and development of tools for direct human-machine interaction have opened completely new opportunities. Efforts must center on individual and collective human advancement, in terms of an enlightened conception of human benefit that embraces change while preserving fundamental values.

Most progress over the next century will require use of converging technologies, and it is advisable to take advantage of these benefits sooner rather than later. However, we may not have the luxury of delay, because the remarkable economic, political, and even violent turmoil of recent years implies that the world system is unstable. If we fail to chart the direction of change boldly, we may become the victims of unpredictable catastrophe. New pathways need to be drawn in all major scientific, technological, and societal activities.

The history of science across the vast sweep of human history destroys complacency that progress will somehow happen automatically, without the necessity for vigorous action. Most societies at most points in their history were uninterested in science, and they advanced technologically only very slowly, if at all. On rare occasions, such as the pyramid building age in Ancient Egypt or the roughly contemporaneous emergence of intensive agriculture and trade in Babylon, the speed of progress seemed to accelerate, while remaining much slower than the rate experienced by Europe and North America over the past five centuries. At times, one or another civilization would take the lead, notably China or Islamic Civilization, before falling into utter stagnation.

For modern civilization, the most relevant and instructive precursor remains the classical civilization of Greece and Rome. Building on the scientific accomplishments of the Babylonians and Egyptians, the Greeks accomplished much in mathematics, astronomy, biology, and other sciences. Their technological achievements probably peaked in the Hellenistic Age as city-states gave way painfully to larger political units, culminating in Roman dominance of the entire Mediterranean area. By the end of the second century, if not long before, scientific and technological progress had slowed to a halt, leading to economic and political decline and the inevitable fall of Rome. Historians debate the degree to which technology advanced during the following Dark Ages and Medieval Period, but clearly a mighty civilization had fallen into bloody chaos and widespread ignorance.

The Renaissance, coming a thousand years after the decline and fall of the Roman Empire, reestablished science on a stronger basis than before, and technological advancement has continued unabated since then. The hallmark of the Renaissance was its holistic quality, as all fields of art, engineering, science and culture shared the same exciting spirit and many of the same intellectual principles. Creative individuals were schooled in multiple arts, and a man might be a painter one day, an engineer the next, and a writer the day after that. However, as the centuries passed and institutions such as universities, corporations and government agencies proliferated bureaucratic units, the holism of the Renaissance gave way to specialization and intellectual fragmentation.

It is time to rekindle the spirit of the Renaissance, returning to the holistic perspective on a higher level, with a new set of principles and theories. Essential features of the new society will be established in the novel, unified structure defined by converging technologies to improve human performance.

This report underlines several broad, long-term implications of converging technologies in key areas of human activity:

- Societal productivity, in terms of well-being as well as economic growth
- Security from natural and human-generated disasters

- Individual and group performance and communication
- Life-long learning, graceful aging, and a healthy life
- Coherent technological developments and their integration with human activities
- Human evolution, including individual and cultural evolution

Fundamental scientific research needs at least ten years to be implemented in new technologies, industries, and ways of life. Thus if we want the great benefits of NBIC convergence within our own lifetimes, now is the right time to begin. The impact of advancing technology on the quality of life as it is now (United Nations Development Program 2001) will be accelerated by NBIC, and new possibilities of the human performance will be unleashed.

We are aiming at strategies that would preserve and enhance human values, and would not bring offense to human dignity. The perception of technological changes that would preserve the human condition may evolve in time, such as the increased acceptance of medical implants, but they must not alter the foundations of human life and ethics.

3. Vision for Enhancing Human Abilities and Societal Performance

Despite moments of insight and even genius, the human mind often seems to fall far below its full potential. The level of human thought varies greatly in awareness, efficiency, creativity and accuracy. Our physical and sensory capabilities are limited and susceptible to rapid deterioration in accidents or disease and gradual degradation through aging (Stern and Carstensen 2000). All too often we communicate poorly with each other, and groups fail to achieve their desired goals. Our tools are difficult to handle, rather than being natural extensions of our capabilities. In the coming decades, however, converging technologies promise to increase our level of understanding significantly, transform human sensory and physical capabilities, and improve interactions between mind and tool, individual and team. This report addresses key issues concerning how to reach these goals.

Each scientific and engineering field has much to contribute to enhancing human abilities, to solving the pressing new problems faced by our society in the twenty-first century, and to expanding human knowledge about our species and the world we inhabit. But combined and beginning from the fundamental building blocks, their potential contribution is vast. Following are twenty ways the workshop determined that convergent technologies could benefit humanity in the time frame of 10 to 20 years in the future.

- Fast, broad-bandwidth interfaces directly between the human brain and machines will transform work in factories, control of automobiles, ensure superiority of military vehicles, and enable new sports, art forms and modes of interaction between people.
- Comfortable, wearable sensors and computers will enhance every person’s awareness of his or her health condition, environment, concerning potential hazards, local businesses, natural resources and chemical pollutants.
- Robots and software agents will be far more useful for human beings, because they will operate on principles of human goals, awareness, and personality.
- People from all backgrounds and of all ranges of ability will learn valuable new knowledge and skills more reliably and quickly, whether in school, on the job, or at home.

- Individuals and teams will be able to communicate and cooperate profitably across traditional barriers of culture, language, distance, and professional specialization, thus greatly increasing the effectiveness of groups, organizations, and multi-national partnerships.
- The human body will be more durable, healthy, energetic, easier to repair, and resistant to many kinds of stress, biological threat, and aging process.
- Machines and structures of all kinds, from homes to aircraft, will be constructed of stronger materials that have exactly the desired properties, including the ability to adapt to changing situations, high energy efficiency, and environmental friendliness.
- A combination of technologies and treatments will compensate for many physical and mental disabilities and altogether eradicate some handicaps that have plagued the lives of millions of people.
- National security will be greatly strengthened by light-weight information-rich war fighter systems, capable uninhabited combat vehicles, adaptable smart materials, invulnerable data networks, superior intelligence gathering systems, and effective measures against biological, chemical, radiological, and nuclear attacks.
- Anywhere in the world, an individual will have instantaneous access to needed information, whether practical or scientific in nature, in a form tailored for most effective use by the particular individual.
- Engineers, artists, architects, and designers will experience tremendously expanded creative abilities, both with a variety of new tools and through improved understanding of the wellsprings of human creativity.
- The ability to control the genetics of humans, animals, and agricultural plants will greatly benefit human welfare, in accordance with a widespread consensus about ethical, legal, and moral issues.
- The vast promise of outer space will finally be realized by means of efficient launch vehicles, robot construction of extraterrestrial bases, and profitable exploitation of the resources of the Moon and Mars.
- New organizational structures and management principles based on fast, reliable communication of needed information will vastly increase the effectiveness of administrators in business, education, and government.
- The average person, as well as policy makers, will have a vastly improved awareness of the cognitive, social, and biological forces operating on his or her life, enabling far better adjustment, creativity, and daily decision making.
- Factories of tomorrow will be organized around converging technologies and increased human-machine capabilities as “intelligent environments” that achieve the maximum benefits of both mass production and custom design.
- Agriculture and the food industry will greatly increase yields and reduce spoilage through networks of cheap, smart sensors that constantly monitor the condition and needs of plants, animals, and farm products.

- Transportation will be safe, cheap, and fast, due to ubiquitous real time information systems, extremely high efficiency vehicle designs, and the use of synthetic materials and machines fabricated from the nanoscale for optimum performance.

- The work of scientists will be revolutionized by importing approaches pioneered in other sciences, for example genetic research employing principles from natural language processing and cultural research employing principles from genetics.

- Formal education will be transformed by a unified but diverse curriculum based on a comprehensive, hierarchical intellectual paradigm for understanding the architecture of the physical world from the nanoscale through the cosmic scale.

If we make the correct decisions and investments today, any 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. The twentieth century could well be described by the words of Charles Dickens: "It was the best of times, it was the worst of times." Unparalleled social progress was countered by untold brutality (Caplow et al. 2001), and the twenty-first century dawned with new forms of lethal conflict. Thus, a failure to take advantage of these possibilities could lead not only to lost opportunities but also to catastrophe.

Technological convergence could become the framework for human convergence (Ostrum et al. 2002). The twenty-first century could end in world peace, universal prosperity, and evolution to a higher level of compassion and accomplishment. It is hard to find the right metaphor to see a century into the future, but it may be that humanity would become like a single, transcendent nervous system, an interconnected "brain" based in new core pathways of society. If a concrete image like that shown in Figure 2 seems too confining, then perhaps the right way to sense the convergent future is through a pure, uncluttered emotion: hope.

Figure 2. Vision of the world as an interconnected brain with various architectural levels.

Table 1 shows a simplified framework for classifying improving human performance areas as they relate to an individual (also, see Spohrer 2002, in this volume).

Table 1. Main improvement areas relative to an individual

Relative position	Improvement area
External (outside the body), environmental	New products: materials, devices and systems, agriculture and food New agents: societal changes, organizations, robots, chat-bots, animals New mediators: stationary tools and artifacts New places: real, virtual, mixed
External, collective	Enhanced group interaction and creativity Unifying science education and learning
External, personal	New mediators: mobile/wearable tools and artifacts
Internal (inside the body), temporary	New ingestibles medicines, food
Internal, permanent	New organs: new sensors and effectors, implantables New skills: converging technologies, new uses of old sensors and effectors New genes: new genetics, cells

4. Strategies for Transformation

The main organizations and societal activities are expected to change. To achieve such goals, it is not enough to wait patiently while scientists and engineers do their traditional work. Rather, special efforts are required to break down barriers between fields and to develop the new intellectual and physical resources that are needed. The workshop identified the following general strategies for achieving convergence.

a) We should prepare key organizations and societal activities for the envisioned changes made possible by converging technologies. This requires establishing long-term goals for major organizations and modeling them to be most effective in the new setting.

b) Activities must be enhanced that accelerate convergence of technologies for improving human performance, including focused research, development and design, increased synergy from the nanoscale, developing interfaces among sciences and technologies, and a holistic approach to monitor the resultant societal evolution. A research and development program for exploring the long-term potential is needed.

c) Education and training at all levels should use converging technologies and prepare people to take advantage of them. Interdisciplinary education programs, especially in graduate school, can create a new generation of scientists and engineers who are comfortable working across fields and collaborating with colleagues from a variety of specialties. Essential to this effort is the integration of research and education that combines theoretical training with experience gained in the laboratory, industry, and world of application. A sterling example is NSF's competition called Integrative Graduate Education and Research Training (IGERT). A number of comparable graduate education projects need to be launched, at the intersections of crucial fields, to build the scientific community that will achieve the convergence of technologies that can greatly improve human capabilities.

d) Innovative ideas should be experimented with to focus and motivate needed multidisciplinary developments. For example, there could be a high-visibility annual event, comparable to the sports Olympics, between information technology interface systems that would compete in terms of speed, accuracy, and other measurements of enhanced human performance. Professional societies could set performance targets and establish criteria for measuring progress toward them.

e) Concentrated multi-disciplinary research thrusts could achieve crucially important results in their own right, while integrating nano-bio-info-cogno communities to transform science and engineering. Among the most promising such mega-projects are the Human Cognome Initiative to understand the nature of the human mind, the development of a Communicator system to optimize human teams and organizations, and the drive to enhance human physiology and physical performance. Such efforts probably require the establishment of networks of research centers dedicated to each goal, funded by coalitions of government agencies and operated by consortia of universities and corporations.

f) Flourishing communities of NBIC scientists and engineers will need a variety of multi-user, multi-use research and information facilities. Among these will be data infrastructure archives, employing advanced digital technology to serve a wide range of clients, including government agencies, industrial designers, and university laboratories. Other indispensable facilities would include regional nanoscience centers, shared brain scan resources, and engineering simulation supercomputers. Science is only as good as its instrumentation, and information is an essential tool of engineering, so cutting-edge infrastructure must be created in each area where we desire rapid progress.

g) Integration of the sciences will require establishment of a shared culture that spans across existing fields. Interdisciplinary journals, periodic new conferences, and formal partnerships between professional organizations must be established. A new technical language will need to be developed for communicating about the unprecedented scientific and engineering challenges, based in the mathematics of complex systems, the physics of structure at the nanoscale, and the hierarchical logic of intelligence.

h) We must find ways to address ethical, legal, and moral concerns, throughout the process of research, development, and deployment of convergent technologies. This will require new mechanisms to ensure representation of the public interest in all major NBIC projects, incorporation of ethical and social-scientific education in the training of scientists and engineers, and ensuring that policy makers are thoroughly aware of the scientific and engineering implications of the issues they must face. To live in harmony with nature, we must understand natural processes and be prepared to protect or harness them as required by human welfare. Technological convergence may be the best hope for preservation of the natural environment, because it integrates humanity with nature across the widest range of endeavors, based on systematic knowledge for wise stewardship of the planet.

i) It is necessary to accelerate developments in medical technology and healthcare that would take advantage of converging technologies, including molecular medicine and nano-engineered medication-delivery systems, assistive devices to alleviate mental and emotional disabilities, rapid sensing and preventive measures to block the spread of infectious and environmental diseases, continuous detecting and correcting abnormal individual health, and the integration of genetic therapy and genome-aware treatment into daily medical practice. To accomplish this, research laboratories, pharmaceutical companies, hospitals and health maintenance organizations, and medical schools will need to expand greatly their institutional partnerships and technical scope.

General Comments

There should be specific partnerships among high-tech agencies and university researchers, in areas such as space flight, where a good foundation for cutting edge technological convergence already exists. But in a range of other areas it will be necessary to build scientific communities and research projects nearly from scratch. It could be important to launch a small number of well-financed and well-designed demonstration projects to promote technological convergence in a diversity of currently low-tech areas.

The American economy has benefited greatly from the rapid development of advanced technology, both through increased international competitiveness and through growth in new industries. Convergent technologies could transform some low-tech fields into high-tech fields, thereby increasing the fraction of the American economy that is both growing and world-preeminent.

This beneficial transformation will not take place without fundamental research in fields where it has tended to be rare, and without the intensity of imagination and entrepreneurship that can create new products, services, and entire new industries. We must begin with a far-sighted vision that a New Renaissance in science and technology can be achieved through the convergence of nanotechnology, biotechnology, information technology and cognitive science.

5. Towards Unifying Science and Converging Technology

Although recent progress in the four NBIC realms has been remarkable, further rapid progress in many areas will not happen automatically. Indeed, science and engineering have encountered several barriers, and others are likely to appear as we press forward. In other areas, progress has been hard-won, and anything that could accelerate discovery would be exceedingly valuable.

For example, cognitive neuroscience has made great strides recently unlocking the secrets of the human brain, with such computer-assisted techniques as functional magnetic resonance imaging (fMRI). However, current methods already use the maximum magnetic field strength that is considered safe for human beings. The smallest structures in the brain that can routinely be imaged with this technique are about a cubic millimeter in size, but this volume can contain tens of thousands of neurons, so it really does not let scientists see many of the most important structures, which are closer to the cellular level. To increase the resolution further will require a new approach, whether novel computer techniques to extract more information from fMRI data, or a wholly different method to study the structure and function of regions of the brain, perhaps based in a marriage of biology and nanotechnology.

Progress in information science has depended largely upon the constant improvement in the speed and cost effectiveness of integrated circuits. However, current methods are nearing their physical limits, and it is widely believed that progress will cease in a few years unless new approaches are found. Nanotechnology offers realistic hope that it will be possible to continue the improvement in hardware for a decade or even two decades longer than current methods will permit. Opinion varies on how rapidly software capabilities are improving at the present time, but clearly software efficiency has not improved at anything like the rate of hardware, so any breakthrough that increases the rate of software progress would be especially welcome. One very promising direction to look for innovations is biocomputing, a host of software methods that employ metaphors from such branches of biology as genetics. Another is cognitive science, which can help computer scientists develop software inspired by growing understanding of the neural architectures and algorithms actually employed by the human brain.

Many other cases could be cited in which discoveries or inventions in one area will permit progress in others. Without advances in information technology, we cannot take full advantage of biotechnology in areas such as decoding the human genome, modeling the dynamic structure of protein molecules, and understanding how genetically engineered crops will interact with the natural environment. Information technology and microbiology can provide tools for assembling nanoscale structures and incorporating them effectively in microscale devices. Convergence of non-organic nanoscience and biology will require breakthroughs in how we conceptualize and teach the fundamental processes of chemistry in complex systems, which could be greatly facilitated by cognitive science research on scientific thinking itself.

The goal is nothing less than a fundamental transformation of science and engineering. Although the lists of potential medium-term benefits have naturally stressed applications, much of the unification must take place on the level of fundamental science. From empirical research, theoretical analysis, and computer modeling we will have to develop overarching scientific principles that unite fields and make it possible for scientists to understand complex phenomena. One of the reasons why sciences have not merged in the past is that their subject matter is so complex and challenging to the human intellect. We must find ways to rearrange and connect scientific findings so that scientists from a wider range of fields can comprehend and apply them within their own work. Thus it will be necessary to support fundamental scientific research in each field that can become the foundation of a bridge to other fields, as well as supporting fundamental research at the intersections of fields.

Fundamental research will also be essential in engineering, including computer engineering, because engineers must be ready in future to take on entirely new tasks from those they have traditionally handled. The traditional toolkit of engineering methods will be of limited utility in some of the most important areas of technological convergence; so new tools will have to be created. This has already begun to happen in nanotechnology, but much work remains to be done developing engineering solutions to the problems raised by biology, information, and the human mind.

It is possible to identify a number of areas for fundamental scientific research that will have especially great significance over the coming twenty years for technological convergence to improve human performance. Among these, the following four areas illustrate how progress in one of the NBIC fields can be energized by input from others.

- *Entirely new categories of materials, devices and systems for use in manufacture, construction, transportation, medicine, emerging technologies and scientific research.* Nanotechnology is obviously preeminent here, but information technology plays a crucial role in both research and design of the structure and properties of materials, and in the design of complex molecular and microscale structures. It has often been pointed out that industries of the future will use engineered biological processes to manufacture valuable new materials, but it is also true that fundamental knowledge about the molecular-level processes essential to the growth and metabolism of living cells may be applied through analogy to development of new inorganic materials. Fundamental materials science research in mathematics, physics, chemistry, and biology will be essential.

- *The living cell, which is the most complex known form of matter with a system of components and processes operating at the nanoscale.* The basic properties and functions are established at the first level of organization of biosystems that is at the nanoscale. Recent work at the intersection of biotechnology and microelectronics, notably the so-called gene-on-a-chip approach, suggests that a union of nanotechnology, biotechnology, and computer science may be able to create "bio-nano processors" for programming complex biological pathways on a chip that mimic cellular processes. Other research methodologies may come for the ongoing work to understand how genes are expressed in the living body as physical structures and chemical activities. Virtual reality and augmented reality computer technology will allow scientists to visualize the cell from inside, as it were, and to see exactly what they are doing as they manipulate individual protein molecules and cellular nanostructures.

- *Fundamental principles of advanced sensory, computational and communications systems, especially the integration of diverse components into the ubiquitous and global network.* Breakthroughs in nanotechnology will be necessary to sustain the rapid improvement of computer hardware over the next twenty years. From biology will come important insights about the behavior of complex dynamic systems, and specific methods of sensing organic and chemical agents in the environment. Cognitive science will provide insights about how to present information to human beings so they can use it most effectively. A particularly challenging set of problems confronting computer and information science and engineering at the present time is how to achieve reliability and security in a ubiquitous network that collects and offers diverse kinds of information in multiple modalities, everywhere and instantly at any moment.

- *The structure, function, and occasional dysfunction of intelligent systems, most importantly the human mind.* Biotechnology, nanotechnology and computer simulations can offer powerful new techniques for studying the dynamic behavior of the brain, from the receptors and other structures far smaller than a single neuron, up through individual neurons, functionally specific modules composed of many neurons, the major components of the brain, and then the entire brain as a complex but unified system. Cognition cannot be understood without attention also to the interaction of the individual with the environment, including the ambient culture. Information technology will be crucial in processing data about the brain, notably the difficult challenge of understanding the mature human brain as a product of genetics and development. But it will also be essential to experiment with artificial intelligent systems, such as neural networks, genetic algorithms, autonomous agents, logic-based learning programs, and sophisticated information storage and retrieval systems.

The complementarity of the four areas is suggested by the statement of workshop participant W.A. Wallace:

> If the *Cognitive Scientists* can think it
> the *Nano* people can build it
> the *Bio* people can implement it, and
> the *IT* people can monitor and control it

Each of the four research challenges described above focuses on one of the areas (nanoscience, biology, information science, and cognitive science) and shows how progress can be catalyzed by convergence with the other areas. They are not merely convenient didactic examples, but represent absolutely fascinating questions, the answers to which would enable fantastic improvements in human performance. However, convergence will be possible only if we overcome substantial intellectual barriers.

Especially demanding will be the development of a hierarchical architecture for integrating sciences across many scales, dimensions, and data modalities. For a century or more, educated people have understood that knowledge can be organized in a hierarchy of sciences, from physics as a base, up through chemistry and biology, to psychology and economics. But only now is it really possible to see in detail how each level of phenomena rests upon and informs the one below. Some partisans for independence of biology, psychology, and the social sciences have argued against “reductionism,” asserting that their field had discovered autonomous truths that should not be reduced to the laws of other sciences. But now we realize that such discipline-centric propaganda is self-defeating, because only through recognizing their connections with each other can all the sciences progress. A trend towards unifying knowledge by combining natural sciences, social sciences and humanities using cause-and-effect explanation has already begun (NYAS 2002), and it should be reflected in the coherence of science and engineering trends (Roco 2002, in this report) and in the integration of R&D funding programs.

The architecture of the sciences will be built through understanding of the architecture of nature. At the nanoscale, atoms and simple molecules connect into complex structures like DNA, the subsystems of the living cell, or the next generation of microelectronic components. At the microscale, cells such as the neurons and glia of the human brain interact to produce the transcendent phenomena of memory, emotion, and thought itself. At the scale of the human body, a myriad processes of chemistry, physiology and cognition unite to form life, action, and an individual capable of creating and benefiting from technology.

Half a millennium ago, Renaissance artist-engineers like Leonardo da Vinci, Filippo Brunelleschi, and Benvenuto Cellini 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 understanding of the physical world from the nanoscale to the planetary scale. In the New Renaissance, everyone will be able to achieve creative excellence.

6. Major Themes

A planning group meeting was held May 11, 2001, at the National Science Foundation to develop the agenda for the December workshop and to identify key participants from academia, industry and government. Scientific leaders and policy makers across a range of fields were asked to prepare formal speeches for plenary sessions, and all participants were invited to contribute written statements evaluating the potential impact of NBIC technologies on improving human capabilities at the microscopic, individual, group, and societal levels.

Participants in the December workshop on Convergent Technologies to Improve Human Performance submitted more than fifty written contributions, and each is like a single piece in a jigsaw puzzle. Together, they picture the future unification of nanotechnology, biotechnology, information technology, and cognitive science, with the amazing benefits they promise. Roughly half of these, which we call *statements*, describe the current situation and suggest strategies for building upon it. The other half is *visions* of what could be accomplished in ten or twenty years. During the workshop, participants examined the vast potential in five different areas of relevance, as well as the overall potential of changing the economy, society and research needs:

a) **Overall Potential of Converging Technologies.** In plenary sessions of the workshop, representatives of government agencies and the private sector set forth the mission to explore the potential of converging technologies to improve human performance. They have identified the synergistic development of nano, bio, information and cognition-based technologies as the outstanding opportunity at the interface and frontier of sciences in the following decades. They proclaimed that it is essential to courageously identify new technologies that have great potential, develop transforming visions for them, and to launch new partnerships between government agencies, industry and educational institutions to achieve this potential. Government has an important role in setting long-term research priorities, respecting ethical and social aspects of potential uses of technology, and ensuring economic conditions that facilitate the rapid invention and deployment of beneficial technologies. Technological superiority is the fundamental basis of the economic prosperity and national security of the United States, and government agencies need progress in NBIC in order to accomplish their designated missions. Science and engineering must offer society new visions of what it is possible to achieve through interdisciplinary research projects designed to promote technological convergence.

b) **Expanding Human Cognition and Communication.** This group of workshop participants examined needs and opportunities in the areas of human cognitive and perceptual functions, communication between individuals and sociable machines, and the ways that convergent technologies could enhance our understanding and effective use of human mental abilities. It identified five areas where accelerated efforts to achieve technological convergence would be especially worthwhile. Highest priority was given to what Robert Horn called *The Human Cognome Project*, a multidisciplinary effort to understand the structure, functions, and potential enhancement of the human mind. The four other priority areas were: personal sensory device interfaces; enriched community through humanized technology; learning how to learn; and enhanced tools for creativity.

c) **Improving Human Health and Physical Capabilities.** This group also focused primarily on the individual, but on his or her physical rather than mental abilities. Essential to progress in this area is comprehensive scientific understanding of the fundamental chemical and biological processes of life. Control of metabolism in cells, tissue, organs, and organisms is sought. Direct conversion of bio-molecular signals and useful neural codes to man-made motors will open opportunities to direct brain control of devices in neuromorphing engineering. Six technological capabilities for improvement of human health and physical performance received high priority: bio-nano processors for development of treatments; nanotechnology-based implants as replacement for human organs (M. Lavine et al. 2002) or for monitoring of physiological well-being; nanoscale robots and comparable unobtrusive tools for medical intervention; extending brain to brain and brain to machine interfaces using the neural system; multi-modality platforms for visual and hearing impaired people; and virtual environments for training, design, and forms of work unlimited by distance or the physical scale on which it is performed.

d) **Enhancing Group and Societal Outcomes.** This group examined the implications of technological convergence for human social behavior, social cognition, interpersonal relations, group processes, the use of language, learning in formal and informal settings, and the psychophysiological correlates of social behavior. A wide range of likely benefits have been identified to communities and the nation as a whole, and a specific vision has been proposed of how these could be achieved through a focused research effort to develop a system it called *The Communicator*. This NBIC technology 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.

e) **National Security.** This group of workshop participants examined the radically changing nature of conflict in this new century, and the opportunities to strengthen national defense offered by technological convergence. It identified seven highly diverse goals: 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; exoskeletons for physical performance augmentation; preventing brain changes by sleep deprivation; and applications of brain-machine interfaces. These highly varied goals could be achieved through distinctive convergences of technologies.

f) **Unifying Science and Education.** The final group examined the opportunities form unifying science and the current limitations of scientific education, which is poorly designed to meet the coming challenges, and documented the need for radical transformation from elementary school through post-graduate training. Part of the answer will come from the convergence of NBIC technologies themselves, which will offer valuable new tools and modalities for education. But 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 across (Figure 3; see Tolles 2002, in this volume).

New curriculum, new concepts to provide intellectual coherence, and new forms of educational institution will be necessary.

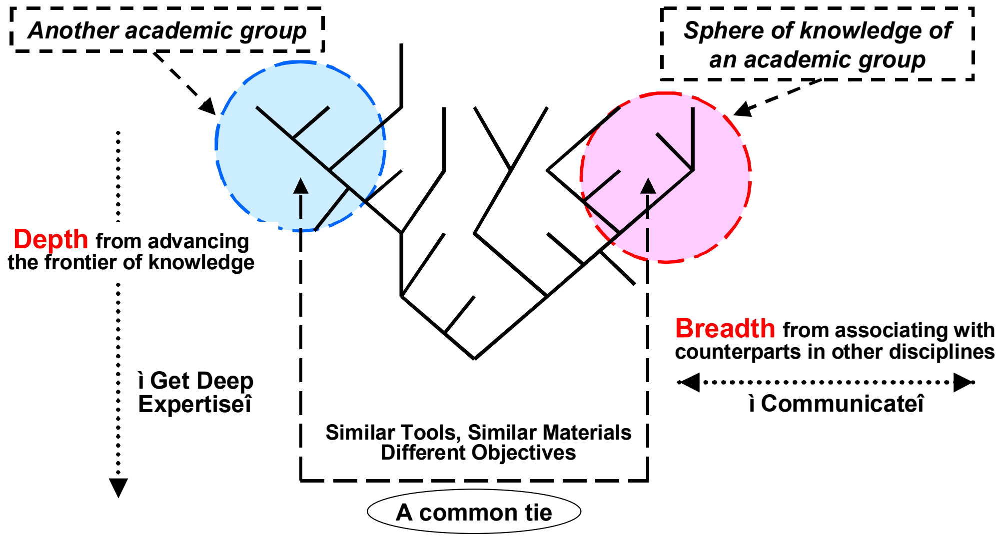

Figure 3. Combining "depth with breath" in NBIC education and research of various groups.

Thus, based on the contributions of individual participants and the work of the five sub-groups, the meeting identified the major areas where increased human performance is needed, and identified both short-term and longer-term opportunities to apply convergent technologies to these needs. A summary of key visionary projects in the next decades that are discussed in the present report is given in Table 2. Progress was made in developing a transforming management plan for what should be done to integrate the sciences and engineering in accordance with the convergent technologies vision, including advice to government policy makers. In addition, the meeting recognized specific needs to develop meaningful partnerships and coherent interdisciplinary activities.

7. Future Prospects

Nanotechnology, biotechnology and information technology are moving closer together, following an accelerated path of unparallel breakthroughs. Their focus on human dimensions is still emerging but promises to dominate the next decades. Despite the efforts organizing this report, given the broadness of the field, it was impossible to recruit leading experts in all the areas where the convergence of NBIC technologies are obviously likely to have significant impacts in 10 to 20 years. In addition, work has really not begun in some of the key application areas, and new areas are likely to emerge that have not yet attracted the attention of many scientists and engineers. Thus, it is worth considering the following admittedly speculative additional ideas on how technological convergence may transform human abilities two decades and more in the future. Many of them emerged during the workshop, and others were suggested in discussions with participants afterward.

Table 2. Key visionary ideas and projects discussed in this report

Theme	Key visionary ideas/projects
A. Overall Potential of Converging Technologies	NBIC strategy for technological and economical competitiveness
	New patterns for S&T, economy, and society
	Enhancing individual and group abilities, productivity and learning
	Changing human activities towards the "innovation age"
B. Expanding Human Cognition and Communication	Human cognome project, and cognitive evolution
	Brain to brain interactions, and group communication
	Spatial cognition and visual language using converging technologies
	Enhanced tools for learning and creativity
	Predictive science of societal behavior
C. Improving Human Health and Physical Capabilities	Healthcare, body replacements, and physiological self-regulation
	Brain-machine interfaces, and neuromorphing engineering
	Improving sensorial capacities and expanding functions
	Improving quality of life of disabled people
	Aging with dignity, and life extension
D. Enhancing Group and Societal Outcomes	The Communicator: enhancing group interaction
	Cognitive engineering and enhancing productivity
	Revolutionary products, including "aircraft of the future"
	Networked society, with bio-inspired culture
E. National Security	Enhancing physical and mental capacity of a soldier
	Enhancing readiness, and threat anticipation tools
	Globally linked detection devices
	Uninhabited combat vehicles
F. Unifying Science and Education	Unifying science from the nanoscale and integrative principles
	Cognitive, civic, and ethical changes in a netwoked society
	Breadth, depth, trading zones, and reshaping education at all levels
	Changing the human culture

Work Efficiency

Improvement of human physical and mental performance, at both the individual and group level, can increase productivity greatly. Several concepts are in development that could enhance working environments (cf. IBM 2002). To remain competitive, American industry must continue to find ways to improve quality and efficiency (Mowery 1999; Jorgenson and Wessner 2002). Nanotechnology promises to become the most efficient length scale for manufacturing (NNI priorities 2001) because rearranging the matter at the nanoscale via weak molecular interactions would require less energy and material. The recent trend toward intensive electronic monitoring and just-in-time inventories has reduced waste, but tightening the efficiency of manufacturing and distribution supply chains could prove to be a one-time-only improvement in profitability that could not be duplicated in the future (Committee on Supply Chain Integration 2000).

However, application of new generations of convergent technology has the potential to provide better value to customers at lower cost to producers, offering the possibility of further profitability improvements. For example, even more intensive use of information technology in conjunction with nanotechnology, biotechnology and cognitive sciences could reduce waste and pollution costs near zero, and permit very rapid reconfiguration of manufacturing processes and product lines (Committee on Visionary Manufacturing Challenges 1998). Business and industry are already beginning to restructure themselves on a global scale, as network-based organizations following fundamentally new management principles.

Biology in conjunction with nanoscale design and IT control has the potential to contribute both abstract models and specific physical processes to the development of customer-centric production that blends the principles of custom-design craftsmanship (which maximizes customer satisfaction) with the principles of assembly-line mass production (which minimizes production costs). In the gestation of higher animals, a single fertilized egg cell differentiates rapidly into specialized cells that grow into very different organs of the body, controlled in a complex manner by the messenger chemicals produced by the cells themselves. Whether based in nanotechnology, information technology, biotechnology, or cognitive based technology, new adaptive production systems could be developed that automatically adjust design features in a way analogous to the growing embryo, without the need to halt production or retool. Convergence of these four technologies could also develop many bio-inspired processes for "growing" key components of industrial products, rather than wastefully machining them out of larger materials or laboriously assembling them from smaller parts (cf. Committee on Biobased Industrial Products 1999).

The Human Body and Mind Throughout the Life Cycle

Improving perceptual capabilities, biohybrid systems, exoskeletons, and metabolic enhancement can be considered for human performance augmentation. Medical implants for sensory replacement, including multi-modalities for visually and hearing impaired, and direct brain-machine interfaces are real possibilities. Controlled metabolism in cells, specific tissues, organs, or the entire body is possible. One application would be increased endurance and resistance to sleep deprivation, while another is a method of optimizing oxygenization of blood when metabolism is compromised in a critical medical situation. Others would be real time genetic testing so that individually tailored drugs can be provided to patients, and an artificial pancreas that would monitor and adjust the release of hormones in the human body.

Increasing intellectual capabilities requires understanding the brain and simulating its processes. Knowledge about the structure, function, and occasional dysfunction of the human mind will provide new ways to increase cognitive capabilities (Steve et al. 2002; National Research Council 1988). Reverse engineering of the human brain is envisioned to be accomplished in about two decades, and it would allow for better understanding of its functions. An artificial brain could be a tool for discovery, especially if computers could closely simulate the actual brain. It would be revolutionary to see if aspects of human consciousness could be transferred to machines (Kurzweil 1999) in order to better interact and serve humans.

Sustaining human physical and mental abilities throughout the life span would be facilitated by progress in neuroscience (Stern and Carstensen 2000) and cellular biology at the nanoscale. An active and dignified life could be possible far into a person's second century, due to the convergence of technologies (cf. Saxl 2002). Gene therapy to cure early aging syndromes may become common, giving vastly improved longevity and quality of life to millions of people.

Communication and Education

New paradigms in communication (brain-to-brain, brain-machine-brain, group interaction) are promising to become reality in 10-20 years. Neuromorphic engineering will allow transmitting thoughts and biosensor output from the human body to devices for signal processing. Wearable computers with power similar to that of the human brain will act as personal assistants or brokers, providing valuable information of every kind in forms optimized for the specific user. Visual communication will complement verbal communication, sometimes replacing spoken language when speed is a priority or enhancing speech when needed to exploit maximum mental capabilities (Horn 2002; Hewlett Packard 2002).

People will acquire a radically different instinctive understanding of the world as a hierarchy of complex systems rooted in the nanoscale. Advances in cognitive science will enable nanoscience education, by identifying the best ways for students to conceptualize nanostructures and processes, at increasingly advanced stages in their learning (National Institute of Mental Health 2002). Education at all levels will exploit augmented reality, in which multi-media information displays are seamlessly integrated into the physical world. Strategies for hierarchical, architectural, global analysis and design of complex systems will integrate the curriculum of schools and inform management decisions across a diverse range of fields.

Mental Health

In many respects, perhaps the most difficult challenge we face in improving human performance is mental illness (Anderson 1997). For fully the past two centuries, psychiatry has alternated between periods of optimism and pessimism, as well as between competing psychological, social, physiological, chemical, and genetic theories of mental illness. We can hope that these disputes could be resolved through physiological and psychological understanding of mental processes, and that scientific convergence will achieve lasting cures through a combination of biological and cognitive treatments, all assisted by information and nanoscale technologies.

Nanotechnology will provide means to deliver medications to the exact location within the brain where they are needed, thus minimizing negative side effects elsewhere in the nervous system. The convergence of cognitive science with the three technologies should permit systematic evaluation of the bewildering range of current psychiatric theories and therapies, and allow clinicians to improve the best treatments. It is also possible that convergent communications and robotics technologies may produce an entirely new category of prosthetic or assistive devices that compensate for cognitive or emotional deficiencies.

Aeronautics and Space Flight

NBIC synergies could greatly expand human adaptive aircraft, unmanned aircraft and human space flight capabilities. Nanostructured materials and advanced electronics have the promise of reducing the weight of spacecraft by ¾ in the next 10-20 years. Specific subsystems for human space flight may also be revolutionized by the same combination of technologies, for example durable but light and self-repairing spacesuits, high performance electronics with low demands for electric power, and low-cost but high-value large orbiting structures. If the problems of orbital launch and efficient subsystems can be solved, then human society can effectively exploit and inhabit Earth orbital space, the Moon, and the planet Mars. Several participants in the workshop noted the potential for intelligent machines of the future to take on progressively more human characteristics, so we can well imagine that the first pioneers that take "humanity" far into space will be descendents of Pathfinder and the Voyagers that have been endowed not only with intelligence but also with personality.

Food and Farming

Farmers have long appreciated the advantages of science and technology, and the convergence of nanotechnology, biotechnology, and information technology could significantly improve their effectiveness. For example, nanoscale genetics may help preserve and control food production. Inexpensive nano-enabled biosensors could monitor the health and nutrition of cattle, transmitting the data into the farmer's personal computer that advises him about the care needed by the animals. In the same way, sensors distributed across farmland could advise the farmer about need for water and fertilizer, thus avoiding wastage and achieving the most profitable acreage crop yield (Committee on Assessing Crop Yields 1997). Bio-nano convergence can provide new ways of actually applying the treatment to the crops, increasing the efficiency of fertilizers and pesticides.

Use of nano-enabled biosensors would monitor freshness to help grocers avoid selling stale goods and to avoid the wastage of discarding perfectly good packaged food that had merely reached an arbitrary shelf life date. The consumer should have access to the same information, both before and after purchase. Many consumers are dissatisfied with the limited information about ingredients on many packaged foods, and the total lack of information about foods served in restaurants. Convergent technologies could provide portable instruments, for example packaged into a pen-like device or perhaps a ring, that could instantly tell the consumer how much sodium, fats, or allergenic substances a food contained.

Sustainable and Intelligent Environments

Sustainable resources of food, water, energy and materials are achievable through converging technologies. Exact manufacturing, exact integration in biosystems, and IT control will lead to a long period of stability in the supply of resources. Value will inhere in information, including that embodied in the complex structure of manufactured items made from the nanoscale out of common chemical elements, rather than in rare metals or non-renewable energy supplies. Sensing the environment and biosystems of the world will become essential in global monitoring and remediation. New sources for a distributed energy system are envisioned, as well as new solutions, like highly efficient photosynthetic proteins, membranes and devices.

External surfaces of buildings could automatically change shape and color to adjust to different conditions of temperature, lighting, wind, and precipitation. Once the science, manufacturing processes, and economic markets had developed sufficiently, adaptive materials need not be especially expensive, especially when the increased performance and energy efficiency are factored in. For example, nanotechnology materials and information technology assisted design could produce new, durable house paints that change color, reflecting heat on hot days and absorbing heat on cold days. Indoors, ordinary walls could be vast computer displays, capable of enhancing the residents' aesthetic experience by displaying changing virtual artworks and wallpapers. Adaptive materials could obtain their energy from temperature differentials between different surfaces (thermocouples) or naturally occurring vibrations (piezoelectric), rather than requiring any electrical input. The ability to engineer inexpensive materials on the nanoscale will be crucial, and information technology can help design the materials as well as being designed into some of the adaptive systems. There also will be a role for cognitive science, because architects need to take account of human needs and the often unexpected ways that human beings may respond to particular design features.

Self-Presentation and Fashion

Government-supported academic researchers frequently ignore many economically important industries, in part because traditionally they have not involved advanced technology but also perhaps because they were not perceived as "serious" fields. Among these are clothing fashions, jewelry, and cosmetics. Stereotypes aside, these are multi-billion dollar industries that could benefit from the new opportunities afforded by convergent technologies. In social life, physical attractiveness is very important. Anything that enhances a person's beauty or dignity improves that individual's performance in relations with other people.

Convergence of nanotechnology and biotechnology with cognitive science could produce new kinds of cosmetic that changed with the user's moods, enhancing the person's emotional expressiveness. Components of wearable computers could be packaged in scintillating jewelry, automatically communicating thoughts and feelings between people who were metaphorically and electronically "on the same wave length." Biotechnology could produce new materials that would be combined in manufacturing with nanotechnology-based information technology to produce clothing that automatically adjusted to changing temperatures and weather conditions. Perhaps the colors and apparent textures of this "smart clothing" would adjust to the wearer's activities and social environment.

Transformation of Civilization

The profound changes of the next two decades may be nothing compared to the utter transformation that may take place in the remainder of the century. Processes both of decentralization and integration will render society ever more complex, resulting in a new, dynamic social architecture. There will be entirely new patterns in manufacturing, economy, education, and military conflict. Communities, government and business administrations, and communication channels will be distributed geographically and across various levels of reality: material, informational, and cultural.

People will possess entirely new capabilities for relations with each other, with machines, and with the institutions of civilization. In some areas of human life, old customs and ethics will persist, but it is difficult to predict which realms of action and experience these will be. Perhaps wholly new ethical principles will govern in areas of radical technological advance, such as the routine acceptance of brain implants, political rights for robots, and the ambiguity of death in an era when people upload aspects of their personalities to the Solar System Wide Web. Human identity and dignity must be preserved. In the same way in which machines were built to surpass human physical powers in the industrial revolution, computers can surpass human memory and computational speed for designed actions. The ultimate control will remain with humans and human society. With proper attention to safeguards, ethical issues, and societal needs, quality of life could increase significantly.

New professions for humans and new roles for machines may arise to mediate between all this complexity and the individual person. Art, music, and literature may attain new levels of subtlety and sophistication, enhancing the mental qualities of life, or the innate human love for beauty may cherish the simple feelings of joy that people have shared since the dawn of our species.

A networked society of billions of human beings could be as complex compared to an individual human being as a human being is to a single nerve cell. From local groups of linked enhanced individuals to a global collective intelligence key new capabilities would arise from relationships arising from NBIC technologies. Such a system would have distributed information and control, and new patterns of manufacturing, economic activity and education. Far from unnatural, such a collective social system may be compared to a larger form of a biological organism. Biological organisms themselves make use of many structures such as bones and circulatory system. The networked society anticipated through NBIC convergence will explore new pathways in societal structures, in an increasingly complex system (Bar-Yam 1997).

It may be possible to develop a predictive science of society and to apply advanced corrective actions, based on the convergence ideas of NBIC. Human culture and human physiology may undergo rapid evolution, intertwining like the twin strands of DNA, hopefully guided by analytic science as well as traditional wisdom. As Table 3 suggests, the pace of change is accelerating, and scientific convergence may be a watershed in history to rank with the invention of agriculture and more significant than the Industrial Revolution.

Table 3. History of some very significant augments to human performance: Improving our ability to collectively improve ourselves (see also Spohrer 2002)

Generations	Several Key Advancements (human kind, tools and technology, communication)
	Cell, body and brain development
- 100,000	Old Stone Age (Paleolithic), Homo Erectus, speech
-10,000	Homo Sapiens, making tools
-500	Mesolithic, creating art
-400	Neolithic, agricultural products, writing, libraries
-40	Universities
-24	Printing
-16	Renaissance in S&T, accurate clocks
-10	Industrial revolution
-5	Telephone
-4	Radio
-3	TV
-2	Computers
-1	Microbiology, Internet
0	Reaching at the building blocks of matter (nanoscience) Biotechnology products Global connection via Internet; GPS/sensors for navigation
1/2	Unifying science and converging technologies from the nanoscale Nanotechnology products Improving human performance advancements Global education and information infrastructure
1	Converging technology products for improving human physical and mental performance (new products and services, brain connectivity, sensory abilities, etc.) Societal and business reorganization
n	Evolution transcending human cell, body, and brain?

8. Recommendations

The recommendations of this report are far-reaching and fundamental, urging the transformation of science at its very roots. But the recommendations also seek to preserve the wonderful accomplishments of science and sustain the momentum of discovery that has been energized by generations of scientists. Only by evolving, can science continue to thrive and make the vast contributions to society of which it is capable in the coming decades. There are outstanding opportunities that were not available in the past. The new developments will be revolutionary and must be governed by respect for human welfare and dignity.

Specific Areas for Research and Education Investment

The research and education needs are both deep and broad. In order to connect disciplines at their interfaces, understand and assemble matter from its building blocks, while focusing on a broad system perspective and improving human performance, research and education must have deep scientific roots and superior communication among the fields.

The following general integrative approaches have been identified as essential to NBIC:

- Development of the NBIC tools for investigation and transformational engineering at four levels: nano/microscopic, individual, group, and society
- NBIC integration of fundamental concepts across all scales, beginning with the nanoscale
- System, holistic based investigations of converging technologies
- Focus of future technological developments on implications for improving human performance

These principles concern the research methods, theoretical analyses, systemic perspective, and human benefit dimensions of scientific and technological integration. Sharing research techniques and engineering tools is one way that scientists in traditionally different fields can integrate their work. Another is utilization of similar ideas, mathematical models, and explanatory language. In approaching complex systems, the hierarchical architecture in which various components are integrated and used is expected to be a major challenge. Consideration of the human implications of converging technologies will include examination of potential unexpected consequences of NBIC development, ethical, and legal aspects.

Recommendations to Individuals and Organizations

This report has educational and 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 main transforming measures are outlined in section 4 of this summary. The opportunity is broad, enduring and of general interest. The report contributors addressed the roles that individuals, academe, the private sector, US Government, professional societies and other organization should play in this converging technology priority area.

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 technology convergence for enhancing human performance.

b) **Academe.** Educational institutions at all levels should undertake major curricular and organizational reforms to restructure the teaching of science and engineering so that previously separate disciplines can converge around common principles to train the technical labor force for the future. The basic concepts of nanoscience, biology, information and cognitive sciences should be introduced at the beginning of undergraduate education; technical and humanistic degrees should have common courses and activities related to NBIC and human dimensions of science and technology. System based investigations of converging technologies will focus on the holistic aspects and synergism. The hierarchical architecture in which various components are integrated and used is expected to be a major challenge.

c) **Private Sector.** Manufacturing, biotechnology, and information service corporations will need to develop partnerships of unparalleled scope to exploit the tremendous opportunities from technological convergence, engaging in joint ventures with each other, establishing research linkages with universities, and investing in production facilities based on entirely new principles and materials, devices and systems.

d) **Government.** Establish a national research and development priority area on converging technologies focused on enhancing human performance. Organizations should provide leadership to coordinate 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. Special effort will be required to identify future technological developments, explore their implications for human performance, study unexpected consequences of NBIC development, and consider ethical, legal and policy issues. Governments must provide support for education and training for future NBIC workers and to prepare society for the major systemic changes envisioned in a generation from now. Policy makers must envision development scenarios to creatively stimulate the convergence. Societal implications must be addressed from the beginning, involving leading NBIC and social scientists and a broad coalition of professional and civic organizations. The transforming measures outlined in section 4 suggest the dimensions of the Federal Government role.

e) **Professional Societies.** The scientific community 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 organizations, and address ethical issues related to technological developments. Through mechanisms like conferences and publications, professional societies can seed the NBIC ideas in learning organizations, society at large, and funding agencies.

f) **Other Organizations.** Non-governmental organizations that represent potential user groups should contribute to the design and testing of convergent technologies and recommend NBIC priorities, 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 public media 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. Therefore, 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*. Advancing knowledge and transforming tools will move our activities from simple repetitions to creative, innovative acts, and transfer the focus from machines to human development.

Converging technologies are at the confluence of key disciplines and areas of relevance, and the role of government is important because no other participant can cover the breath and level of required collective effort. Without special efforts and coordination, the path of science is unpredictable, and might not lead to the fundamental unification envisioned here. 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.

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